UNDER THE SEA IN NORWAY

Over 100 km of subsea tunnels have been constructed in Norway, and during the last ten years most of these have been for transport purposes, although some have also been built to bring pipelines ashore from the North Sea oil fields. Altogether more than 80 km of subsea tunnels have been constructed since 1980, as shown in Table I. More than 500 intakes in reservoirs have been made by submerged piercing[1]: this Norwegian speciality, known as 'lake tap', is not dealt with in this article.

Among the subsea tunnel projects under construction in the summer of 1995 the following should be mentioned:

- Slöverfjorden, a 3.3 km long two-lane road tunnel (50 m^2) in gneiss and gabbro with the deepest point 110 m below sea level. It has a maximum gradient of 1:12.
- Mageröy, a 6.8 km long two-lane (53 m^2) road tunnel in rocks of sedimentary origin (meta-greywacke, clay schist, sandstone) with the deepest point 220 m below sea level. It has a maximum gradient of 1:12.
- Bjoröy tunnel, a road tunnel with its lowest point 82 m below sea level. This tunnel has experienced very difficult ground conditions with highly permeable and partly unstable ground over a large part of its 2 km length.

Many possible subsea tunnel projects have been studied over the last 10 years, including three parallel 6 m diameter TBM tunnels 60 km long at 500 m depth to bring pipelines from a near offshore oil field to the Norwegian mainland[2], and a 45 km long railway tunnel beneath a deep fjord.

DESIGN

All Norwegian subsea tunnels have been excavated by drill-and-blast and have achieved an average advance rate of 40-80 m/week. The total construction cost of a subsea road tunnel amounts to $4,500-10,000/m of tunnel, of which the excavation part (drill, blast and mucking out) constitutes about $1,500/m. The rock supporting works, which are designed for the rock-mass conditions encountered in the tunnel, mainly consist of fibre-reinforced shotcrete and rock bolts.

The permanent water leakage amounts to 0.1-0.45 m^3/min/km of tunnel.

Over the past 40 years, Norwegian contractors have become some of the most skilled in hard-rock tunnelling. The many hundreds of kilometres of tunnel driven in connection with hydropower development, underground storage and transport have resulted in an accumulation of experience which is equalled in few other countries in the world. An important feature has been the willingness of the tunnelling

Mainland portal for Vardö tunnel with Vardö Island.

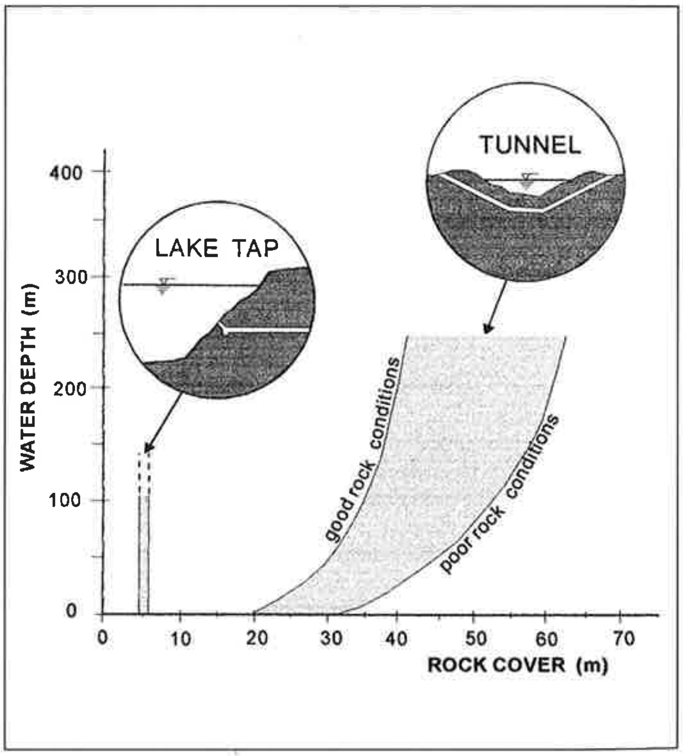


Fig. 1: Minimum rock cover used in Norwegian subsea tunnels.

Portal on Bjoröy Island. This tunnel broke through on August 16, 1995.

Table I: Subsea tunnels constructed in Norway after 1980 (revised after Ref. 1)

TUNNEL	TYPE	YEAR	LENGTH	DEEPEST POINT	CROSS SECTION	ROCK
Slemmestad	W	1980	1.0 km	-93 m	10 m²	clays, limestone
Vardö	R	1982	2.6 km	-88 m	46 m²	slate, sandstone
Kärstö	W	1983	0.4 km	-58 m	20 m²	phyllite
Karmsundet	O	1984	4.7 km	-180 m	26 m²	gneiss, phyllite
Fördesfjord	O	1984	3.4 km	-160 m	26 m²	gneiss
Förlandsfjord	O	1984	3.9 km	-170 m	26 m²	gneiss, phyllite
Ellingsöy	R	1987	3.5 km	-140 m	68 m²	gneiss
Valderöy	R	1987	4.2 km	-137 m	68 m²	gneiss
Hjartöy	O	1987	2.3 km	-110 m	26 m²	gneiss
Kvalsund	R	1988	1.5 km	-56 m	43 m²	gneiss
Godöy	R	1989	3.8 km	-153 m	48 m²	gneiss
Flekkeröy	R	1989	2.3 km	-101 m	46 m²	gneiss
Hvaler	R	1989	3.8 km	-120 m	45 m²	gneiss
Nappstraumen	R	1990	1.8 km	-60 m	55 m²	gneiss
Maursundet	R	1990	2.3 km	-93 m	43 m²	gneiss
Fannefjord	R	1990	2.7 km	-100 m	43 m²	gneiss
IVAR, Jaeren	W	1991	1.9 km	-80 m	20 m²	phyllite
Kalstö	O	1991	1.2 km	-100 m	38 m²	greenstone
Byfjord	R	1992	5.8 km	-223 m	70 m²	phyllite
Mastrafjord	R	1992	4.4 km	-133 m	70 m²	gneiss
Freifjord	R	1992	5.2 km	-130 m	70/54 m²	gneiss
Tromsöysund	R	1994	3.4 km	-101 m	2 x 57 m²	dioritic gneiss
Hitra	R	1994	5.3 km	-267 m	70 m²	gneiss
Troll	O	1995	3.8 km	-260 m	66 m²	gneiss
Total			**75.2 km**			

R = Subsea road tunnel; W = Subsea water tunnel; O = Subsea tunnel for oil/gas pipeline

industry to accept new methods resulting in safer techniques and cost savings.

The alignment for a subsea tunnel is largely influenced by the geological and the topographical conditions as well as the requirement of the maximum gradient of the tunnel. The minimum safe distance between the tunnel roof and the rock surface under the sea (the rock cover) is a crucial dimension in locating a subsea tunnel. The minimum rock cover must be sufficiently thick to allow unexpected rock falls or cave-ins to occur without causing a critical situation in the tunnel[3]. For road tunnels a minimum cover of 50 m is used during planning, until the results of detailed investigations are available. The rock cover requirements may be reduced to 40 m if the ground conditions are thoroughly documented to have a satisfactory quality[4] (Fig. 1).

In addition to documentation of ground conditions, cross sections and gradients which are common for all tunnels, subsea tunnels require special design criteria. These are mainly related to the conditions mentioned in Table II. A special feature for subsea tunnels is the relatively steep gradient these tunnels have in order to reach the lowest point beneath the sea bed within shortest possible tunnel length. For road tunnels the maximum gradient is between 1:10 and 1:16, depending on the traffic load. For other tunnels the gradient is generally restricted to the limitations of the tunnelling equipment, which often is 1:7 for tunnel slopes less than 1 km and 1:9 for very long slopes.

GEOLOGY

Many engineers involved in tunnelling outside Scandinavia believe that all rock conditions in Norway are good. This is true on many occasions as the rocks found are 'hard rocks' - old igneous and metamorphic rocks with compressive strengths of more than 50 MPa. These ancient rocks have, however, suffered several periods of earth movement resulting in numerous faults, shear zones and thrust zones[2]. Such features often cause great challenges and problems for tunnel excavation.

Another important feature of Scandinavian geology is the effect of the Ice Age. Erosion from the glacier activity 'cleaned' rock surfaces by removing weathered rocks, leaving fresh

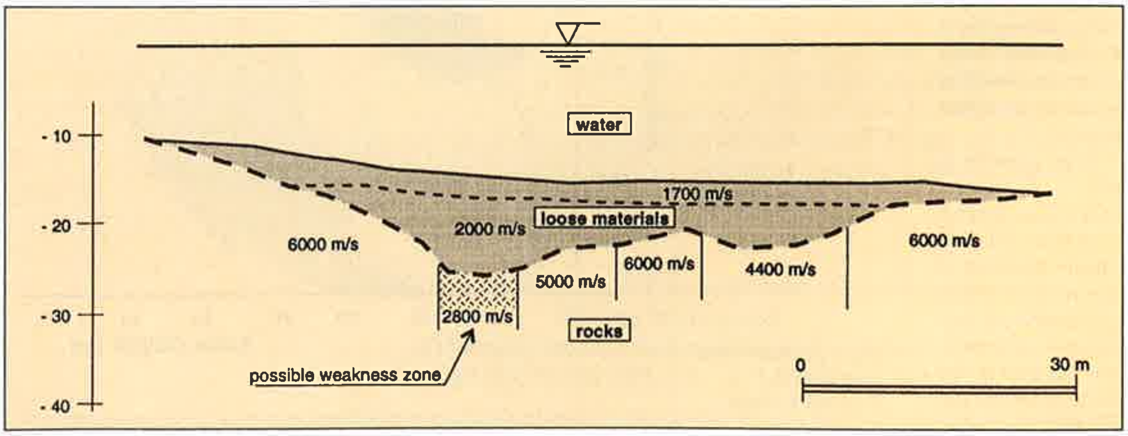


Fig. 2: Example of results from a refraction seismic profile (Ref. 6).

Table II: Special requirements for subsea tunnelling in hard rock.

FIELD INVESTIGATIONS
Subsea tunnels require generally a higher amount of investigations than ordinary 'land' tunnels, because of their complexity and the fact that a large part of the area is 'hidden' by water.
ROCK COVER OVER THE SUBMERGED PORTION
The minimum rock cover must be sufficiently great to allow unexpected rock falls or cave-ins to occur without permitting a critical situation to arise in the tunnel.
EXPLORATORY DRILLING AND PRE-GROUTING
For subsea tunnels it is important to avoid large water leakages. This is achieved by performing systematic exploratory drilling ahead of the tunnel's working face so that leakage zones are discovered far enough from the face to seal them by pre-grouting.
SUPPORT MEASURES
As the environment in a subsea tunnel is particularly aggressive, special requirements are made for the materials used.
TUNNELLING TECHNIQUES UNDER THE SEA
Special emergency arrangements such as a high pumping capacity have to be made to deal with major water leakages. Also rapid execution of pre-grouting constitutes an important measure.
DRAINAGE
The pumping system is equipped with an emergency reservoir having a capacity for at least 24 hours of water leakage.
TECHNICAL INSTALLATIONS
Cable bridges and similar equipment have an anti-corrosive coating, 80 microns hot dip galvanisation and powder lacquering with epoxy.

Table III: Approximate cost of geophysical measurements for subsea tunnels).

Geophysical method	Total cost
Echo sounding and reflection seismic measurements	30 km profiling: from $ 15,000 to $ 35,000
Refraction seismic measurements	2 km profiles: from $ 40,000 to $ 100,000

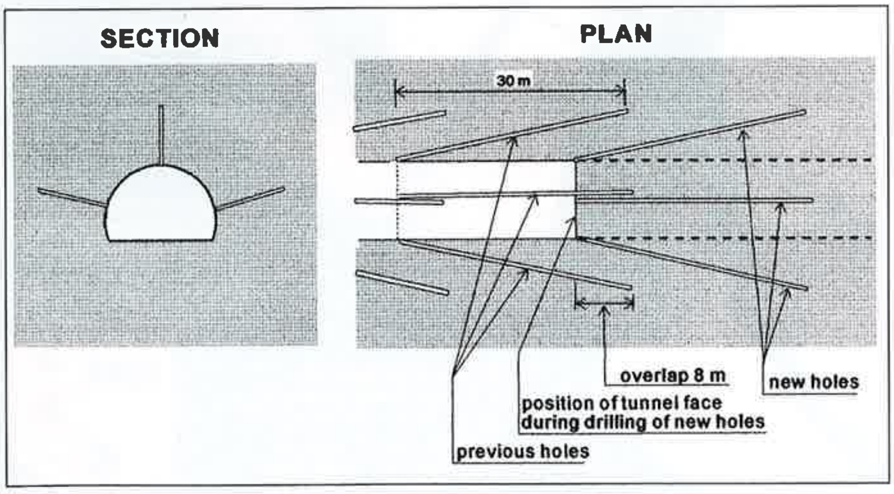
surfaces where the *in-situ* state of the ground can be easily observed. Where the rocks are exposed at surface, it is possible to predict the underground conditions from simple observations[5]. The cost of the required investigations are therefore generally low and confidence in the geological prognosis relatively good[6]. The prediction of subsea ground conditions is mainly based on geophysical investigations and engineering geological mapping. The cost for these preliminary investigations is 1.5%-5% of the construction cost.

Subsea tunnels, where the majority of the rock and the surface are covered by water, require an extended investigation programme compared with ordinary 'land' tunnels[6]. Special investigation techniques have been developed to collect information on the rock mass conditions. These are generally carried out at two stages:

- The field investigations made before tunnelling starts;
- The exploratory works performed during tunnel excavation.

First evaluations for the possible alignment for the subsea part of the tunnel are based on studies of naval maps and charts produced from echo soundings, showing water depths in the sea. These do not, however, indicate the presence of possible loose materials covering the bedrock. Shallow reflection seismic profiles produce a more accurate map of the sea

Fig. 3: Principles of probe drilling ahead of tunnel face.



bottom in the area of interest. It is also possible from these measurements to evaluate the thickness of possible loose deposits covering the rock surface. Based on this information a tentative tunnel alignment can be decided.

The next step in the investigations is refraction seismic measurement to obtain more information about the ground conditions along the tunnel alignment. In addition to a more accurate location of the rock surface and thickness of possible loose deposits, these measurements give qualitative information of the rock-mass conditions (Fig. 2). Especially important is interpretation of the measurements to locate weaker zones or faults below sea bottom. Together with other information, such as geology on land, the stratigraphy subsea can be fairly well indicated, together with assumed ground conditions.

Core drilling is performed to investigate the rock and ground water conditions as well as possible weakness zones. Investigation of the ground conditions beneath the sea bottom has, whenever possible, been undertaken by inclined holes from the shore. However, for the Vardö and the Hvaler tunnels expensive core drilling was carried out from a drill-ship to check the geology in crucial areas beneath the sea bottom.

Based on the results from geological maps and geophysical measurements the expected ground conditions are evaluated and the major weakness zones located. This is utilised for the selection of the final tunnel alignment. The expected types, methods and amounts of rock support and the system for exploratory investigations are decided. This information is used for the detailed cost estimate and the tender documents[7].

An important part of the site investigation for a subsea tunnel is exploratory or probe drilling during tunnel excavation. The aim of this is to detect any water leakage zones or adverse ground conditions before they are encountered. Experience has shown that the effect of water sealing is significantly better when it is carried out as pre-grouting ahead of the tunnel face rather than grouting from behind the face. Another important effect is that pre-grouting may prevent serious problems from possible large water inflows at the face.

The practical implementation of exploratory works is that the ordinary drilling and blasting work is stopped and the drilling rig is used to perform the probe drilling. Normally the minimum level of drilling carried out under the sea consists of two holes, each 30 m long with a minimum of 6-8 m overlap (Fig. 3); this takes one to two hours. The number of holes are increased either where faults or weakness zones are expected and there is a risk of leakage or where it is important to check the rock cover[2,8]. In special cases additional core drilling is carried out from the working face. For this the tunnel excavation work has to be stopped for one to three days. Core drilling provides significantly better information about the quality of the rock conditions than normal probe-holes performed by the drilling rig. When probe-holes or blast holes reveal water bearing

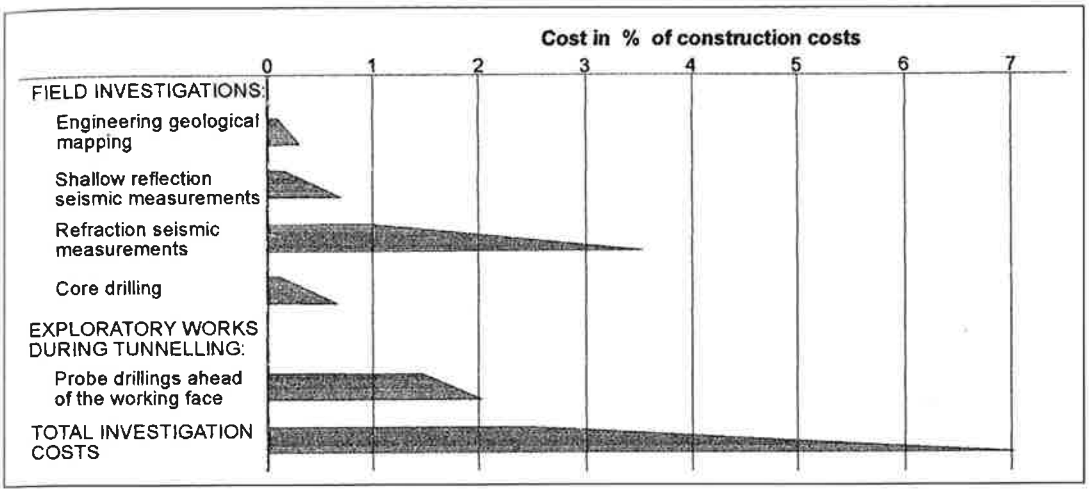


Fig. 4: Approximate distribution of investigation costs for Norwegian subsea tunnels (Ref. 1).

rocks in front of the face, the use of pre-grouting is evaluated as described later.

Experience over the last 10 years of subsea tunnel construction is that the total cost for investigation is in the range of 2.5%-7% of the construction cost, and probe drilling amounts to 1.5%-2 % (Fig. 4). As mentioned earlier these low figures are mainly due to information obtained from surface observations of exposed rock combined with the tunnelling experience and confidence in ground conditions.

CONSTRUCTION

All Norwegian subsea tunnels have been excavated by the drill-and-blast method. Successful tunnel driving depends heavily on craftsmanship and the flexible design adopted to the local ground conditions. Foreign visitors to Norwegian tunnel construction sites are often surprised that only three men are doing the drilling, blasting, mucking out and rock support works.

Usually there are two shifts each day working 5 days/week. Each shift is 10 hours: shift I from 0600 to 1600 and shift II from 1600 to 0200. In addition to the normal shift labour force there are a number of specialists who work daytime and the full tunnel crew of the main contractor consists of 12 persons. Table IV shows the normal division of tasks for the tunnel workers. Subcontractors traditionally transport the blasted rock from the face and usually supply all the concrete.

The management of the main contractor will vary according to the size and requirements of the project; as a rule four to six engineers are needed for a one-face job with an addition of three or four when tunnelling is carried out at two faces.

Table IV: Division of tunnel crew tasks at a one-face excavation.

Activities	S (3)	R (3)	F (3)	W (1)	E (1)	A (1)
	Crew members and tasks					
TUNNEL EXCAVATION:						
Drilling rig	●	●	●			●
Probe drilling	●	●	●			
Drilling of the round	●		●			
Charging	●	●	●			●
Scaling and loading blasted rock	●		●			(●)
ROCK SUPPORTING WORKS						
Rock bolting	●	(●)	●			
Shotcreting	●	(●)	●			●
Concrete lining (24 hours)	●	●	●		●	●
Grouting (24 hours)	●	●	●		●	●
SERVICE ON THE SHIFT						
Drilling rig		●				
Loader			●			
SERVICE ON DAYS						
Ventilation					●	●
Lighting					●	
Pumping stations					●	●
Electrical supply unit					●	
WEEKLY REPAIR AND CLEANING OF MAIN MACHINES				●		
MIXING EXPLOSIVES						●

S = Foreman, R = Repairman, F = Face Worker, W = Repairman in workshop, E = Electrician, A = Ancillary worker

Table V shows the main equipment used apart from trucks for hauling out the rock, which as already noted is usually undertaken by a sub-contractor. All the equipment is generally subjected to severe corrosion by salt water which affects its performance and durability. This can largely be overcome by established routines to check, clean and protect exposed parts by special coatings.

EXCAVATION

Blasting rounds are usually drilled with 4.8-5.5 m long drill rods resulting in a round length of 4.2-4.5 m. The diameter of the holes is 43 mm and for the cut three to five uncharged holes are reamed to 75-100 mm. Some 90 to 100 charged holes/round are drilled to blast a two-lane road tunnel with cross section 60 m^2.

Special care is taken to achieve an accurate tunnel profile to minimise rock support and overbreak in blasted tunnels. The requirement for accuracy in positioning the holes is usually +/- 10 cm, with a direction deviation better than 5%. To meet this the drilling rig may be equipped with positioning and guidance systems and automatically follow a preset drilling pattern.

The explosive is usually ANFO, a mixture of ammonium nitrate and diesel oil. In addition to its low price, close to one quarter of ordinary dynamite, ANFO has safety benefits regarding storage. Production of the required amount of ANFO is carried out each shift.

Haulage of blasted rock out of the tunnel is in trucks with a loading capacity of 10-15 m^3, chosen because of the relatively steep and long descending parts of the tunnel with gradients between 1:7 and 1:12. The number of vehicles varies from two to three in the outer part of the tunnel and increases by approximately one vehicle for each kilometre of tunnel length.

The time required for the various operations using 4.8 m long drilling rods (4.3 m round length) in a two-lane road tunnel is generally:

Scaling	45 min
Drilling (60 m^2 cross section)	2 h 30 min
Ventilation	15 min
Mucking-out	2 h 00 min
Total	5 h 30 min

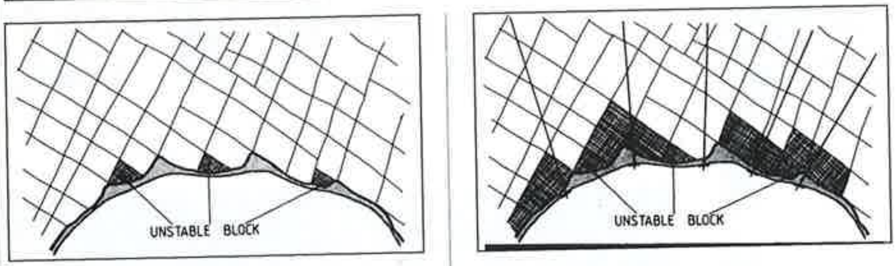


Fig. 6: Left: Sprayed concrete (shotcrete), often fibre reinforced, applied for support of unstable rock fragments or smaller blocks (Ref. 12). Right: Combination of rock bolts and shotcrete. The bolts support the larger blocks whilst the shotcrete supports the unstable rock fragments between the blocks (Ref.12).

Though yielding of the tunnel surface has been recorded in some clay zones, instability from squeezing is not a problem encountered in Norwegian subsea tunnels. Nor have rock bursts caused significant problems.

The main principle is to design the rock support for the actual ground conditions encountered. This requires flexible support methods which can be quickly adjusted to meet the continuously changing quality of the rock. Such flexibility is achieved by the use of rock bolts, shotcrete and cast-in-place concrete lining, either alone or as an integral element of the support. Norwegian contractors have long experience in using these types of support. Shotcrete, which today mainly is fibre reinforced, can be applied quickly and at a high capacity. Where reduction in the tunnel stability requires additional support, this is achieved by installing additional bolts or by adding shotcrete layers with or without fibre reinforcement. These two methods are suitable for a number of ground conditions and are easily adapted to changing rock-mass conditions. (Fig. 6).

Large faults or weakness zones with highly unstable rock-masses may be supported by a cast-in-place concrete lining, using a full lining shield designed to fit the actual cross section of the tunnel (Table V). Normally it takes only two to four hours from taking the decision to use this type of support until concrete casting can start. In adverse rock conditions with short stand-up times, shotcreting can be carried out shortly after blasting and then a concrete lining installed as a permanent support.

The rock support evaluations are partly based on experience from tunnels in the same region and partly by using the Q-system. As the underground conditions are never known until they are revealed during excavation, final decisions about the amount and methods for rock support are not taken before they can be studied in the tunnel. The supporting works are carried out in two main stages:

- Initial support. The amount is determined by the tunnel miners and their foremen. The main types to be used have been decided in the agreement between the owner and the contractor;
- Permanent support. This is carried out to meet the requirements for satisfactory functioning of the tunnel during its life, and is determined after excavation by engineering geologists who must consider the long-term behaviour of the rock masses. Based on the results from mapping of the ground conditions in the tunnel the amount and types of support can be found according to the Q-system.

The types of support used for initial and permanent support are generally selected so that they may be combined. In this way the initial support to secure safe working conditions for the tunnelling crew can be included as a part of the permanent support. The latter is therefore installed only where it is necessary to strengthen the initial support.

The salt environment in subsea tunnels requires resistant materials. Thus concrete structures, including sprayed concrete (shotcrete), are made of concrete according to environmental class MA (very aggressive) as specified in the Norwegian standard NS 427A. Rock bolts of normal steel quality may be used, but stringent demands are made on the anti-corrosive coatings for bolts used in a salt water zone, and bolts are treated with a combination of hot dip galvanisation, minimum thickness 80 microns and powder lacquering with epoxy, or a coating that gives comparable protection.

CONCLUSIONS

A key to successful construction of subsea projects in Norway has been the continuous exchange of experience and the close cooperation between the engineering geologists, the designers and the contractors. This has contributed to tunnelling advances of 40-80 m/week and low excavation costs (Fig. 7). Experience from seven subsea tunnels proved that the permanent water inflow varies between 100 - 450 litres/min per km of tunnel[11].

Using the two-lane Fannefjord tunnel as an example of a typical Norwegian subsea road tunnel, the total costs including excavation, rock support, sealing works (grouting) and installations are $5,000/m tunnel (NOK 35,000/m).

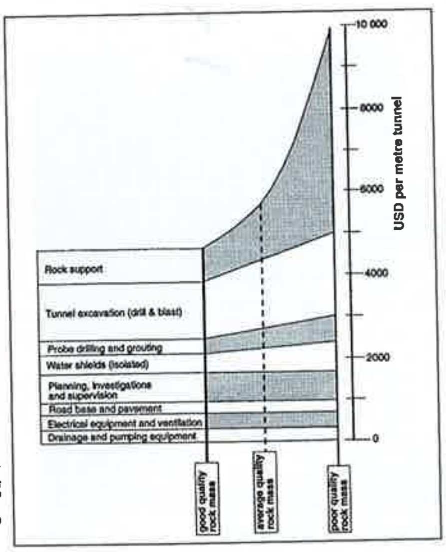


Fig. 7: Approximate distribution of total costs for Norwegian two-lane subsea tunnels with 55 m² cross section (Ref. 1).

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