Freezing under the sea rescues Oslofjord highway tunnel

Shani Wallis

A 15 m wide zone of loose glacial moraine deposits at the bottom of a deep channel under the sea of the Oslo Fjord brought tunnelling on the 7.2 km long subsea highway tunnel in Norway to a stop in December 1997. A bypass allowed tunnelling to continue around the offending zone but only now is this final 46 m length of tunnel being excavated from within the safety of a 3m wall of –28 °C frozen ground.

The 7.2 km long Oslofjord highway tunnel connection passes 130 m maximum below sea level beneath the bottom of the fjord with a maximum overburden of 80 m to tunnel invert and a maximum 50 m water depth. The tunnel is part of the new 26.5 km long two-lane connection on the E18 Highway which will allow through traffic from Europe and from the south and west of Norway to bypass the city of Oslo and the top end of the fjord.

There were several options for the crossing including a high bridge spanning the islands further into the fjord. But environmental, social and political opposition to a bridge, despite its potential as a 'golden gate' of Norway, carried sway and the subsea tunnel was selected. The tunnel had the lowest cost estimate of the options.

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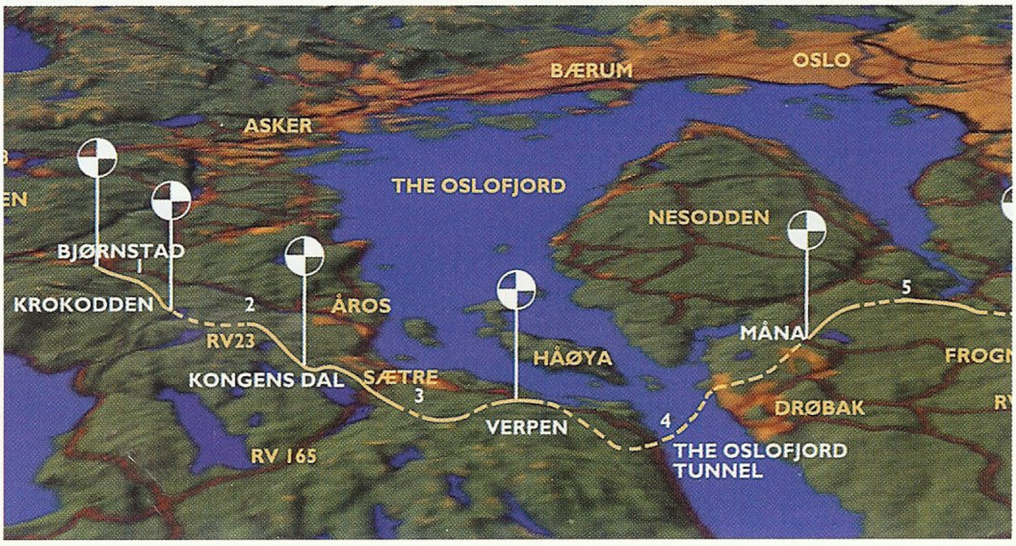
Norwegian tunnellers are well experienced in the design, investigation and excavation of subsea tunnels. The Oslo Fjord connection is the 19th subsea highway tunnel to be constructed and there are still many, many candidates for fixed fjord crossings in the country's efforts to replace the costly and weather-dependent ferry crossings in the national highway network. Norway can rely on its massive good quality metamorphic rock but site and geological investigation is thorough particularly in areas of suspected weak zones.

For the Oslo crossing particular investigation was undertaken for a narrow channel between the west portal landfall and a small island just 500 m offshore. Seismic survey, indicating a major fault in this area, led to the decision to use core drilling to investigate the rock cover further. Two diagonal core holes were drilled into the rock from each side of the channel. Using sophisticated directional drilling techniques developed and used by Norway's oil exploration industry, the holes were guided to cross each other at about 120 m below the bottom of the channel and within the zone of the proposed tunnel alignment. In addition to core recovery, hole-to-bottom-seismic survey was also carried out from the drilled holes.

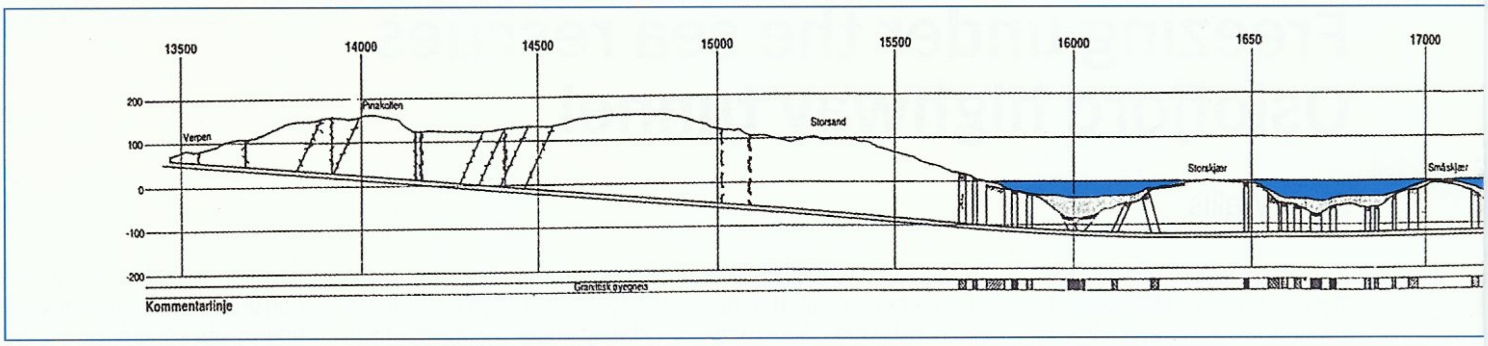
"From these investigations we knew that the zone at the bottom of this channel would be weak," explained Fridtjof Andreassen, tunnel project manager for Norway's Public Roads Administration (PRA), the client. "We could have continued taking three, four, five or more core holes but we believed that we had sufficient information to know that this section would require special treatment during excavation including consolidation grouting and installing the final in-situ concrete lining immediately behind excavation. The biggest surprise was that when we tried to stabilise the area with cement grout, the effort was totally ineffective. More drastic measures were required if we were to come through this zone."

Tunnel excavation

The full 26.5 km long highway connection, with its 6 tunnels totalling some 12 km, is split into 4 contracts. Contract 4, the Oslofjord tunnel, was won in March 1997 by SRG (the Scandinavian Rock Group AS), which also won Contract 3 with two further tunnels. "We started work on the site in April 1997," said Stein Schanke, SRG's site manager for Contract 4. "We started 3 headings, one from the east portal, and two in each direct from a



1 Plan of the new 26.5 km long highway connection under the Oslo Fjord



2 Geological cross section of the 7.2 km passage under the Oslo Fjord

730 m long adit at the sea front on the west side of the fjord. Homes close the tunnel's east portal at Verpen dismissed this as a working access."

Schanke told TUNNEL that work progressed very well to start. The full 80m² face of the tunnel was being excavated by drill+blast in rounds of about 5.4 m and excavation was progressing according to programme and without major problems.

To limit the length of the subsea crossing, the tunnel on this otherwise two-lane highway has a steep 7 % gradient. Three traffic lanes are therefore required – one going downhill and two on the uphill slope, the second one for heavy trucks and slow moving vehicles. The construction access adit on the Verpen side landfall will be a permanent escape route from the subsea tunnel.

"It was from the east bound heading from the adit that the weak zone was first encountered by a probe hole," said Schanke. "Probing is an accepted essential part of subsea tunnelling in Norway and we were drilling three 30 m long probes in the crown and have a 15 m overlap. It was soon after the 15 m overlap with the previous probe that the new probe struck water at enormous pressure and we knew we had intersected with the full hydrostatic pressure of the 130 m head of the fjord above us. We stopped immediately and the discussions of what to do began."

Grouting was to be the planned solution for progressing through this zone but initial attempts to inject grout and seal the zone had no effect. In fact, more than 700 t of cementiteous grout was pumped into the zone but without the slightest effect in cutting off the water ingress or reducing the water pressure.

Shortly into the grouting phase it was realised that the zone could hold up progress on the tunnel for some time. Further investigation of the area illustrated that top third to 50 % of the tunnel had run into the loose glacial moraine at the bottom of the fjord with hard but fractured rock prevailing in the lower half.

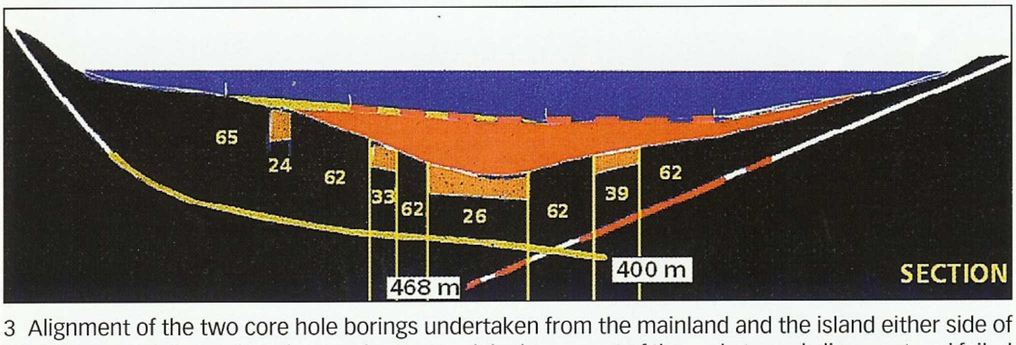
Early discussions about realigning the tunnel to go down beneath the channel were dismissed quickly. "The tunnel is already on the maximum 7 % gradient and to maintain a reasonable slope we would have to go back a long way to start the new gradient," said Schanke. "This was too expensive and time consuming."

It was also impossible to go around the zone as the deep glacial channel – cut, it is believed, by a glacial melting-age river – extends the full length of the fjord.

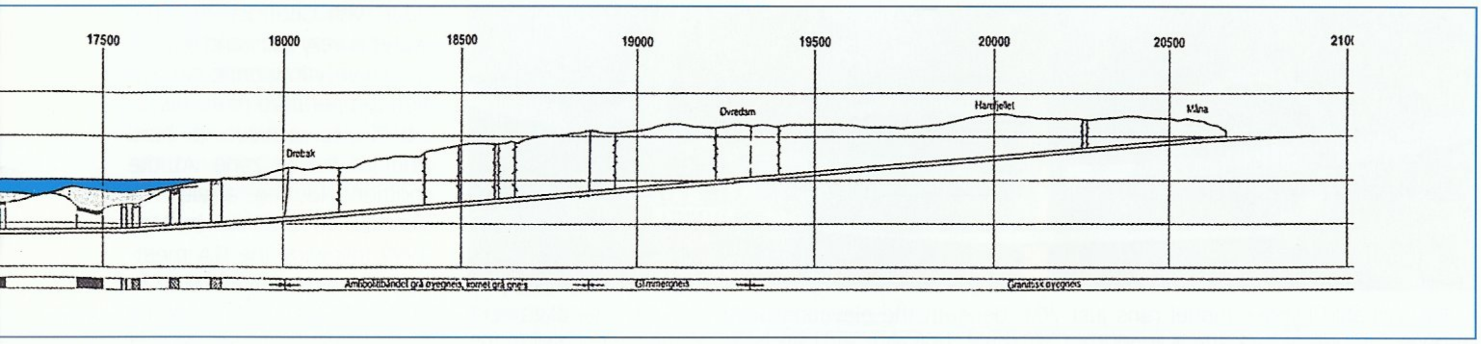
With sound rock beneath the zone it was decided to excavate a lower bypass tunnel, spiralling away from the main tunnel alignment, passing some 20 m under the glacial channel and rising up to main tunnel alignment on the other side about 100 m from the zone. "From here we were able to continue east under the fjord to meet the heading from the west portal as well as work back towards the trouble zone," said Schanke.

The ability to excavate the bypass tunnel is agreed by all as the real saviour of the project. "The bypass allowed excavation of the main tunnel to progress according to programme and without being held up by the bad zone," said Andreassen. "And excavation of the bypass is not wasted as this will become the tunnel's drainage sump, replacing the original 140 m long or 7,000 m³ excavation designed to provide this facility."

"With the bypass we were able to advance the eastbound heading and actually achieved breakthrough under the fjord in February '99, some 6 or 7 weeks ahead of schedule," said Schanke. "The 2 km drive west from the construction adit on the east side broke through on programme at the Verpen portal in Octo-



3 Alignment of the two core hole borings undertaken from the mainland and the island either side of the deep glacial channel. Both cores intersected the lower part of the main tunnel alignment and failed to identify the loose sand and cobbles of the glacial channel just meters above in the upper half of the tunnel. Seismic surveys also wrongly indicated a 30m cover of sound rock above the tunnel under the deep channel



ber 1998. This section has been finished with the water- and frost-protection lining, and the road deck, and was handed over to the owner for M&E finishing works in September 1999. The section from the east portal is also nearing completion and is scheduled to be handed over to the owner by May 2000. This left us with just this 46 m which includes the 15 m bad zone to finish and we should be able to complete the contract in summer 2000."

Ground freezing

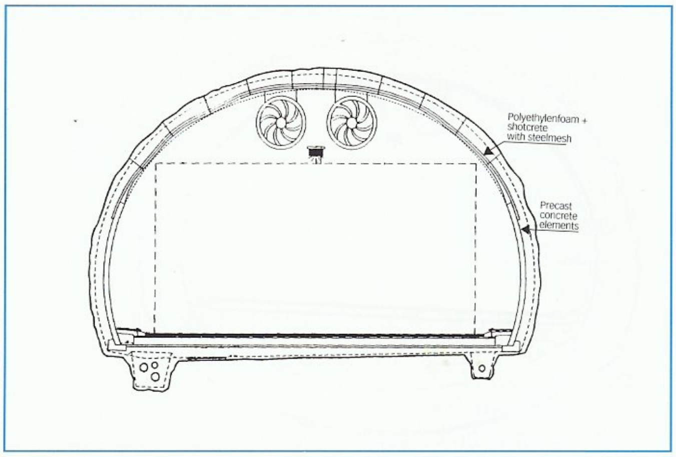
On reaching the difficult zone, when both grouting and ground freezing were being considered as possible solutions, Ms Anne-Lise Berggren, founder of the Norwegian company Geofrost Engineering A.S. was consulted regarding the freezing option. "Freezing was obviously a solution," said Ms Berggren, "even in these permeable soils and under such high water pressures. The challenge would be accurate drilling through these glacial deposits which include boulders of very hard rock in a sand/gravel matrix with very little to no clay, and under the high water pressure."

Having stopped tunnelling at the zone in December 1997, and after realising that grouting was having no effect, the decision to adopt the freezing solution was taken in April 1998 and a NKr 10 million contract, including drilling, was signed with Geofrost.

In preparing the freezing design, it was calculated that the freeze wall in the crown would have to support a total load of approximately 1400 kPa comprising the 1200 kPa of the 120 m hydrostatic load or a 12 bar pressure, plus about 200 kPa for the 80 m of material overburden. "At that time, and before we had conducted laboratory tests on the moraine material collected from the initial freeze-drilling holes, our expectations were that a freezing temperature of –10 °C would create the necessary frozen support," said Berggren, "and we started therefore with a circle of 51 freeze holes around the perimeter of the tunnel's excavation profile."

In addition, the in-situ concrete lining would advance with excavation. This is also designed to carry the full hydrostatic and material overburden load and is therefore substantial. It is heavily reinforced with 280 kg/m^3 of steel and is up to 1.2 m thick. The freezing design allowances were made for the concrete's 70 °C curing temperature as well as the heat generated by the immediate shotcrete applied to seal each exposed round of frozen rock and moraine.

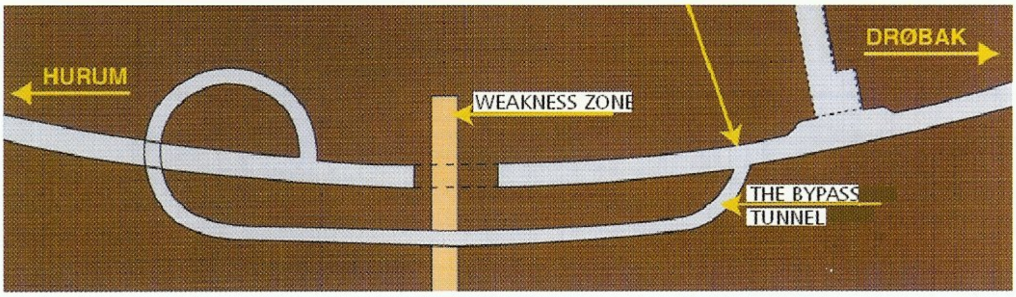
Freezing would be installed from the eastbound heading from the mainland access adit and excavation would progress back from the other side of the 46 m zone toward the west portal using the bypass tunnel for access.



4 Cross section of the new three-lane tunnel with its longitudinal ventilation and polyethylene foam drip-shed cladding lined with a layer of wire-mesh supported shotcrete as a fire retarding coating

The programme started in the west side of the zone by enlarging the tunnel to create a 20 m long 220 m^2 freeze-installation working site. This also provided the collar into which the first row of 53 x 30 to 40 m long freeze-pipe holes were drilled in a cone array around the full tunnel profile, including across the invert. Drilling with high water pressure drilling equipment was used to install the freeze holes and special packers were used to prevent drill-hole blowouts under the high water pressure. Brødrene Myhre A/S and Båsum Boring A/S were the engaged drilling subcontractors and the Devico A/S surveying system was used to check the accuracy of each hole.

While drilling progressed, laboratory tests of the moraine material were also underway. The material retrieved from the drill holes was frozen and the mechanical properties studied. "The test results showed much lower strength parameters than originally expected due to the salinity of the pore water," said Berggren. "We needed either a colder freeze zone or a thicker freeze zone to provide the necessary pre-support through the soil. Of the two, we chose to install a



5 The valuable bypass tunnel runs just 20m beneath the elevation of the main tunnel alignment through competent rock and is supported with only shotcrete and rock bolts. As the lowest part of the excavations, it will become the main tunnel's drainage sump replacing the original sump excavation

colder freeze zone to take the temperature below the –21 °C eutectic point of salty water. To achieve this we needed a second row of drill holes in the upper half of the tunnel profile through the moraine material."

A 3 m thickness of material frozen to –28 °C was calculated to be the requirement, to support the zone during excavation and include a sufficient margin for safety. The second row of 28 holes in the moraine material in the crown zone were drilled inside the first set of holes and as close to the tunnel's excavation profile as possible. This extra row of holes increased the original NKr10 million contract with Geofrost.

Freezing of the zone using a brine circulation system designed for –40 °C started in May 1999.

Stein Schanke of SRG had had experience with freezing before on the road tunnel beneath the streets of Olso City in the early-1990s where Geofrost was also the engaged specialist freezing contractor. On that occasion, the water was under 45 m of hydrostatic pressure, it was much less salty and freezing was into a material with a higher clay content. The Oslofjord freezing operation was to be an entirely different undertaking.

The original expectation – after grouting but before the drilling experience and before laboratory testing of the moraine material – according to Schanke, was that the last 46 m section of tunnel would take about 6 months to complete from the time the decision to use freezing was taken. In fact it will have taken nearly two years, with completion now expected in December 1999.

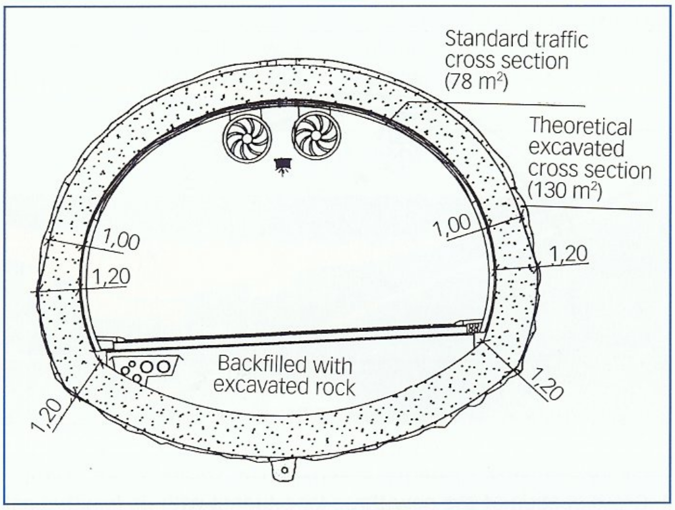
A major reason for taking much longer than expected was to complete the drilling phase. First ther was a lot of steel left from the difficult grouting operation. Secondly the rounded stones and hard boulders in the glacial deposits and the high water pressure created difficult drilling conditions. A water hammer was used for the first time in soil conditions to overcome water pressure problems.

With the extra 28 holes in the moraine material and the two freeze pipes in the middle of the tunnel profile, the freeze drilling pattern totals 83 holes. In addition there are 17 survey holes installed to monitor the temperature. Drilling started in spring 1998 and took until spring 1999 to complete. Only 11 holes in total were rejected.

Another reason for taking longer than expected, was that the material as tested required a much colder temperature than originally expected and it has taken time to achieve that necessary temperature. "The ground water is almost still, there is not much velocity at all," explained Trond Egeberg, a senior engineer with Geofrost "But the water is very salty and this requires very low brine-circulation temperature of as low as –40 °C, to achieve a hard enough freeze zone. At the moment (during a visit by TUNNEL to the site in May 1999 following the ITA meeting in Oslo) we have a temperature of about –20 °C in the freeze wall and we need at least –28 °C".

Eventually, the necessary freeze was achieved, and the decision to restart excavation was taken in August 1999. As was always the plan, the in-situ concrete final lining would progress with excavation. The excavation cycle was therefore based on one 1.5 to 2 m blast per week. Layers of shotcrete up to 20 cm thick in the crown are applied immediately to protect the exposed frozen soil and the final in-situ concrete lining is cast in two stages. First the theoretical 1.2 m thick invert slab, followed by the theoretical 1 m thick arch cast behind a 5 m long form. To provide the final 3 lane clearance and accommodate the 1 to 1.5 m thick lining, the profile through the frozen zone is increased from the normal 80 m^2 profile to 130 m^2. The reinforcement cages for lining are prefabricated and erected into the concreting bay in order to accommodate the one blast per week cycle. The arch is poured the day before the next blast which starts the next weekly cycle.

The in-situ concrete lining is installed within 70 cm of the frozen tunnel face leaving very little space for working the next face. Hand held drilling equipment is therefore used to drill some of the 243 charge holes and seven cut holes into the 120 m^2 face. Special cartridge explosive, developed specifically for the project by the Norwegian ex-



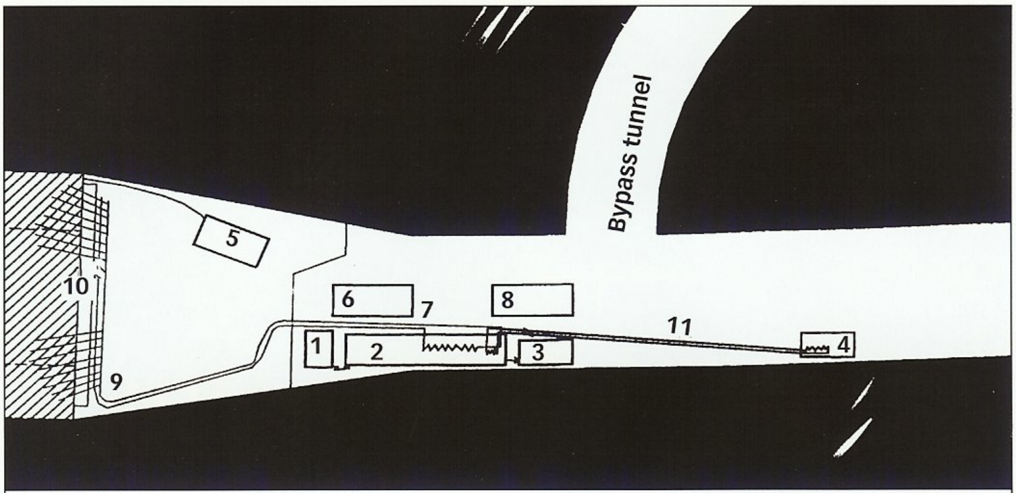
6 Design of the thick, heavily reinforced concrete lining installed as part of the excavation cycle through the frozen zone

plosives experts Dyno Nobel for application at such low temperatures, is used to charge the face. There is one cartridge of explosive at the bottom of each hole to initiate the blast, and bulk Anolit is pumped in to fill the remainder of each hole.

In addition to special explosives, the site is also using newly developed electronic detonators developed in Germany. These are microchip controlled and the delays can be programmed individually in order to achieve the smoothest of blasts and at very low ppv. "Smooth blasting and low peak particle velocities are needed to protect both the integrity of the freeze zone and the installed freeze pipes," said Schanke.

"The most exciting part of the process other than getting started again," said Schanke, "was to expose the glacial moraine, to see what it looks like and know what it is like to drill. We are now (mid-October during TUNNEL's second visit to the site) two blasts into the zone and the material is as we expected. The matrix is mostly sand and dirt and the smooth rounded stones are of various sizes and covered with a skin of the ineffective grout. The bottom section of the zone is moraine material and the top section is glacifluvial material. The freezing is holding very well and we have not had to change our pre-planned method of getting through this difficult zone."

The most critical part of the excavation cycle, according to Andreassen, is the 70 cm overlap between the last concrete arch and next cycle of drilling. This 70 cm section effectively remains 'open' for two weeks. "The freeze wall extends to about 10 m outside the tunnel profile," said Andreassen, "but when you stand at the frozen face, beneath this 70 cm overlap zone, it is something to think that it is only a wall of ice protecting the safety of us and of the tunnel from the 130 m of the fjord above. This two-week 70 cm 'opening' of the frozen soil between the concrete phase and the next blast equals the frozen material's minimum stand up time. In essence, the –28 °C x 3 m thick beam of ice over the crown of the tunnel must be able to take the full load – which it is obviously doing."



1 Electric Power
2 Freezing plant, Ammonia
3 Security tank, water
4 Heat exchanger water/air
5 Temperature measurement sentral
6 Work shop
7 Pressure holding system
8 Rescue container
9 Closed circuit with brine
10 Scaffolding
11 Cooling water circuit

7 Thick frost crusts the brine-freezing circulation pipes as they disappear into the zone of glacial moraine to freeze and stabilise the loose material with a wall of –28 °C ice

The biggest risk to the operation, all agreed, was the possibility of a water seepage event, which, if significant enough, would be unstoppable and would lead to failure of the ice barrier and inrush, over time, of the loose glacial moraine and a flood of high pressure water. One potential problem within the frozen zone, according to Andreassen, is shear pressure in the ice which could create a leakage crack and initiate seepage. Another, according to Schanke, is the fact that immediately on being exposed to the air, the temperature rises and the frozen rock of the tunnel starts to melt. This phenomenon is recognised by the crust of frosty moisture condensation that forms on the frozen rock immediately after the blast. At this point, loose rocks and stones in the frozen moraine could fall out and initiate a ravelling effect. The coating of flash shotcrete prevents any loose stones falling but nevertheless, both scenarios are possible, if highly unlikely, and the site team had to make provisions for such an eventuality.

The 'insurance', as it is called on site, against an inrush is a massive steel and concrete composite wall installed about 30 m behind the zone. This massive 2.6 m thick and some 160 t structure is designed to take the full 1400 kPa hydrostatic and material load of the overburden. A door within the wall is 3.5 m x 3.5 m, just enough to accommodate the excavation equipment, and is designed to close within minutes. The remaining zone of solid rock provides the necessary barrier on the opposite side of zone.

"Before each blast," explained Andreassen, "the tunnel and underground environment is evacuated leaving only a senior manager from both the PRA and the contractor, the blasting master, a shift foreman and a driver of the loader which is hooked to the cable to close the barrier door. It is within the first minutes after each blast that the decision of whether or not to close the door is taken."

Although an expensive item in the cost of getting through this difficult zone, the barrier is in reality seen as cheap insurance. Had there been an inrush and without the barrier, the entire tunnel would have been lost. The flooded tunnel could never have been recovered. An inrush held by the barrier would at least save the tunnel and allow other options of getting

8 The final lining reinforcement cages being pre-fabricated before being erected in the next concrete lining pour

through the last 46 m zone. These could include either re-establishing the freezing or excavating a realignment of the main tunnel.

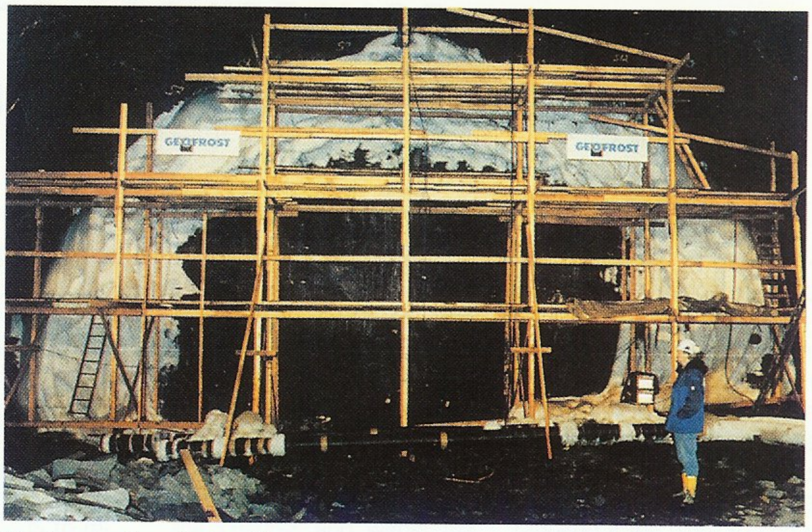
"We have not had to close the door so far, although the closing procedure is rehearsed before each blast," said Schanke. "We are now beyond the most critical part of the work where the zone of loose moraine extended into about half of the tunnel face. We have about 25 m or 11 to 12 blasts or 11 to 12 weeks to go and we hope to hole through in December 1999. Once the road deck is installed we hope to hand over the finished job to the PRA by summer 2000. This is just a few months later than the original programme and includes delays accumulated on other areas of the work."

Tunnellers around the world envy the Norwegians their perfect rock conditions for the majority of their thousands of kilometres of tunnels for hydropower, roads and other installations. But when the good quality rock fails them, the solutions required are often spectacular. Freezing is often considered a very expensive solution of last resort but as illustrated on the Oslofjord project, freezing proved to be a highly effective and cost competitive method of rescuing the subsea tunnel crossing. Freezing is a valuable addition to the Norwegian subsea tunnelling experience and one that may well be required to solve equally challenging situations in future.

9 The 3 m x 3 m door in the massive steel/concrete composite wall installed in the tunnel as an "insurance" against a possible but highly improbable inrush while excavating through the freeze zone

10 The shotcrete-covered face of the frozen zone with the charge holes drilled and the formwork of the previous concrete pour just 70 cm behind

Freezing installation



The freezing installation, illustrating the main components of equipment and their location within the enlarged freeze-installation working chamber

The set up required to accomplish the freeze wall in the Oslofjord tunnel is a major operation in itself. The illustration indicates the different types of equipment needed to establish a freeze operation including the ammonia plant, the heat exchange system, the temperature monitoring station, the brine circuit and the cooling water cycle.

"We are using approximately 330 kW of electric energy to maintain the freeze," said Anne-Lise Berggren director of Geofrost. Berggren founded the company 14 years ago. Geofrost has undertaken several freezing contracts in Norway as well as in Sweden and more recently in Hong Kong.

In the circulation system of the Oslofjord installation, only two freeze pipes in the upper moraine zone are linked to one return cycle. In the lower part of the tunnel, through more competent rock and where only water sealing is required, three pipes are linked to each return cycle. The Oslofjord installation is a closed pressurised circulation system, rather than a system with an open brine reservoir, because the freezing plant is lower in elevation than the freeze holes.

The brine is pumped around the system at a reasonably fast velocity. "The velocity is required to limit the temperature difference between the in-going brine and the return flow to only a few degrees centigrade," explained Berggren. "This is needed to help maintain a uniform freeze across the zone. But in reducing the ground water temperature from its natural 10 °C to the frozen temperature of –28 °C we are generating about 500 kW of heat energy. The brine circulation system is about 15 to 20 m^3 in volume and it is this volume flow that gathers the heat from just small temperatures difference in the return brine flow. This heat must be dissipated in steps, through #, via cooling water and by air. Release of the heat into the air must take place some distance from the working area and we have a 500 m long x 1.8 m diameter ventilation duct delivering 90 m^3/s leading away from the water/air heat exchanging unit into the tunnel toward the Verpen tunnel portal."

Having established the freeze wall, it will be maintained until the soil zone is excavated. The inner row of freeze pipes will be disconnected first when they intersect the tunnel profile, and the rest will be disconnected before the last section of blasting through the 10 m barrier of good rock on the Verpen side.

Once the freezing system has been disconnected it will take several months for the ice barrier to melt. The concrete lining will then be the only barrier to the loose moraine material and the 130 m water pressure of the fjord above in this section of the operating tunnel.

Project finance and funding

The total cost of the 26.5 km long highway is NKr 1,306 million or about $US 200 million. The total cost of the Oslofjord tunnel is NKr 440 million or about $US 60 million.

The cost of advancing the 35 m through the freezing zone is about NKr 35 million or about 10 % of the original NKr 347 million bid price of the tunnel. This is a major addition to the tunnel cost but savings in other parts of the tunnel operation, including less support installed than originally envisaged, has controlled overall cost increases. Passing through the known weakness zone was expected to cost about NKr 10 to 12 million, according to Andreassen.

The overall project has risen from its original start-of-construction budget of NKr 1,076 million to the current NKr 1,306 million.

For comparison, the cost of the three-lane fjord tunnel is approximately NKr 60,000 per m, including the freezing operation. The cost of a 6 km section of the open highway with small viaducts and a short two-lane tunnel is NKr 35,000 per m.

The project is funded by a public/private arrangement. The national government is funding 38 % of the cost and a private company has funded the remaining 62 %. This will be repaid from tolls that will be collected for 15 years from 2000 to 2015. When the highway opens in summer 2000, traffic is expected to be about 4,200 vehicles per day. This is not expected to rise significantly until the toll is removed in 2015. The toll is set at NKr 50 per car and NKr 220 per large freight-carrying truck.