Application of Norwegian Subsea Tunnel Experience to Construction of Xiamen Xiang'an Subsea Tunnel

挪威海底隧道组经验及其在厦门海底隧道建设中的应用

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关健词：挪威海底隧道，厦门海底隧道，封闭可能的渗水，预灌浆，坍塌，地层冻结

Abstract:

Norway has the largest number of subsea tunnels in the world. During the last 30 years, more than 40 subsea tunnels have been constructed, totalling more than 240km. Though most of these tunnels are located in fair to good ground conditions, some challenging ground conditions have been encountered in connection with faults. A main feature during planning and construction of the Norwegian subsea tunnels is sealing the potential inflowing water. A systematic method for detecting such water in time and to seal it has been developed and refined over the years, and has been used in all Norwegian subsea tunnels. This is presented in this paper, together with few of the more problematic construction experiences - involving ground freezing - to prevent a cave-in to develop. Further the application and implementation of the Norwegian experiences is discussed in the planning and during construction of the Xiamen Xiang'an subsea road tunnel, located in partly problematic and challenging ground conditions. The application of the Norwegian experiences is assisted through the consulting services provided by Norconsult experts during the tendering and the undergoing construction period of the Xiang'an subsea tunnel.

摘要：挪威在全世界有最多的海底隧道。最近 30 年修建了 40 条海底隧道，总长达 240 公里。尽管大部分隧道位于较好的地层条件，也遇到与断层相关的具挑战性的地质条件。挪威海底隧道规划与施工中的一个主要特点是封闭可能的渗水。多年的实践发展出一套系统的及时探测和封闭渗水的方法。挪威所有的海底隧道都应用了这一方法。本文介绍了此方法，同时介绍了处理更困难的地质情况的经验，包括防止进一部坍塌和地层冻结。本文还讨论了有关把挪威海底隧道经验应用到厦门海底隧道规划与建设中的问题。厦门海底隧道一些隧道段所处地质条件差，具挑战性。挪威顾问集团专家参与了把挪威经验应用到厦门海底隧道建设的过程。

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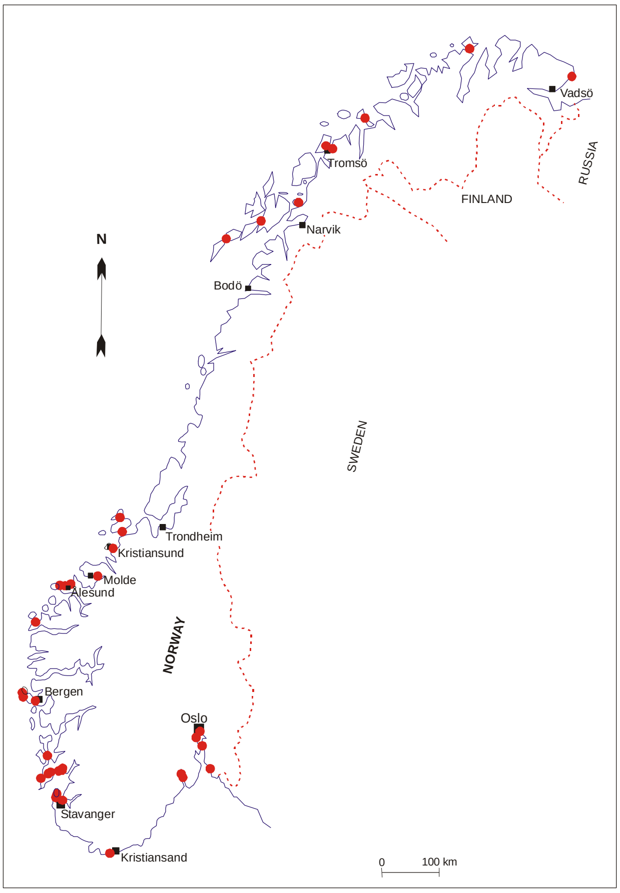
1. Introduction

As the 5.95km long Xiang'an road tunnel of Xiamen is the first subsea tunnel to be constructed in China, experience from similar tunnel constructions in other parts of the world will help in achieving a successful result. In this connection, the construction of more than 40 subsea tunnels in Norway over the last 30 years offers interesting aspects. The total length of these tunnels is about 240km, the longest being 7.9km and the deepest (under construction, 2007) 287m below sea level.

Figure 1. The size of Norway with about 4.5 mill. inhabitants compared to the size of China with about 1300 mill. inhabitants



As shown in Figure 2, most of the subsea tunnels in Norway link an island to the mainland and or cross a fjord or bay. Norway has by these tunnels shown that it is possible to construct tunnels under water and has for such tunnels developed suitable excavation methods, equipment and materials.

The Road & Bridge Construction Investment Corporation of Xiamen (R&B) with its consultants made a visit to Norway in 2002 to study about the Norwegian subsea experience. On that occasion they visited Norconsult and were shown the Oslofjord tunnel – a one lane, steep tunnel without continuous concrete lining. A stop was made in the leakage water cavern at the lowest part of the tunnel, the dark and wet conditions there seemed not to have frightened the R&B, because a couple of years later they decided to construct the Xiang'an subsea road tunnel.

Figure 2. Most of the subsea tunnels in Norway are located along the long coast to connect islands to the mainland or connection across a fjord or bay, as shown in the red dots.

The Xiang'an tunnel was planned to be a high traffic tunnel, half as steep as the Norwegian tunnels, consisting of two large traffic tunnels, each with 3 lanes + a service tunnel. This layout will, of course, be much better for the users than any of the steep Norwegian tunnels (with low traffic). All in all, the Xiang'an tunnel is a much larger and costly project – and also in part more challenging than any of the Norwegian subsea tunnel projects.

2. How can Norwegian techniques best be applied in the Xiang'an subsea tunnel?

When applying experience from other projects, it is important to compare and evaluate the similarities between the projects and the actual types of works in question. The similarities between Norwegian tunnels and the Xiang'an tunnel are mainly connected to the ground conditions as a large part of the Xiang'an tunnel will be located in granitic rocks penetrated by some faults where water inflow and poor stability (in faults) may be encountered. Many Norwegian subsea tunnels are located in similar fair to good rocks having comparable conditions; however, few in highly weathered troughs. Challenging ground conditions have been encountered in many of the Norwegian tunnels in connection with faults. A few of these problematic conditions are presented in Sections 5.1 and 5.2 and Chapter 6.

Also the cross sections of the tunnels are in the same range: 13 - 14m span for the Xiang'an main tunnels and 5 - 6m span for the service tunnel, compared to 8 -13m for the Norwegian tunnels, which are horse-shoe shaped. Therefore, the Norwegian subsea tunnelling experiences both in hard rock and faults zones could be applied to a successful result of the construction of the Xiang'an subsea tunnel.

The two main aspects in subsea tunnelling are:

- to prevent inflow of water, and/or (presented in Chapter 4)
- to prevent large cave-in (especially where flowing water occurs, presented in Chapter 5).

To meet these challenges, some special excavation methods or systems are taken into use during the tunnel excavation in Norway, such as:

- the measures to detect water, and
- the sealing of potential water zones ahead of the tunnel working face.

Another important issue is the implementation conditions for applying the Norwegian experiences. Given the difference stages of development in Norway and in China, especially the difference labour cost, there is a certain gap to fully apply the Norwegian experiences in practice. However, efforts have been made to adapt the principles to the practical work conditions. More advanced equipments have been used in the Xiang'an subsea tunnelling and skilful works have been training.

The designer of the project applied the principles of the methods in the planning and design of the Xiang'an subsea tunnel. Based on the consulting service contract between the owner of the project, The Road & Bridge Construction Investment Corporation of Xiamen (R&B) and Norconsult AS during tendering and the excavation processes of the Xiang'an subsea tunnel, the implementation of the methods were consulted through the works carried out by the experts at Norconsult AS. So far, several site visiting consulting services have taken place (Norconsult AS, Advisory Reports, 2005-2007). The works have been well acknowledged by R&B and the Xiamen municipal government.

Recently, in May, 2007, during the excavation through the first weathered trough Norconsult experts visited the Xiang'an subsea tunnel site and provided advices. The weathered trough was pre-grouted for water tight in the way as shown in Figure 3. The first portion of the trough section has been successfully excavated. Even it took some more time due to lack of advanced equipments and skilful crews and a real time consulting from experts.

3. Excavation challenges for the Xiang'an tunnel

The Xiang'an tunnel area is characterized by the basement rock with overburden layers in Quaternary system. The rock is dominated by types of granitic diorite, biotite granite and vein rock. The fresh rock is dense, hard and monolithic with few joint sets. Four strata were identified in terms of weathering with a successive range from complete weathered rock to strongly, weakly and slightly weathered rock. However, the boundary of layers can only be roughly quantified. In shallow sea water region and onshore, the rock is general strongly to completely weathered. The major portion of the tunnel is designed deeply to go through the slightly weathered basement rock. The Quaternary overlying stratum includes mainly residual soils from invaded rocks (1~19m) in deep and some alluvial deposits of clay and clayey sand in Pleistocene (1~3m) in the middle, with minor marine deposit of sand, clay and silt (up to 5m) on the top.
There are two major faults in the region far away from the tunnel. No local faults striking parallel and intersect with the tunnel were investigated. Along the longitudinal axis of the tunnel, three strongly weathered rock zones were identified by seismic refraction. The weakness zones with deep weathering will intersect the tunnel.

Table 1. Mechanical properties of the rock masses (Zhou et al. 2004)

Rock type	Young's modulus, E (GPa)	Poisson ratio, ν	Cohesion, *c* (MPa)	Friction angle, ϕ (°)	Unit weight (kN/m³)	Seismic velocity (m/s)
Completely Weathered Rock (CWR)	0.05	0.3	0.033	30	19.5	1200-1500
Strongly Weathered Rock (SWR)	1	0.3	0.2	35	26.5	2100-2300
Weakly Weathered Rock (WWR) to Slightly Weathered Rock (SLWR)	15	0.25	1	50	26.5	3800-4500

Table 2. The main forecasted excavation difficulties for the Xiang'an tunnel

Main known challenging ground for tunnel excavation	Solution used / or to be used	Alternative
A. Highly weathered rock from both portals, where sectional excavation with steel arches must be used for safe tunnel excavation.	Sectional excavation with steel arches (CRD excavation) and a progress around 0.5 - 1m/day.	*Freezing from the surface. (see Chapter 6)
B. Additional problems in permeable parts from inflowing water eroding the fine-grained, friable materials, which is difficult to seal by grouting.	*Local pre-grouting where permeable materials are encountered (see Chapter 4).	
C. 2 to 3 large fault zones to pass beneath the sea bottom. Two of them are expected to have weathered trough consisting of completely and highly weathered rocks, comparable to the conditions in the weathered rocks at the tunnel portals mentioned above.	*Comprehensive pre-grouting (see Chapter 4) before CRD sectional excavation with rock support of steel arches.	*Freezing from the tunnel face.
D. A permeable, highly friable sand layer within the zone of weathering on the Tongan side.	Installation of a wall through and around the sand layer and drainage of the sand layer within the wall.	*Freezing from surface.
E. Other faults to cross, but below the weathered trough. Open water-conducting, open joints.	*Pre-grouting and support adapted to the local conditions.	-
*Where Norwegian experience can be utilized.		

The rock quality changes with depth and thus the degree of weathering. Basement rock, including weathered rocks except the completely weathered rock, has the minimum friction angel of about 35 degree and Youngs Modulus greater than 1GPa as listed in Table 1 (Zhou, et al. 2004). Field test showed that in the weakly to slightly weathered rock masses, the hydraulic conductivity is low, about 10^{-7} m/s, and about 10^{-6} m/s in stongly to completely weathered rock mass. The predicted maximum inflow is about 11.18m^3/day. The regional seismic intensity is grade VII (Zheng and Zhang, 2005).

Though the Xiamen tunnel is located in massive granite of generally good quality for tunnel construction, it has many excavation challenges. Those detected from the field investigations before construction and the planned or used solutions are shown in Table 2. Outside of the faults, the granite is massive and exhibit good qualities for tunnel excavation.

4. Norwegian experience on sealing permeable water zones and joints by grouting

4.1 General

It is said that sealing of water by grouting is an art. The reason is that there are so many conditions included in this work, which therefore, is highly founded on experience. The main variables being:

- equipment (pump, mixer, agitator);
- analysis and understanding of the site conditions;
- suitable grout mix;
- execution of the grouting work (hole length, number of holes, pressure, grout mix, etc.);
- practical experience on how to adjust the grouting works to the actual conditions.

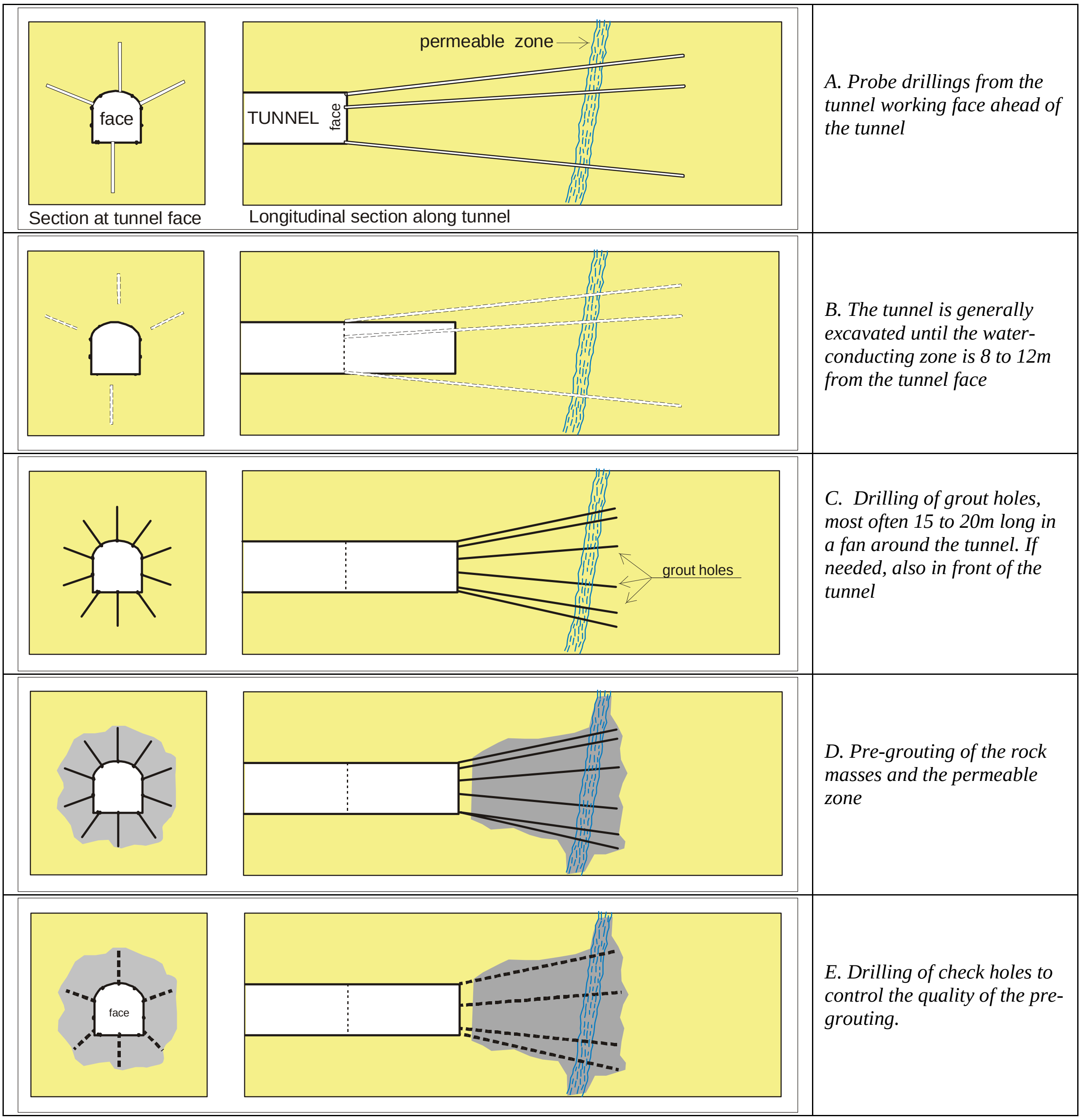


Figure 3. The principles of probe drilling to detect potential water-conducting zones (A), the pre-grouting to seal the zone (C-D), and the checking of the sealing result (E).

Based upon the Norwegian subsea tunnelling experiences, the principles of probe drilling to detect potential water-conducting zones, to seal the zones are summarised in Figure 3 which is self illustrated. Detailed explanations are in the following sections.

4.2 Probe drilling (Figure 3A)

A main experience from Norwegian subsea tunnel construction is that it is of utmost importance to seal the water ahead of the tunnel working face (i.e. as pre-grouting). This requires that potential water-conveying joints and zones are detected in time before the tunnel has been excavated into them and released the inflowing water. A system for probe drilling by 20 to 30m long holes performed by the tunnel drilling jumbo has been found suitable and efficient.

4.3 Execution of the pregrouting (Figures 3B to 3D)

The experience from numerous grouting jobs in poor ground conditions is that the holes should not be longer than 20m. This is because the grouting result will be better and that the longer holes are more problematic to drill. Therefore, the tunnel is often excavated until the water conducting zone is some 15m ahead of the tunnel face (Figure 3B).

The grout holes can preferably be drilled by the tunnel drilling jumbo. The drilling capacity can be significantly improved if the tunnel drilling jumbo is equipped with a service basket, or even better, a rod-changing device. They make the changing of drilling rods much easier and quicker.

The number and location of the grout holes and the grout mixture should preferably be determined from the geology and the information of the probe holes.

4.3.1 Grout mix

To best avoid that the grout mixes with the ground water during penetration, a stable mix with good cohesion is important. Also the recommended use of high grouting pressure at the end of grouting in a hole put requirements to the grout mix. In this respect, the use of microsilica slurry (about 20%) has shown good results under difficult grouting conditions.

The use of blocker during the grouting will in many cases significantly reduce the grout take (grout consumption) and hence lower the grouting time.

Grout mix in normal types of ground

Ordinary Portland cement can probably be used in most types of jointed rocks in the tunnel. Additives of superplastisizer and microsilica slurry will significantly improve the result and give shorter grouting time. Table 3 shows an example of a grout mix for such cases using microsilica.

Pre-grouting in problematic ground (faults etc.)

In difficult ground with frequent transitions from clay-rich materials to grainy materials with little clay, strict requirements are put to the grout mix. It will be necessary to use a very fine-grained, stable grout with good penetration. Examples of such mixtures are shown in Table 3. The water sealing works ahead of the tunnel face are very important for a successful result, and put strong requirements to the grout mixture and the execution of the grouting work. Addition of bentonite does not work well in the mixtures presented.

Table 3. Example of a grout mix with ordinary Portland cement

MATERIAL	MIX		COMMENT
	(w/c = 1.2)*)	(w/c = 0.8)	
Ordinary Portland cement	127.5kg	170kg	
Water	153 litres	136 litres	
GroutAid	37.3 litres	36.3 litres	GroutAid is a microsilica slurry product
SP-40	2.5 litres	3.1 litres	SP is a superplastisizer
Volume	233.5 litres	230 litres	

*) w/c is water to cement ratio

4.3.2 The grouting works

The number, placing and length of grout holes, the possition of packer, the grouting pressure, the grout mix and pumping rate are all influencing on the sealing result. Grouting is, as mentioned earlier, an art. Therefore, the grouting team should have a specialist with long and wide experience.

Table 4. Mixtures with microsilica, and blocker mixtures

MATERIAL	MICROCEMENT MIX		BLOCKER MIX			
	(w/c = 1.5)	(w/c = 0.8)	slow blocker	medium blocker		rapid blocker
			(w/c = 1.4)	(w/c = 0.88)		-
Microcement	100kg	140kg				
Water	150 litres	112 litres	40 litres	2 minutes mixing	40 litres	20 litres
GroutAid	30 litres	17.4 litres	10 litres		10 litres	5 litres
C-max	-	-	45.4kg		45.4kg	22.7kg
Thermax	-	-	50kg	2 minutes mixing	75kg	50kg
SP-40	2 litres	3 litres				
Volume	214 litres	177.4 litres	96 litres		104 litres	60 litres

Grouting is often time-consuming. But application of modern equipment, grouting mix, and not least, grouting know-how to match the actual ground conditions, the time for grouting can be significantly reduced. The microfine cement requires a very good mixing. A shear mixer with minimum 1500 rev/min. should be used. With modern drilling and grouting equipment and suitable grout materials, the drilling and grouting of a round with 15 to 18 holes takes normally 24 hours or less. With experienced crew and appropriate mix is often sufficient with only one round to achieve an acceptable sealing result. By this, much time can be saved. However, in problematic ground with difficult rock mass conditions, the grouting may take significantly longer time.

4.4 The checking of the grouting performed (Figure 3E)

If any of the check holes made after the grouting round shows larger water inflow than required, new round of pre-grouting is performed. Then new check holes are performed. Further excavation can be started when all check holes show acceptable water inflows.

5. Examples of methods used to prevent a cave-in to further develop

Two examples are presented below where special methods have been used to solve a cave-in to develop into a collapse.

5.1. Example 1: Excavation through a very unstable fault where a slide took place in the Vardo subsea road tunnel

This tunnel is linking the Vardo island with the mainland. It was constructed 1978 – 82 and is the first subsea road tunnel in Norway. It is 5.4km long with the deepest point 88m below sea level. The cross section is $50m^2$ (8.5m span) and the rocks are metamorphosed sandstone with frequent bedding planes often with a coating or thin layer of clay. As shown in Figure 4, there are many faults in the strait crossed by the tunnel. In one of them, sliding took place and started to develop upwards towards the sea bottom. The works connected to this are shown in Figure 5.

This was one of the first times spiling bolts were systematically used to reinforce the rock masses in front of the tunnel working face. 6m long rebar bolts were installed in a fan above the tunnel and grouted. When the next round was excavated, the rock masses with very poor stability slided up to the spiling bolts. The main task in the supporting works was to avoid the slide to further develop up to the sea bottom some 30m above. Therefore a quick application of shotcrete was important to temporary stabilize the sliding area. Then the permanent support by cast in place concrete was installed. As it was considered dangerous to work close to the face, tunnel spoil was placed against the face as part of the formwork here, as shown in Figure 9. Then it was only necessary to make the formwork in the upper part of the face.

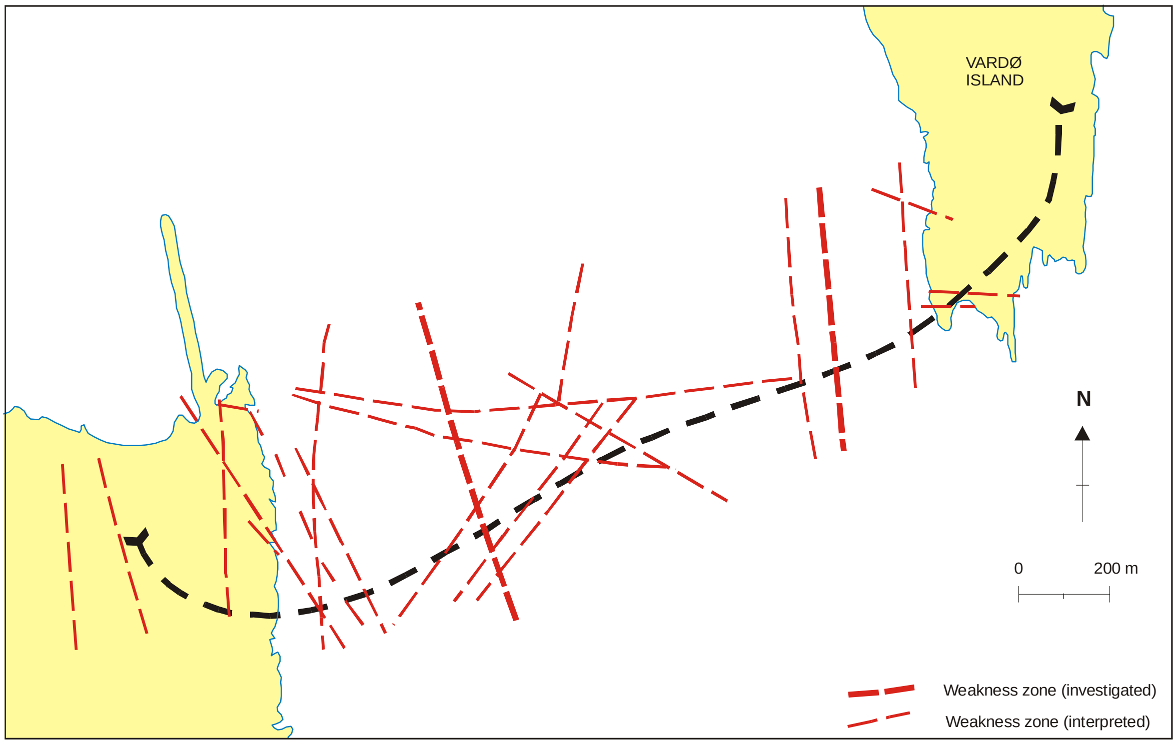
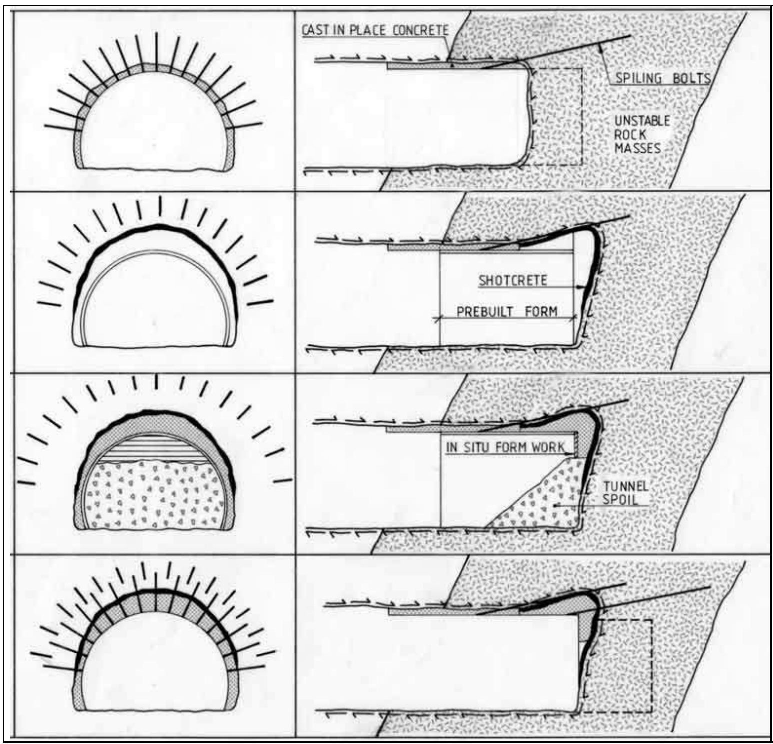


Figure 4. The Vardo tunnel and forecasted weakness zones (faults). Most of them were encountered during the tunnel excavation (Palmström A., 1982)



Step I
- Step concreting before excavating into the extremely unstable zone.
- Spiling bolts through this concrete and into the zone

Step II
- Excavation into the zone by short blasting rounds
- Removal of blasted material.
- Shotcreting of roof, face and walls of the blasted round.
- Positioning of prebuilt form as close to the face as possible.

Step III
- Tunnel spoil placed against the face.
- Formwork between top of tunnel spoil and ceiling of prebuilt form.

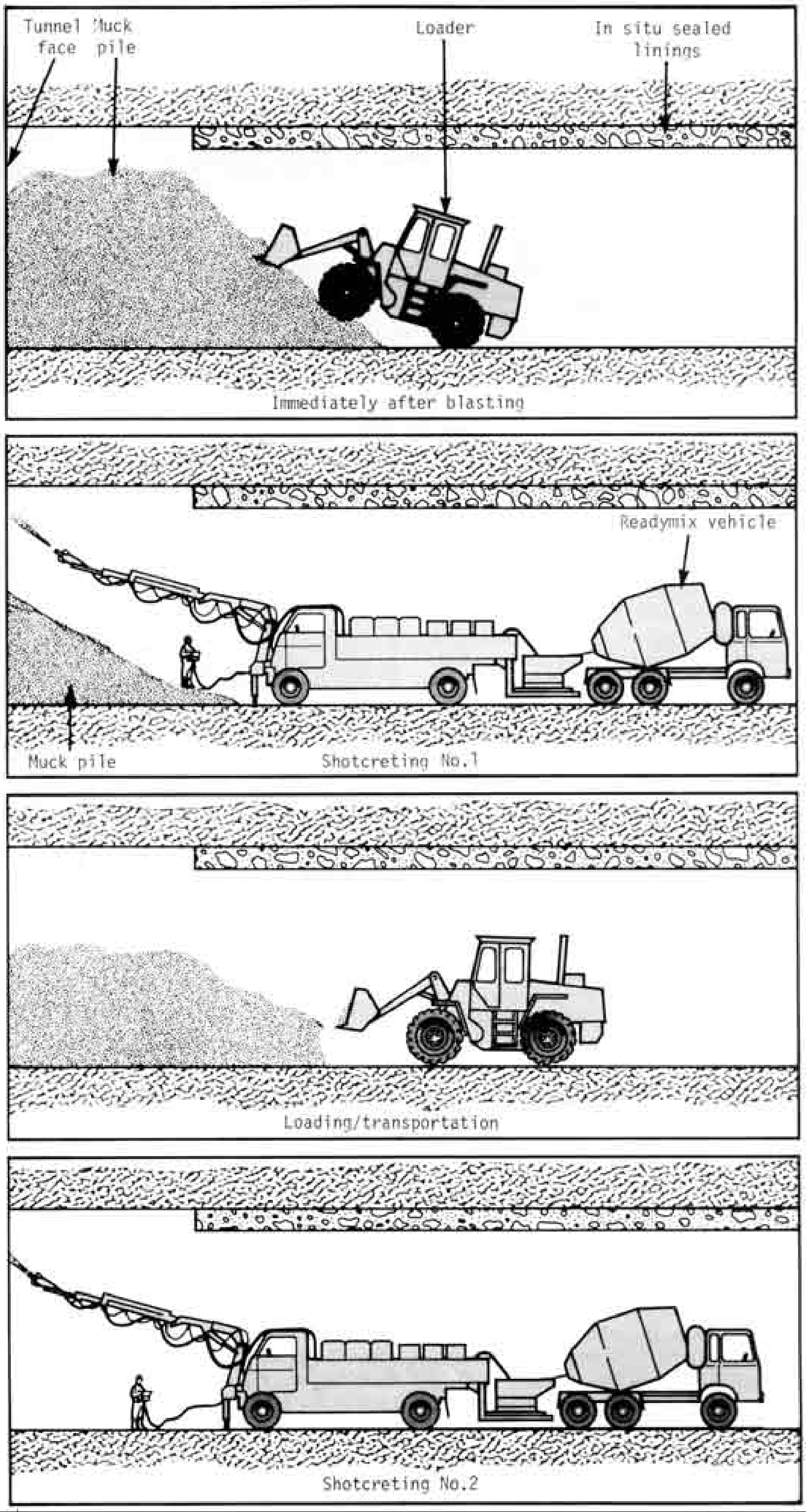
Step IV
- Tunnel spoil, prebuilt form and the formwork removed.
- Spiling bolts installed through the new concrete and into the zone.
- Start of new excavation round

Figure 5. The technique developed for the Vardo tunnel. By rapid installation of the in situ form work on top of the tunnel spoil prevented a beginning cave-in to further develop. This systematic installation of spiling bolts was first introduced in Norway. (Palmström A., 1982)

The tunnel was constructed during the early development of wet shotcrete, and this method could therefore not be fully utilized, like it was in the next example.

6.2. Example 2: Stepwise excavation and rock support to pass a large zone of poor stability rocks in the Karmsund subsea tunnel

The 25m^2 Karmsund subsea tunnel was constructed in 1982 to 1984 for placement of a gas pipeline. It is 4.7km long and has its deepest point 180m below sea level. In the middle of the tunnel, a 300m long section of a sandy, crushed rock with very poor stability was encountered.



After blasting of a reduced round of 2m, a wheel loader is quickly moved in. It takes only a few minutes for the loader to flatten a path way to be cleared for access of the wheeled shotcreting rig.

A 100 - 200mm thick layer of special quicksetting shotcrete with microsilica is applied to that part of the face that is exposed, together with the roof and adjacent walls, before the rock masses disintegrate.

When this has been done, and only then, the wheel loader moves in again and removes the muck pile by loading it into dumpers for disposal outside.

The shotcreting rig then returns and completes its job on the newly exposed parts of the face and walls.

After this, additional support of the 2m blasted section is performed by in situ concrete lining before start of drilling for the next blast.

Figure 6. The excavation and rock supporting technique applied in the Karmsund tunnel as described in the Tunnels & Tunnelling magazine. A main task was a quick installation rock support after each blast to avoid a cave-in to develop. Application of wet shotcrete quickly after blasting was a very effective means to achieve the successful result.

A special technique for stepwise excavation and rock support was developed, which – for this tunnel – proved to be safe and at the same time effective. The principles of the works here, which are shown in Figure 6, have been described in the Tunnels & Tunnelling magazine for July 1983.

Shotcrete has also in this example shown to be most important. Microsilica additive and fibre reinforcement of the shotcrete were applied in such works for the first time in Norway. A main issue was that shotcrete could be quickly performed after blasting, before a cave-in started in the poor rocks of very low stand-up time.

6. Example of ground freezing in solving very problematic tunnelling conditions

Freezing of the ground ahead of the tunnel along and around it is a method used for special purposes or when no other excavation and/or rock supporting methods work. It is generally a costly method, but may have benefits regarding safety and time. An example from freezing in the Oslofjord subsea road tunnel is given in the following. The 7.2km long Oslofjord subsea road tunnel with a cross sectional area of $78m^2$ (12.5m span) was constructed from 1997 to 2000.

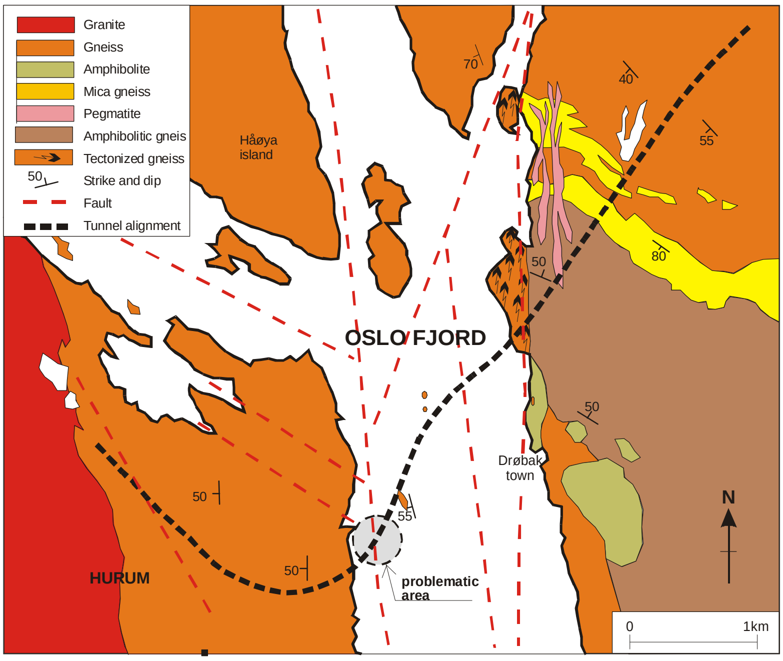


Figure 7. Overview of the Oslofjord tunnel showing the location of the problematic area where freezing was carried out. (Berggren, A.-L, 2000)

It has its deepest point 120m below sea level. The rocks are mainly granite and gneiss pene-trated by some faults, see Figure 7.

On the western side, unexpected problems turned up when the tunnel was 110m below sea level, because a 15 - 20m wide cleft filled with highly permeable, in-washed, rounded stones, gravel and sand was discovered 15m in front of the tunnel during the systematic probe drilling works (see Figures 8 and 9).

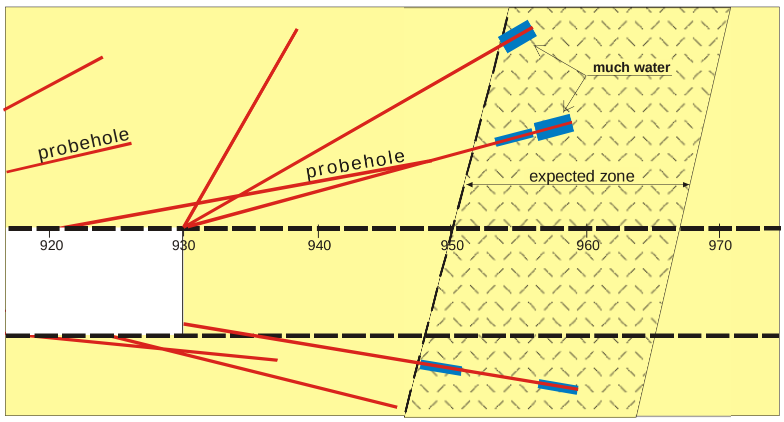


Figure 8. From the systematic probel holes very much water was detected in the expected weakness zone, which showed to be an eroded cleft filled with inwashed, highly permeable, loose materials of stones, gravel and sand. (Berggren, A.-L, 2000)

Core drillings had been performed during the planning of the tunnel, as shown in Figure 9, but the hole along the centreline of the tunnel penetrated just below the bottom of the cleft.

Sealing of the materials in the cleft by pre-grouting was first tried, but it showed to be very difficult as large volumes of grout were injected, without any sealing effect.

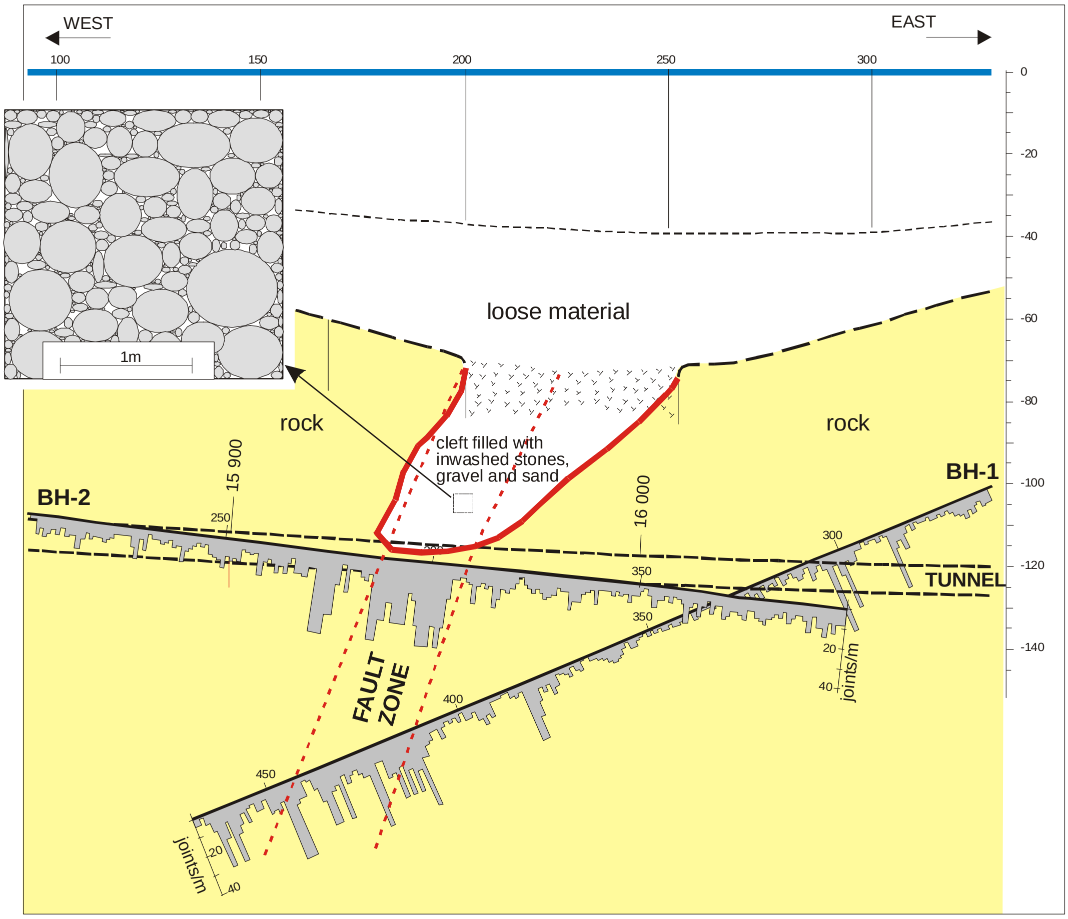
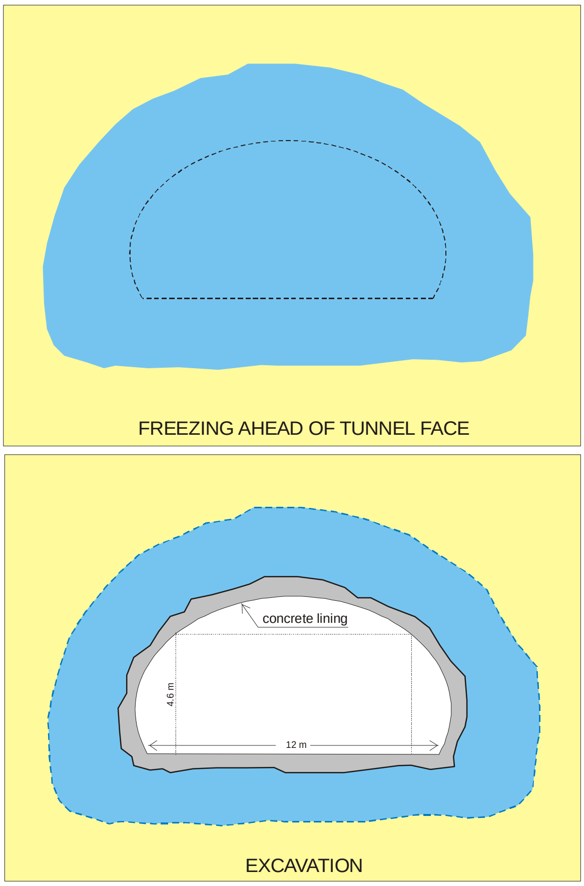


Figure 9. The core drillings (BH-1 and BH-2) performed before construction, and the situation found after numerous probe drillings had been performed (Berggren, A.-L, 2000)



Caused by this, it was decided to perform freezing of the materials in the cleft. A program of drilling holes for the freezing tubes was started. The drilling of the grout holes in the cleft was difficult because the rounded stones were slightly easily displaced from the impact of the drilling and thus locked the drill rod. A special drilling rig was brought to site, and achieved somewhat better drilling results. However in spite of this, the whole process of drilling and freezing took more than a year. A frozen zone around and in front of the tunnel was established (Figure 7) before the successful tunnel excavation through the cleft could start.

Figure 10. Freezing (blue) and later excavation through the frozen zone. The cast-in-place concrete lining was installed as after every blast round. (Berggren, A.-L, 2000)

7. Conclusions and discussions

The main feature of the Norwegian subsea tunnelling experiences of sealing of the potential inflowing water is presented. In addition a few examples are presented of the more problematic construction experiences in preventing cave-ins during tunnelling and in ground freezing of a 15-20m wide undersea cleft filled with highly permeable sand gravel and stones at 100m depth. The experiences are applicable, given there are geological similarities between the projects and the types of works in question. The application of those experiences to the construction of the Xiang'an subsea tunnel may depend upon the real geological conditions of the project and some variables in the construction work, such as equipments available, grout material cost, skill of grout works, especially related to practical experiences on how to adjust the grouting works to the actual site conditions, and the project management. There is currently a certain gap between the Norwegian experience and implementation of this in the excavation of the Xiang'an subsea tunnel. However, the consulting services made by Norwegian experts during the excavation of the Xiang'an subsea tunnel, have provided an effective approach to cover or reduce this gap to some extent. Further efforts should be made, such as site supervision and training of the crews by experienced people from Norway, supply of advanced equipments and grouting material, in order to achieve better solutions, as well as safety and cost saving results.

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