The investigation and planning procedures for the 5.3km long, 160m deep Frøya sub-sea tunnel in Norway are described by Kristin Hilde Holmöy, Engineering Geologist, O T Blindheim; Jon E Lien, Project Manager, Norwegian Public Roads Administration; and Arild Palmström, Norconsult. The area has been exposed to complex faulting, resulting in extreme tunnelling conditions. Special precautions, extensive investigations and measures for quality control have been taken to ensure that the project is finished to time and budget.

Going sub-sea on the brink of the continental shelf

The Frøya sub-sea tunnel is currently under construction on the north-west coast of Norway (Fig 1). Around 30 previous sub-sea rock tunnels along Norway's coastline have yielded valuable information during the planning stages of this tunnel, which is the second sub-sea tunnel in the Hitra-Frøya project.

Pre-investigations for both tunnels started in 1982, and for the Frøya Tunnel continued more or less until construction started in early February 1998[1,3]. Compared to other, similar projects, very comprehensive investigations were carried out, which revealed complicated and, in some cases, uncertain geological conditions. Challenging tunnelling conditions were therefore anticipated, with several large, probably difficult, weakness zones to pass through, and, in addition, the possibility of encountering young, sedimentary rocks.

The Frøya Tunnel is the final leg of the Hitra and Frøya Mainland Fixed Link. The project completes a scheme by the Ministry of Transport & Communications to replace ferries and improve access to the national road network and boost a flourishing local fish farming industry on the largely barren islands of Hitra and Frøya off the Trøndelag coast. The project is part of public policy in Norway to provide infrastructure to outlying areas, a development strategy known as the 'District Policy', which is based on a broad political agreement to preserve traditional population patterns in the country.

The entire package, comprising two tunnels, bridges and roads, is estimated at a total of $124.5m. The enterprise started with the bridge connection to the small island of Fjellvaerøy, east of Hitra, in 1990, which was completed in 1992. It was followed by what is claimed to be the world's deepest road tunnel - between mainland Norway and Hitra - finished in December 1994. Excavation of the Frøya Tunnel is about three quarters of the way through and is almost eight months ahead of schedule, with commissioning predicted for mid-2000.

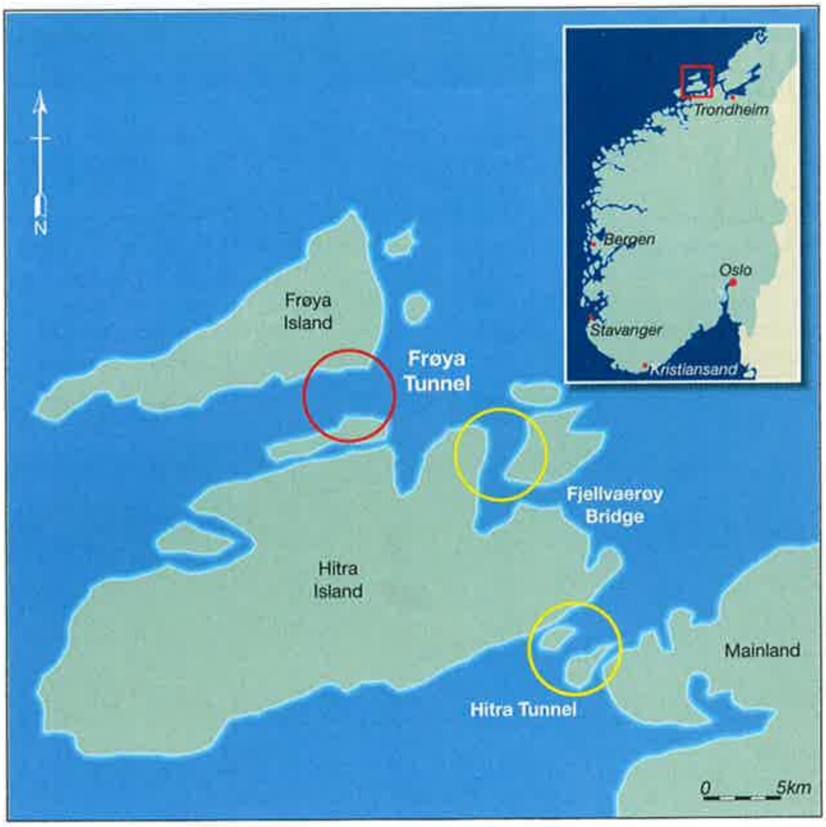


Fig 1. Location of the Frøya Tunnel between the islands of Hitra and Frøya off the north west coast of Norway

Selmer ASA is the main tunnelling contractor and the project is jointly funded by national and local government grants and toll charges.

The Frøya Tunnel

The Frøya Tunnel is 5.3km long, with its deepest point 160m below sea level. The major portion is under the sea (3.6km), where the rock overburden varies between 37m and 155m. The two-lane tunnel has cross sectional area of 50m^2 (T8 tunnel profile). Maximum gradient is 10%.

A reservoir of 1150m^3 was to be excavated at the lowest point, large enough to store four days' worth of

Work under way in the Tarva Fault (Class D zone), a main geological feature which runs for more than 150km NW on the Norwegian mainland

"Unexpected, exceptionally poor, ground conditions were discovered on the northern side of Frøy Fjord"

leakage water if the supply of electricity were to fail. Tunnel cost is estimated at $54.7m, which equals $1032/m of tunnel.

Tunnelling started in February 1998, with a planned hole-through in August 2000 and opening of the tunnel for traffic in June 2001. Nearly all of the constructed was planned to be by drill+blast, with small portions by excavator in the soft ground. Only 1.6km in the middle section remains. However, construction is eight months ahead of schedule and the tunnel might be opened in the summer of 2000.

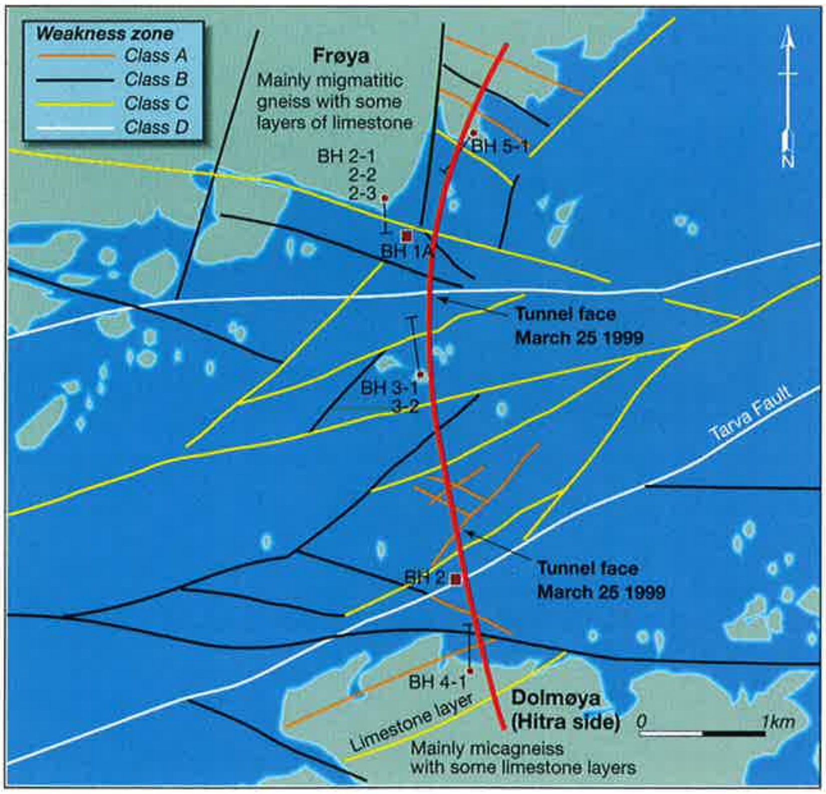


Fig 2. Assumed main weakness zones in the tunnelled area as interpreted from geological maps, aerial photos and field investigations

Geology

The geology comprises metamorphic rocks of Precambrian age, with gradual transitions between various gneissic rocks such as granitic gneiss, micagneiss, and migmatite. A few bands of limestone/marble have been observed in the actual area. The strike of the rocks is mainly ENE-WSW with a steep dip towards the NW. The area has been exposed to major faulting in the Precambrian age as well as the Caledonian and the Alpine Orogenesis. There are several depressions and valleys representing faults and thrusts. Similarly, the map of the seabed shows topography with marked depressions indicating the presence of faults or other weakness zones. Refraction seismic measurements confirmed this (Fig 2).

A main geological feature is the Tarva Fault (see photograph above), which runs more than 150km NW on the Norwegian mainland. This ancient fault was assumed to be reactivated during the Jurassic/Cretaceous and perhaps also in the Tertiary age.

Field investigations

Field investigations started in 1982 with construction of maps, collection of available geological material and initial seismic measurements consisting of shallow reflection seismic (acoustic) measurements and the first refraction seismic profiles. In 1995, during the final design, core drillings were performed from both sides of the Frøy Fjord.

Unexpected, exceptionally poor, ground conditions were discovered on the northern side of the fjord. The tunnel alignment was adjusted to the east in this section, where the following additional field investigations were performed:

The Atlas Copco computer assisted Rocket Boomer 353S drilling jumbo at work on the Frøya Tunnel

■ Refraction seismic profiles along the tunnel alignment with several cross profiles

■ Inclined core drillings from the land and from small islets in the Frøy Fjord. There were many drilling problems caused by the difficult ground conditions:

■ Two drill holes in the fjord from a drill ship

■ Special studies of the tectonic setting in the region

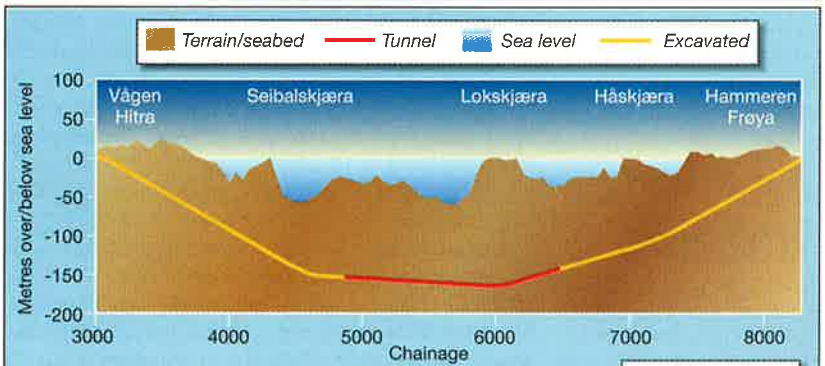
■ Detailed core logging and laboratory testing

The refraction seismic measurements have shown more low velocity (weakness) zones than in any of the other sub-sea tunnels constructed in Norway. The material in many zones consists of clay, silt, sand and gravel. Often, the clay shows a high degree of swelling, having low strength and friction properties. In total, 10 500m of refraction seismic profiles and 1747m of core drilling were carried out. Before the final decision to build the tunnel was taken, two groups of engineering geology experts performed feasibility, risk and cost evaluations.

Feasibility and cost evaluations

Both reports concluded that the tunnel could be constructed within justifiable economic limits using drill+blast, provided that there was thorough quality control during planning and construction. The reports divided the ground into different classes based on a detailed prognosis of expected ground conditions. For each class, the appropriate types and amount of rock support were given. In addition, leakage conditions with a predicted amount of grouting works were assumed along the tunnel.

In the report prepared by Nilsen et al[5], the ground was divided into eight different classes: four for the expected ground quality between weakness zones; and four for the main types of weakness zones - classes A, B, C and D. Weakness zone Class D is expected to be the worst zone to pass through. There are two Class D zones, one of them the Tarva Fault ,



	Hitra	Frøya
Total length	5279	
Start chainage	3000	8279
Progress to date (chainage)	4862	6481
Progress to date (metres)	1862	1798
Total progress	3660	

Remaining (metres)	1620	
Remaining (per cent)	31	
Estimated progress from date (m/week)	28	24
Estimated hole-through (chainage)	5734	
Estimated hole-through (date)	27.11.99	

Fig 3. Tunnelling progress to March 22 1999. 70% of the tunnel had been excavated and many difficult zones had been successfully negotiated. Tunnelling is eight months ahead of schedule

as shown in the photograph on page 26.

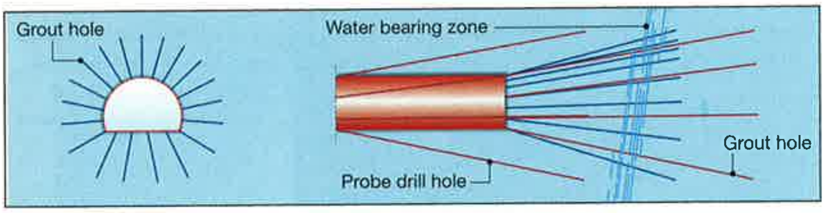
The prognosis has been used to follow up construction time and cost. Fig 5 shows real cost compared to estimated cost.

Results from tunnelling

Probe drilling and pre-grouting: major uncertainties and risks have been, and are, connected with water leakage and unstable, collapsing ground. As part of the quality control, an extensive programme for probe drilling and follow-up of the tunnel works has been implemented. For every 20m of tunnel excavated, three to six exploratory drill holes are being carried out ahead of the working face to gain information on the ground conditions. Below sea level, at least six probe holes at 30m centres are drilled. In this way, the necessary measures can be taken before tunnelling into the difficult ground.

If the probe drilling results in water leakage of more

Fig 4. Basic principles of the probe drilling system. Core drilling is performed where difficult ground is expected



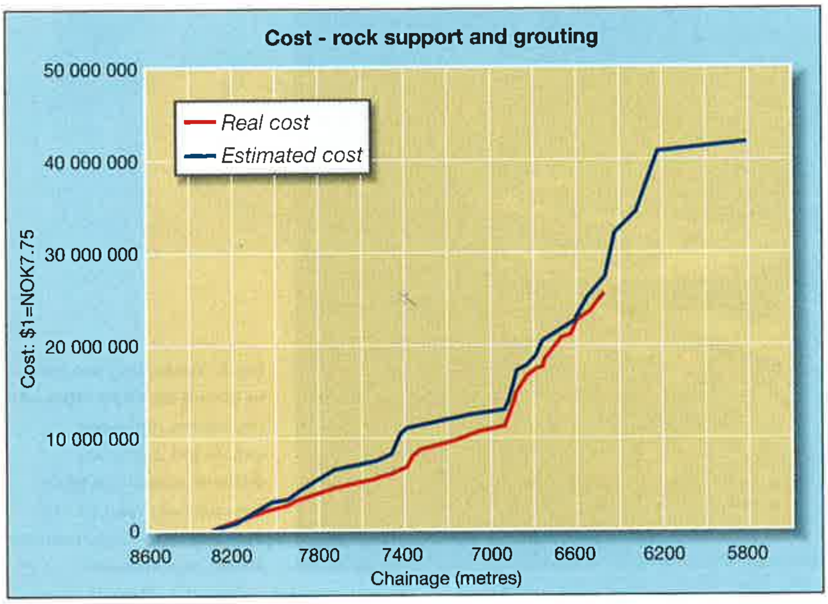


Fig 5. Comparison between estimated and real cost for rock support and grouting works on the Frøya side

than 5 litres/min in one probe hole, or if water leakage from more than one probe hole is between 3 and 5 litres/min, pre-grouting has to be executed. To perform pre-grouting, normal procedure is to drill a total of 21 holes (including the probe holes). The length of the grout holes is 18-24m.

After grouting, four to six control holes are drilled to reveal whether the water leakage is reduced. If there is too much water leakage, more pre-grouting has to be carried out. Microcement is often used when it is difficult to obtain required results with rapid cement; this has typically occurred in zones that contain clay. Maximum pressure used during injection is 50-60 bar.

Pre-grouting has been carried out on both sides, but most frequently on the Hitra side. Total leakage into the tunnel (including both sides) is 310 litres/min, which gives 8.5 litres/min/100m. This is well under the recommended maximum leakage value of 30 litres/min/100m.

Tunnelling through good and weak ground

About 70% of the tunnel has poor to very good ground, with Q-values ranging from 1 to 40. In such ground conditions, normal blast rounds are 5m. The rock support consists of one or two layers of fibre reinforced shotcrete (fibrecrete) 60-120mm thick in the roof and part of the walls, in conjunction with 3m long CT-bolts (fully grouted).

In weakness zones, more thorough measures and rock support are necessary. In addition to probe drilling and occasional grouting, some of the measures taken in difficult ground are:

- Stabilising the ground over and on both sides of the next round by 6m long spiling bolts spaced at 0.3-0.5m
- Using short blasting rounds and spraying fibrecrete on roof, walls and face soon after blasting
- Using stepwise excavation and concrete lining in addition to fibrecrete (above) where stability is very poor.
- Concreting the invert
- Having the equipment available to concrete the face quickly and fully to protect against cave-ins, progressive sliding, etc
- Having high pumping capacity and modern equipment for rock support operating at short notice

To check the stability of the construction, convergence measurements are begun some time after the zones are passed through. Usually the displacement ends after a few months, but in one of the weakness zones the displacement was 17mm and concreting of the invert was carried out to stabilise the movements. The latest measurements show that the concrete invert has slowed down the displacement.

The Tarva Fault is one of two Class D weakness zones. The refraction seismic measurements show a 65m wide zone with a 3km/s velocity. The rock overburden is a minimum of 40m. Probing by core drilling performed from a recess in the tunnel showed that the zone consisted of altered marble, marblebreccia/conglomerate, sandstone, calcite and pegmatite containing clay seams with a thickness of 50mm to 4m. In the middle of the fault there were several places with core loss of 0.5 to 1 m. Tests of the clay at chainage 4444 showed swelling pressure of 0.7MPa.

There was a sharp boundary between good rock conditions (gneiss) and the fault. The weakness zone started with a 4m wide zone consisting mainly of clay. There was no leakage and therefore no problem concerning stability.

Probe drilling at chainage 4469 gave a total water leakage of 59 litres/min·in six probe holes. Grouting was necessary in the remaining part of the weakness zone.

Tarva Fault precautions

Approximately 100 tonnes of cement was injected in the Tarva Fault, of which 60 tonnes were microcement. Poor ground conditions (soil-like material), combined with minor leakage, resulted in less stable conditions. The following steps were implemented in tunnelling through the zone:

- Reduced excavation round, only 3m instead of 5m
- 6m long, fully grouted spiling bolts with 0.2-0.4m spacing (36-95 bolts/round). Steel straps and shotcrete are used to fix the outer end of the bolts to the rock
- One or two layers of fibre reinforced shotcrete (fibrecrete) 60 - 120mm thick in roof and walls, immediately after blasting
- 3m long CT-bolts (fully grouted) with average spacing of 1.5m; and
- Two to three layers of fibrecrete, total shotcrete thickness 120- 310mm
- Three reinforced ribs of sprayed concrete
- The floor along the zone was concreted (69m)
- Concrete lining (64m)

In the poorest ground, at chainage 4476-4483, excavation was carried out using an excavator.

The detailed prediction of expected ground conditions, rock support and construction cost has been used to compare the real cost and the estimated cost for these operations.) As shown in Fig 5, the estimated and real costs for rock support and grouting are close. This is also the case for the southern (Hitra) part of the tunnel.

Exchange rate: $1 = NOK7.75.

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