Published in: Conf. on Modern Tunneling Science and Technology, Adachi et al. (eds), 2001, Kyoto, Japan, pp. 497-502

Stability and water leakage of hard rock subsea tunnels

B. Nilsen
The Norwegian University of Science and Technology, Trondheim, Norway

A. Palmström
Norconsult as, Sandvika, Norway

ABSTRACT: The many undersea tunnels along the coast of Norway offer excellent opportunities to study the key factors determining stability and water leakage in hard rock subsea tunnels. About 30 such tunnels have been constructed in Norway the last 20 years, all of them excavated by drill and blast. The longest tunnel is 7.9 km with its deepest point 260 metres below sea level. Although all tunnels are located in Precambrian or Palaeozoic rocks, some of them have encountered complex faulting or less competent rocks like shale and schist. The severe tunnelling problems met in these tunnels emphasise the need of a better understanding of the key factors determining stability and water leakage of such projects. This has been discussed based on the experience from several completed projects.

1 INTRODUCTION

In Norway, about 30 subsea tunnels, comprising more than 100 km have been built the last 20 years. Most of these are 2 or 3 lane road tunnels, but some are also for water, sewage, or oil and gas pipelines. All tunnels so far are drill and blast. The locations of some key projects, and tunnels being discussed later in this paper, are shown in Figure 1, and some main figures concerning length and depth are given in Table 1.

The tunnels are located mainly in hard, Precambrian rocks (typically granitic gneisses). This also is the case for the deepest tunnel; the Hitra tunnel (260 meters below sea level at the deepest point). Some of the tunnels are, however, also located in less competent Palaeozoic rocks like shale and schist. This is the case also for one of the longest tunnels; the North Cape tunnel (6.8 km).

The last few years, very complex and difficult ground conditions have been encountered in several subsea tunnels. The problems emphasise the need of a better understanding of the key factors determining stability and water leakage of such projects. In this paper the issue will be discussed based on the experience from completed projects, and with particular reference to a recent study of the Fröya subsea tunnel (Nilsen et al. 1997 and 1999, Palmstrøm et al. 2000), where very difficult rock conditions were encountered.

2 CHARACTERISTICS OF SUBSEA TUNNELS

Compared to conventional tunnels, subsea tunnels are quite special in several ways. Concerning engineering geology and rock engineering, the following factors are the most important (see also Figure 4):

- Most of the project area is covered by water. Hence, special investigation techniques need to be applied, and interpretation of the investigation results is more uncertain than for most other projects.
- The locations of fjords and straits are often defined by major faults or weakness zones in the bedrock. Also in generally good quality rock conditions, the deepest part of the fjord, and hence the most critical part of the tunnel often coincides with weak zones or faults, which may cause difficult excavation conditions.
- The potential of water inflow is indefinite, and all water leakage has to be pumped out of the tunnel due to its geometry.
- The saline character of leakage water represents considerable problems for tunnelling equipment and rock support materials.

The consequences of cave-in or severe water ingress in a subsea tunnel may be disastrous. Thus, despite the fact that Norway is a hard rock province, forming part of the Precambrian Baltic Shield as shown in Figure 1, the subsea tunnels often encounter faults of very poor quality, causing challenging ground conditions.

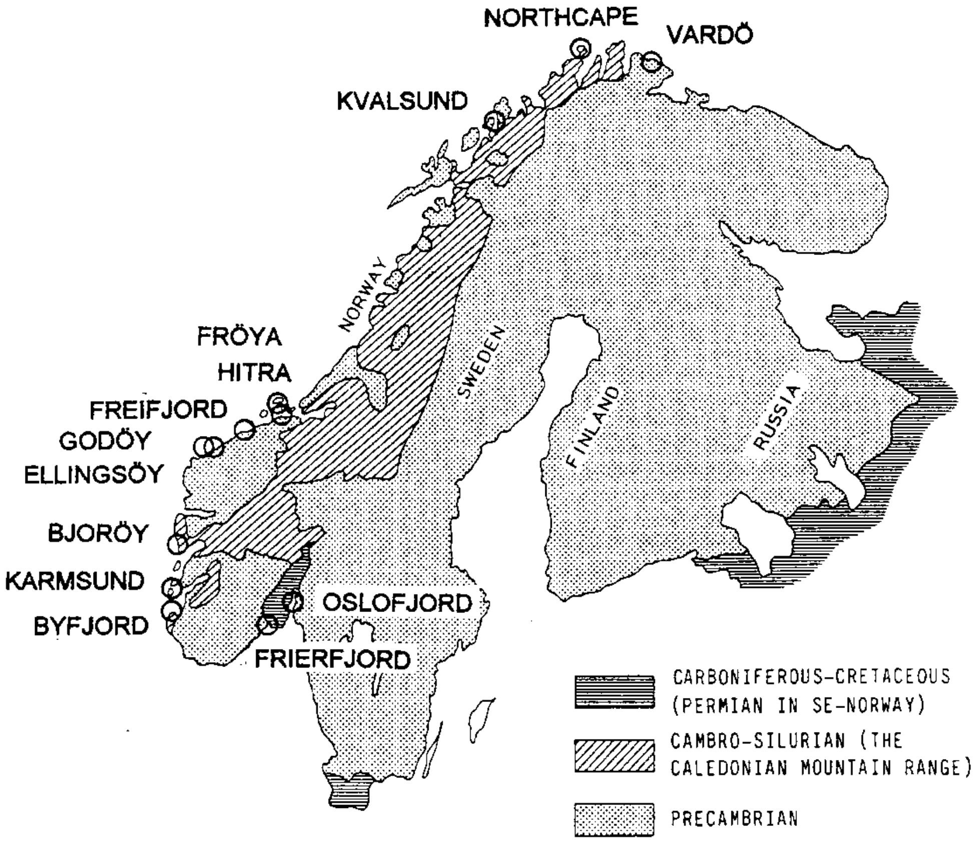

Figure 1. Locations of some of the main Norwegian subsea tunnel projects.

Table 1. Key data of some of the Norwegian subsea rock tunnels.

Project	Tunnel type	Year completed	Cross section (m^2)	Main rock types	Total length (km)	Lowest level (m)
Frierfjord	Gaspipe	1977	16	Limestone/gneiss	3.6	- 252
Vardø	Road	1981	53	Shale/sandstone	2.6	- 68
Karmsund	Gaspipe	1983	27	Gneiss/phyllite	4.8	- 180
Ellingsøy	Road	1987	68	Gneiss	3.5	- 140
Kvalsund	Road	1988	43	Gneiss	1.6	- 56
Godøy	Road	1989	52	Gneiss	3.8	- 153
Freifjord	Road	1992	70	Gneiss	5.2	- 100
Byfjord	Road	1992	70	Phyllite	5.8	- 223
Hitra	Road	1994	70	Gneiss	5.6	- 260
North Cape	Road	1999	50	Shale/sandstone/micaschist	6.8	- 212
Oslofjord	Road	2000	78	Gneiss	7.2	- 130
Frøya	Road	2000	52	Gneiss	5.2	- 157
Bømlafjord	Road	2000	78	Gneiss, greenschist	7.9	- 260

3 FAULTS/ WEAKNESS ZONES

Some of the Norwegian subsea tunnels have been completed without major problems as they have not encountered major weakness zones. This was the case, for instance, for the Kvalsund tunnel in Table1. In all the other tunnels in Table 1, distinct zones with very poor rock quality have, however, been encountered, and the rock support requirement thus has been considerably higher as shown in Table 2. The figures in this table also reflect the traditional Norwegian rock support philosophy that rock support is adjusted or tailored to the actual rock mass conditions, with heavy support like concrete lining applied only in very poor stability conditions. The typical weakness zones have widths of 20-30 meters and more, and consist of heavily crushed and altered rock. Gouge material of swelling type (smectite) is often found in such zones. Swelling pressures of around 1 MPa is common, and in extreme cases swelling pressure of more than 2 MPa has been experienced (clay material with swelling pressure above 0.3 MPa is generally classified as “active”). The particularly high activity of smectite in subsea tunnels reflects the ability of the clay mineral to absorb Na^+ from sea water.

Stability problems due to major weakness zones represent a threat to hard rock subsea tunnel projects. In some cases, severe instability has occurred. In the majority of such cases, the problem has been caused by faulted rock carrying clay minerals and water leakage of relatively high pressure. One such case was the Ellingsøy road tunnel, see Figure 2. Here, despite the fact that continuous probe drilling was carried out, a fault zone containing swelling clay and water-bearing fissures caused a cave-in reaching up to 8-10 meters above the crown before it finally stopped after 24 hours. A concrete plug of approximately 700 m^3 was constructed in order to ensure safe tunnelling through the zone.

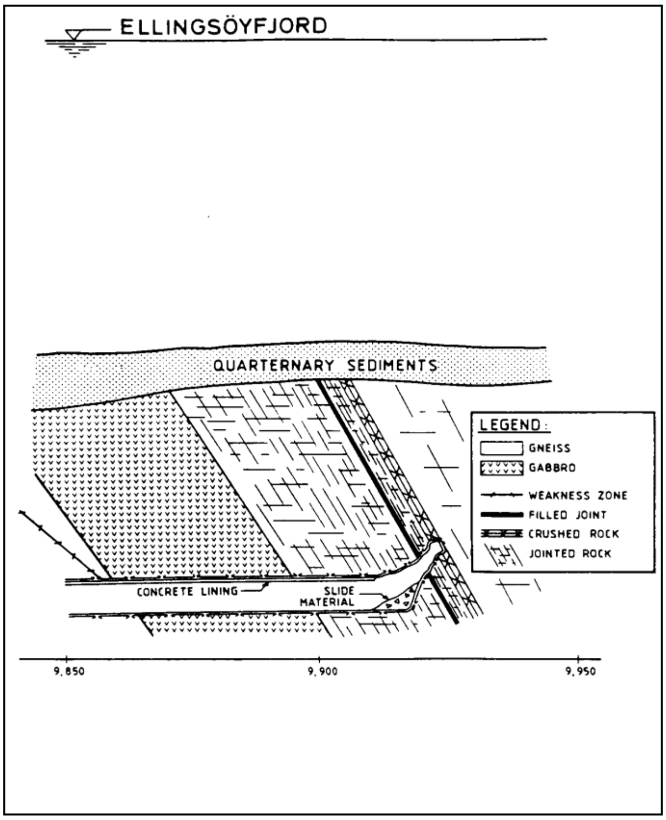

Figure 2. Cave-in situation at the Ellingsøy tunnel (based on Olsen & Blindheim, 1989).

Thanks to comprehensive geological preinvestitions and control as well as effective rock support procedures, cave-in of disastrous consequence has never occurred. In some recent cases, the situation has, however, been even more difficult than in the Ellingsøy case:

- The Bjorøy tunnel, where a more than 10 m wide Jurassic, tensional fault zone filled with clay, sand and coal fragments quite unexpectedly, due to insufficient refraction seismics, was encountered in the Precambrian bedrock. This was a zone of extremely high permeability and very poor stability, and a very time-consuming procedure involving stepwise grouting, drainage,

Table 2 Extent of rock support in some of the Norwegian subsea tunnels.

Tunnel	Excavation rate	Rock support			Concrete lining	Pregrouting	Water leakage	
		Bolts	Shotcrete			Grout consumption	At opening	During operation
	m/week	bolts/m tunnel	m^3/m tunnel	% of tunnel length	% of tunnel length	kg/m tunnel	l/min/km tunnel	l/min/km tunnel
Vardø	17	6.9	0.95	>50	21	31.7	460	*
Karmsund	34	1.5	0.72	65	15	13.4	*	*
Ellingsøy	28	6.4	0.48	20	3	99.1	300	130
Kvalsund	56	4.0	0.31	*	0	0	320	180
Godøy	*	*	0.40	*	0	265	300	90
Freifjord	45	5.3	1.44	*	2.1	13.7	500	280
Hitra	46	4.2	1.44	*	0.2	11.4	60	*
Frøya	37	5	2.9	**	5	197	8.5	*
Bømlafjord	55	3.8	1.9	**	0	36	< 50	*
Oslofjord	47	4.0	1.7	**	1	165	150	*
North Cape	18/56 ***	3.4	4	**	34	10	60	*

* No data available; ** The tunnel roof along the entire tunnel has been reinforced by shotcrete; *** In the shale, sandstone / mica schist, parts

spiling and shotcrete arches was necessary to tunnel through it.
- The North Cape tunnel, where flat laying, broken sedimentary rocks (mainly sandstones), often with thin coating of chlorite clay seams, have caused very poor stability. Comprehensive shotcreting and concrete lining at the face was required for rock support, reducing tunnelling progress to about 20 m/week. The difficult conditions were not realised from the pre-investigations due to the relatively high seismic velocity of the flat laying layers (4,500-5,500 m/sec).
- The Oslofjord tunnel, where a deep cleft filled with Quaternary soil was encountered, necessitating ground freezing to tunnel through. A distinct weakness zone was detected prior to tunnelling. Despite very comprehensive pre-investigations including traditional refraction seismics as well as directional core drilling and seismic tomography it was not found that the zone was eroded to a deep cleft.

In the Frøya subsea tunnel project area, a pattern of very distinct, regional faults were identified, see Figure 3. Some of these faults can be followed over a distance of more than 200 km.

In the planning of the Frøya tunnel, great benefit was gained from the construction of the nearby Hitra tunnel, where the major fault in the fjord proved to consist mainly of a mixture of heavily crushed rock and clay minerals (including swelling clay). The water seepage through the zone was minimal, and no concrete lining, but a combination of short blast rounds, spiling, steel fibre reinforced shotcrete, straps and conventional rock bolts, was used for getting through it.

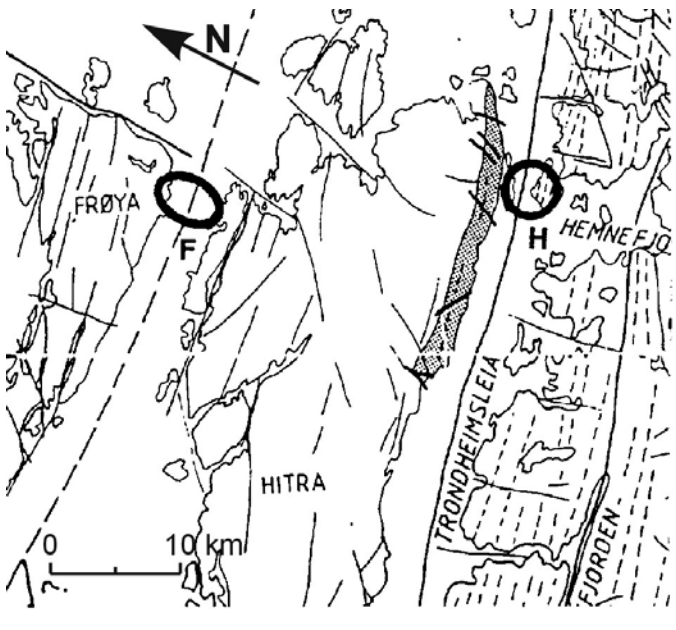

Figure 3. Pattern of regional faults in the area of the Frøya (F) and Hitra (H) subsea tunnels. Shaded area is Palaeozoic rock, the rest Precambrian (after Grønli, 1991)

There were some main differences between the Frøya and Hitra tunnels, making it likely that the former would be more difficult:
- The location closer to the Norwegian Sea, increasing the possibility that fault zones may contain intercalations of young, high porosity, sedimentary rocks.
- The low seismic velocities recorded, indicating rock mass quality far below average.
- The location closer to the main tertiary faults along the Norwegian coast, reducing the normal stress on major faults, and thus increasing the risk of major leakage (see Section 5).
- The less glacial erosion further from the main land (see Section 6).

Very comprehensive pre-investigations were carried out for the Frøya tunnel, and all investigation and planning were thoroughly reviewed by two independent panels of experts. Challenging ground conditions were documented, including high permeability zones as well as weakness zones containing very loose, sandy material and extremely active swelling clay.

Tunnelling for the Frøya project started in early 1998, and was completed in September 1999. The locations of the main weakness zones are shown in Figure 4, and the technique that was commonly used for excavating through such zones is shown in Figure 5.

4 WATER LEAKAGES

A logical assumption, apparently, would be to expect most of the water inflow in a subsea tunnel to come from major faults or weakness zones. This is, however, seldom the case, probably mainly due to the fact that such zones generally have very low permeability due to a high clay content (as was the case for the main zone encountered in the Hitra tunnel). The fact that the major zones are in most cases located under the central part of the fjord or strait, with a low permeability soil cover on top of the rock, probably is also a part of the explanation. This hypothesis is confirmed by the fact that in some subsea tunnels the major leakage has been encountered under land, and not under sea (for instance in the Ellingsøy tunnel, where the maximum inflow of 400 l/min from one single probe drill hole was encountered about 1 km from the sea).

In most cases, the major leakage is encountered at continuous single joints, often near a major fault

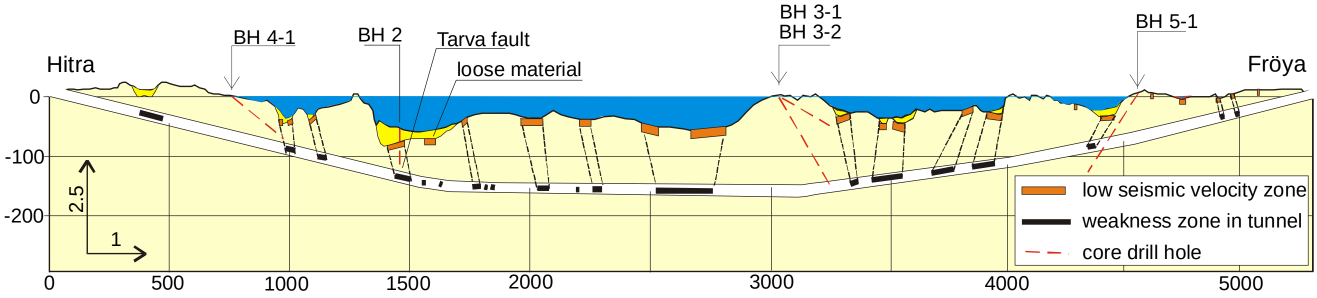

Figure 4. Longitudinal section along the Frøya tunnel

zone. This situation is very difficult to predict. Table 2 gives an indication of the great variations in leakage and thus grout requirements. During tunnelling, the decisions concerning grouting are based on inflow measurement from probe drill holes ahead of the tunnel face. Attempts have been made to correlate leakage to geological and rock mechanical parameters, but with mixed results so far. To be able to make more reliable prognoses on water leakage, more research definitely is required.

There are a few exceptions to the general trend that the major leakage is normally not connected to a weakness zone. The main one is represented by the water ingress in the tensional zone of the Bjoröy tunnel. To withstand the 0.7 MPa water pressure here, installation of blow out preventers in probe and grout drill holes was required.

As can be seen from Table 2, the water leakage in the subsea tunnels typically is reduced considerably with time.

5 ROCK STRESSES

Problems due to high rock stresses are not considered a major issue for the Norwegian subsea tunnels, which are located mainly in medium high, favourable stress conditions. Low minor principle stress of unfavourable orientation with respect to main discontinuities may, however, increase the water inflow considerably. This is a problem of particular relevance for tunnels located far to the West (close to the main Tertiary fault along the Norwegian coast). The high water inflow (and grout consumption) in the Godøy tunnel (see Table 2) was most likely caused by this effect.

In the Frøya area, the minor principal stress is most likely oriented NE - SW (parallel to the coast line), see Figure 3, and NW - SE oriented discontinuities thus in theory are most likely to give major inflow. Because of the location of the Fröya tunnel so far to the West, some of the same effects as in the Godøy were expected, but (swelling) clay content in most joints and zones resulted in small water leakage.

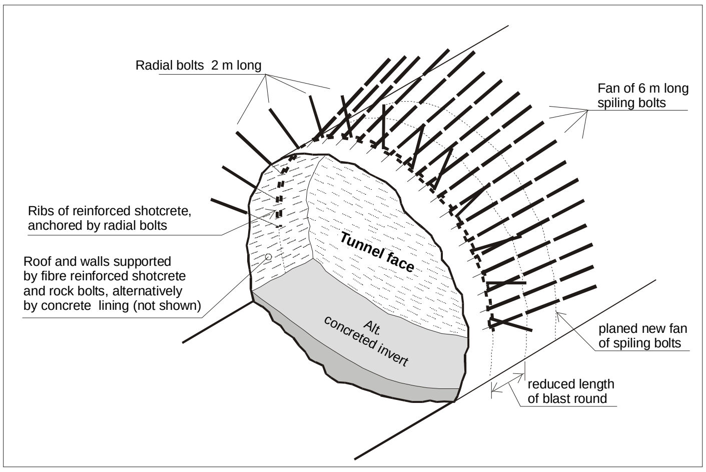

Figure 5. Principles of excavation through poor stability weakness zones applying the spiling technique (revised from Nålsund et al. 1996)

To be able to make reliable prognoses on water inflow based on stress magnitudes and directions, more research is required particularly on the effects of anisotropy and channelling in discontinuities.

6 WEATHERING AND EROSION

In relatively recent geological time, Scandinavia has experienced several glaciations, and is thus in the favourable situation concerning rock engineering, that most weathered material has been removed by the ice. For weakness zones, particularly near the coast (far from the glaciation maximum) this is, however, not necessarily the case, as illustrated in Figure 6.

For the Frøya tunnel, located at a considerable distance from the glaciation maximum, and with a minimum rock cover of about 40 meters, the effect of weathering root is believed to play a significant role. Consequently, the effect has been taken into consideration in the evaluation of investigation results.

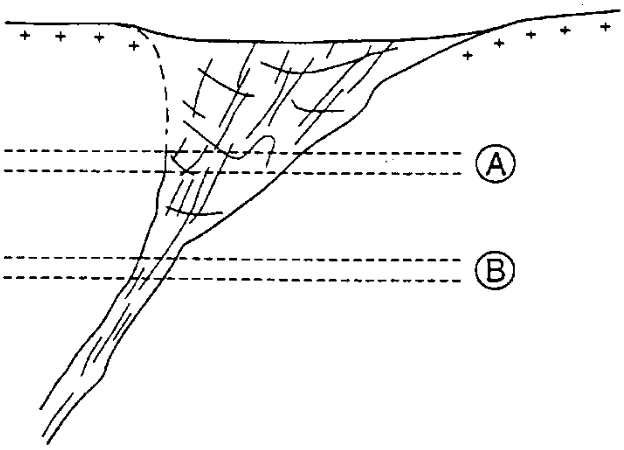

Figure 6. Principle sketch of a weakness zone with weathering root. A shallow tunnel (alternative A) gives a much wider zone crossing than a deeper (alternative B). From Nilsen et al. 1997.

7 CONCLUDING REMARKS

The most unstable conditions in the hard rock subsea tunnels are represented by major faults or weakness zones containing heavily crushed rock and gouge, often including very active swelling clay. Water seepage in such zones may dramatically reduce the stand-up time.

Since the major zones are often located in the middle of the fjord, the most severe problems are generally encountered at a late stage of tunnelling. The tunnelling conditions encountered that far may often have been relatively good, and the problems therefore may come as a surprise if not thorough pre-investigations and following-up during tunnelling are practised. Also, a high degree of readiness for all types of immediate rock support and a continuous quality control of all work are crucial for a successful completion of subsea tunnels.

Major water inflows have been found relatively rarely to be directly connected to the major weakness zones, probably mainly due to the high content of low permeability gouge of such zones. Distinct, continuous single joints apparently are more important. The magnitudes and orientations of rock stresses definitely have influence on water inflow. The effect is, however, complicated by factors like anisotropy and channelling. To be able to make reliable prognoses on water leakage in hard rock subsea tunnels, more research is needed.

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