The Norwegian sub-sea road tunnels: Background and experiences

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ABSTRACT: The opening of the Vardø sub-sea strait crossing, celebrated its 25-year anniversary in 2007. This achievement initiated a new epoch in strait crossings in Norway, and a new sub-sea crossing has opened on average every year since 1982. The sub-sea option includes supplementary risks to tunnelling and requires more in-depth studies than normal for land-based tunnels.
The most important experiences are that in many projects, geological studies have not been performed in sufficient detail and, in addition to this, shotcrete has been applied erroneously. These procedures have resulted in costly and unnecessary challenges for both construction works as well as for maintenance requirements.
After all, the sub-sea crossing projects have been a very successful development for Norwegian communications, and also supplied important experiences that should be applied for future projects.

1 WHY SUB-SEA ROAD TUNNELS?

The long coastline of Norway is continuously incised by long fjords and protected by numerous islands. After the retreat of the glaciers 10,000 years ago, the land was gradually populated from the seaside. For thousands of years, the sea provided the communication. When land-based transportation replaced the seaways in the coastal areas, the demand for sea crossings became a constantly increasing political issue. Ferry connections became a widespread means for strait crossings, but had some disadvantages like interruption or hazards due to weather conditions. In addition, fixed schedules and waiting lines for cars made this solution increasingly unpopular. Gradually, the Public Roads (PR: Statens vegvesen) became a bridge constructor on a large scale. Up to the end of the 1970's, 7,500 bridges were constructed. Still, 200 ferry connections remained, and large government subsidies had to be required to support this transport. Many of the ferry connections were heavily trafficked, or exposed to difficult weather conditions. The problem for not carrying out the remaining crossings was that the strait distances were too long for making bridges an option.

2 TUNNELLING TRADITION

Except for mining, underground construction has not had a long tradition in Norway. In Oslo in the 12th century, the first underground Aker mine was established. Once started, tunnelling became a commonly used method in road and railway construction. It was used for passing mountainous terrain or to avoid rockslide hazards. The first railway tunnel was constructed in Eidsvoll in 1854, excavated in postglacial marine clay. The railway expansion continued with increasing tunnel construction on the east-west connection through the mountains between Oslo and Bergen and north-south connection between Oslo and Stavanger. Higher costs combined with less strict requirements for gradient and curvature were the reason why the PR hesitated to introduce tunnels in road construction.

The development of hydroelectric power plants from the 1960's through the 1980's became a voluminous enterprise, including hundreds of kilometres of tunnels of most dimensions and gradients excavated. The experience gained encouraged the PR to introduce tunnels in road construction, at first for protection against rock fall and slides, also to lead a road where tunnel was the only option, and largely to connect sparsely inhabited and difficult accessible areas to the road net. Mainly this implied low traffic connections where a low standard and low cost design could be accepted. The experience demonstrated that many of the low cost measures for rock support, water and frost protection developed could be applied also for higher traffic road tunnels.

3 SUB-SEA TUNNELLING HISTORY

The concept of establishing connections below the seabed between communities is not new. Again, undersea excavation started with mining. In England, underground coal mining below the sea started at the beginning of the 19th century, and since then large galleries have been excavated. In 1843, Brunel's tunnel through the mud below the Thames River in London was finished, and the 7 km long Severn railway tunnel in Southwest England opened in 1886. Undersea tunnelling also took place in Norway; already the Aker mine in Oslo was excavated below the Aker River and below sea level. More recently, Fosdalen and Vigsnes mines were excavated 750 and 730 meters below sea level respectively. In addition, between 1960 and 1990, extensive undersea excavations were made by the hydropower development in establishing lake tap tunnels. The offshore oil industry also made undersea breakthroughs at large depths providing for oil pipes going onshore.

5 HOW SUB- SEA STRAIT CROSSINGS ARE POSSIBLE IN NORWAY

The Norwegian topography is formed by glacial erosion. This implies a mountainous landscape cut by valleys, which also continues below the fjords. The U-formed cross-section with steep hillsides is typical for a landscape formed by valley glaciers. A so-called "strandflat" is often found between the mountains and the deep ocean. The fjords are in general very deep, and the formation of this over-deepening is a feature difficult to understand. However, they have one or more thresholds at the mouths where major valleys merge. The topography of the longest fjord, Sognefjorden illustrates this. At the village of Lavik, the sea depth is 1200 meters, and a couple of kilometres further out, the seabed has climbed to only 200 meters below sea level. The thresholds therefore are the only feasible locations for undersea tunnel crossings. The exploration for thresholds starts with studies of nautical and geological maps. Many thresholds may consist of or have a cover of end moraine drift with a considerably varying thickness.

6 THE PIONEER PROJECT AT VARDØ

Situated on a small island at the outmost north-eastern corner of Western Europe is the village of Vardø. It lies in the arctic zone 70° north and strangely, east of Istanbul. The island overlooks the Varanger fjord and the inlet to the Russian town of Murmansk, which is visible during clear skies. The glacier melted away 12,000 years ago, being among the first areas in Norway that became free of ice. Shorelines show that the sea level at that time was 80 meters higher than the present. The oldest shoreline on the mainland is 28 meters lower, which proves that the island was free of ice 2,000 years before. Evidence was discovered that human hunters visited the island as early as 6,000 years ago.

The oldest historic information dates back to the year 1307, when the Archbishop of Trondheim consecrated a church on the island. Coincidently, the Norwegian King Håkon V Magnusson built a fortress to confirm his sovereignty over the northern territories. Through the years, Vardø increased its importance as a fishing port and a center of the Pomor trade, by which grain from Russia was traded for fish. In the 1970's, most of the islands were employed in the fishing and fish-processing industry.

At the end of the Second World War, most of Vardø was intentionally burned down. Good arguments to relocate the village on the mainland were put forward, but the inhabitants preferred to relocate their houses at the sheltered harbour on the island. The island was connected to the road on the mainland by a ferry, which had to be harboured during the heavy arctic storms. The harbour soon became too small for the business, and the ferry traffic increased. As time passed, the inevitable claim came up; a strait crossing to the mainland. Eventually, a decision by the Storting (Norwegian Parliament) in 1977 opened for the strait crossing. A cost estimate was to be presented early in 1978 for a construction start in 1979.

7 THE ALTERNATIVES FOR STRAIT CROSSING AND THE DECISION

Already in 1951 planning for a crossing had started with the alternatives; bridge, embankment fill and tunnel in consideration. Moreover, in 1959 the Defence Department wanted to make a tunnel connection across the strait. The Public Roads Administration (PRA) studied the tunnel alternative in 1959 and later in the 1964, since it was found that the other alternatives were frequently subjected to arctic storms. The studies revealed the bedrock was schist and flaggy sandstones, partly soft and permeable. The geology report concluded that the rock conditions were not favourable, and there was risk for heavy water inflow, which was difficult to handle with the existing technology. Studies for crossings by bridge and embankment were continued in 1973/74. High costs in relation to the traffic combined with discussions on the sharing of costs were the reasons for the delays in progress for the project.

By 1976, some interesting undersea projects were under progress. The Japanese Railways, the Seikan tunnel, paid attention in particular to the tunnel crossing of the 100 meters deep and 25 kilometres wide Tsugaru Strait. In addition, the successful tunnel crossings of the Frier Fjord in Norway and the Muskø Island tunnel in Sweden was of notice. The progress in the injection technology demonstrated that it now was possible to control water inflow during tunnel excavation. The experience from the Severn and Seikan tunnels demonstrated clearly that this solution implies hazards and substantial unexpected costs.

However, the excavation of the Muskø tunnel was watched with interest by tunnelling trade engineers, and it was opened in 1964 at a reasonable price. The Vardø project was taken up again in 1976, and now the Road Research Laboratory (Grønhaug 1976) promoted the tunnel alternative, since new experience had been achieved in controlling water leakages. To study how to handle water inflow and poor rock conditions, three engineers from the Public Roads Administration were appointed to visit the Seikan project in the same year. The group was met with very helpful goodwill from the Japanese authorities. All existing information requested was presented, and finally a visit to the tunnel face in the pilot tunnel 200 meters below the Pacific Ocean was made possible, despite the existing delicate situation of the tunnelling coming to a halt. It appeared to be caused by a huge water inflow incident and the main tunnel had to be occupied by large water pipes for pumping the water out. Three events like this happened during the excavation, and all were successfully handled by cement grout injection. The report from the visit concluded that the conditions in Vardø were considerably more favourable than in Seikan. In addition, the new experience with injection for water inflow control gained made the undersea crossing alternative more interesting. It was now concluded to undertake more detailed studies of the geology in the Vardø area, and that the studies from now on should be concentrated on the tunnel project (Knutsen & Boge 2005).

8 DISCUSSION OF GEOLOGICAL STUDIES REQUIRED

To obtain ideas and input for planning process, the problem was presented for a wider forum at the Salzburger Bergmechanischer Colloquium in 1977 (Grønhaug 1978). However, the problem was found interesting, but too rare for any further discussion.

If the Vardø project became successful, it was reasonable to think that this would initiate a new epoch in strait crossings in Norway. Therefore, it was extremely important not to fail. This solution included supplementary risks to tunnelling, and more in-depth studies than normal had to be introduced. Cost effective tunnel planning implies to do a systematic investigation, using each particular step to plan the next one. In this case, time did not allow for it, so the rate of progress had to be increased. Consequently, parallel surveys had to be undertaken on the assumption that the chosen lineage was feasible, preferably the shortest lineage across the sound.

The area is situated on the "strandflat", indicating an even rock surface of the seabed. Four basic factors were absolutely required to outline for a successful performance: the mean depth of the bedrock, the existence of gaps filled with detritus, the stability and structure of the rock, and finally the water conductivity of the bedrock. In Muskø, pilot drifts were excavated on both sides along the planned lineage of the tunnel, from a sink on a rock situated in the middle in the sound. This method was not feasible in Vardø. The available survey methods were extrapolation of the local geology findings, seabed mapping by frogmen, acoustical seismic soundings, refraction seismic profiling, vertical drillings from barge and finally sub-horizontal core drillings, all in the order of increasing costs.

The geology was mapped in more detail in the summer of 1977. At the same time, vertical drillings from a barge were undertaken along a profile above the tunnel lineage in the sound. In addition, refraction seismic profiles were shot both parallel to the tunnel lineage across the sound and some shorter at a right angle to the lineage. The report was presented early in 1978, and it concluded that the project was feasible, but the existence of poor rock conditions was confirmed. To elaborate cost estimates and planning the tunnelling procedures, additional studies were required.

The following items studied were found unsatisfactory: The possible existence of narrow gaps in the rock surface, gaps at small angles to the seismic profiles, faults striking at small angles to the profiles, flat lying faults, fracture zones varying in thickness and rock quality and faults overlaid by strata with a higher seismic velocity. To unravel most of these unsolved factors, the possibility of drilling a cored hole from each side of the sound was investigated. The Norwegian Geological Survey (NGU) had this expertise, and after having studied the geology at the site, they made a proposition for doing it as a part of their own drilling development. However, the project did not get any support, and the supplementary exploration was reduced to performing shorter core drillings from the shorelines and core drillings ahead of the tunnel face during the excavation.

The cost estimate settled on 70 to 110 million NKR for a 2,892-meter long tunnel, as compared to the 120 for the bridge alternative. The tunnel had to have a grade of 8% downwards to the deepest point 88 meters below the sea level, and with an estimated average rock cover of 50 meters. The Storting voted for the project the same year after strong support by the Minister of Transport.

9 THE CONSTRUCTION

The experienced tunnel contractor, Thor Furuholmen, won the contract for carrying out the construction job at a sum of 63 million NKR, which was by far lower than the cost estimate by the PR. The start-up was delayed by three weeks in the summer of 1979, which lead to additional delays because the snow sheds were not installed before the winter season (Grønhaug & Lynneberg 1984). The works included normal blasting procedures, pilot core drilling ahead of the tunnel face for ground exploration, water leakage testing and eventually grout injection. On the mainland, additional delays were caused by poor rock conditions and time-consuming head support installation. A dramatic event occurred when a cave-in below the sound left a 7-meter high outfall in the tunnel crown. The situation was handled by immediately shotcreting, installation of a steel shield and concrete filling of the opening. A couple of similar, but not so dramatic events, happened later on.

On the Vardø island, the progress was on average faster, but a delay was started by a heavy inflow of water below the shoreline. Before excavation could proceed, the section had to be concrete lined to the tunnel face. The tunnelling progress varied from normal 30 to 3 meters per week where steel shield and concrete lining had to be applied. The water leakages were far higher than during normal land based tunnelling, caused by the jointed and fissured bedrock. However, only at four sections, pre-grouting was applied, which became a disadvantage for the permanent security measures and the maintenance. The core drillings, even done from lay-bys behind the tunnel face, were also an obstacle to the excavation. The survey for water and rock quality problems was for this reason not functioning as planned.

Totally, 630 meters of the tunnel was concrete lined, only 60 meters waterproofed with a membrane. Additional 18,000 rock bolts were installed, and 2,300 cubic meters of shotcrete applied. About 2,000 meters of frost insulated aluminium linings were installed for water shielding. These quantities were considerably higher than normal for road tunnels in Norway and a lot higher than the estimate. One other reason for this was unexpected higher construction costs in the far north.

10 OPENING OF THE VARDØ STRAIT CROSSING

The tunnel was opened for traffic by December 22, 1982, and the ferry connection was closed simultaneously. This implied periodic closing of the traffic for completion works in the tunnel. These events passed without protest, not least because the inhabitants were accustomed to waiting connected to fixed ferry schedules. The official opening of the crossing was made by his majesty King Olav on August 16, in the presence of most of Vardø's 3,000 inhabitants. Special honour was rendered to the indefatigable advocate for the project, the Mayor of Vardø, Hjalmar Halvorsen. At the occasion, he was honoured by the County Governor Anders Aune with the unveiling of a bust of him.

11 A SUBSEQUENT DEMAND FOR SUB-SEA CROSSINGS

The excessive costs and construction difficulties connected to the Vardø project did not stop advocates for the many strait crossings, where this solution was the only option, from promoting plans. The advocates pointed out that the geology of the Vardø area was very unfavourable related to normal geology in coastal Norway. An avalanche of sub-sea crossings all over the country were presented to the authorities following the Vardø crossing. The demand for road links on many islands was highly needed. An inventory made by the PRA in 1987 included 38 projects. In the county of Møre and Romsdal, the demand was highly felt and a list 22 of projects was promoted. In the years that have followed, 25 crossings have been constructed, on average one per year. A list of the crossings is given in table 1.

The optimism following in the footsteps of the Vardø strait crossing became in some cases somewhat overheated. The worst case happened with the "Ålesund og Giske Bruselskap A/S" (Bridge company) and the bank "Sunnmørsbanken" as guarantor financed the sub-sea crossings to the Ålesund airport at Vigra, also including the tunnel to Godøy island. Insufficient toll income led to bankruptcy, and the deficit had to be covered by public funding. (Knutsen & Boge 2005).

Table 1 (*m.b.l: below sea level)

No	Name and area	Year opened	Length km	Max. * m.b.l.
1	Vardø, Finnmark	1983	2.6	88
2	Ellingsøy, Sunnmøre	1987	3.5	140
3	Valderøy, Sunnmøre	1987	4.2	145
4	Kvalsund, Troms	1988	1.6	56
5	Godøy, Sunnmøre	1989	3.8	153
6	Hvaler, Østfold	1989	3.8	121
7	Flekkerøy,Vest-Agder	1989	2.3	101
8	Nappstraumen, Lofoten	1990	1.8	60
9	Fannefjord, Møre og Romsdal	1991	2.7	100
10	Maursund, Troms	1991	2.3	92
11	Byfjord, Ryfylke	1992	5.8	223
12	Mastrafjord, Ryfylke	1992	4.4	132
13	Freifjord, Nordmøre	1992	5.2	132
14	Hitra, Sør-Trøndelag	1994	5.6	264
15	Tromsøysund, Troms	1994	3.4	101
16	Bjorøy, Hordaland	1996	2.0	85
17	Sløverfjord, Lofoten	1997	3.3	100
18	Nordkapp, Finnmark	1999	6.8	212
19	Oslofjord, Akershus	2000	7.2	134
20	Frøya, Sør-Trøndelag	2000	5.2	164
21	Ibestad, Troms	2000	3.4	125
22	Bømlafjord, Hordaland	2000	7.9	260
23	Skatestraumen, Nordfjord	2002	1.9	80
24	Eiksundet, Sunnmøre	2007	7.8	287
25	Halsnøy, Hordaland	2008	4.1	135
26	Finnøy, Ryfylke	2009	5.7	200
27	Averøy, Nord-Møre	2009	5.7	251
28	Knappen, Bergen	2009	6.4	30

12 EXPERIENCES GAINED

The development of sub-sea tunnels did not pass without unforeseen events and experiences. These are tied to all elements in the sub-sea project activities, from planning, excavation, materials used, traffic conditions and maintenance.

12.1 Traffic safety:

The anxiety for passing road tunnels has always been shared by some people, and not at least when they are curved or lying on a steep grade. In the

Vardø case, some of the inhabitants were reluctant that a sub-sea tunnel should replace the ferry. Experience from other areas indicated that this feeling would decrease as time went on when experience in tunnel traffic has been gained. In addition, here the fright was gradually diminished with time and soon the connection became for most of the people a boon when they learned that during winter storm rages, when all road connections were closed, the only place for walks were in the sub-sea tunnel free of motorized traffic.

Former and recent studies of traffic accidents confirm that safety is considerably higher in tunnels than on the adjacent road (Ranes 1998, Amundsen & Engebretsen 2008). The only exception is entrance zone in the tunnels, which have an accident rate about the same as on the adjacent road. This is also a fact for sub-sea tunnels, even having a difficult inclination that supposedly should require additional attention for drivers.

Still, much should be done to improve safe and comfortable tunnel traffic. To contribute to safer, more comfortable and confident transport in the tunnels, the Norwegian Road Research Laboratory (NRRL) arranged the "Road Tunnel Linings International Symposium on Designs for Safety, Comfort and Aesthetics" in 1998. The documentation provided included several measures for achieving this goal. The most mentioned proposal was to use higher levels of light, and make interior surfaces light in color (Juncà Ubierna 1998, Carmody 1998). These proposals are not considered for Norwegian tunnel linings, where a dark crown and grey walls are specified. A light colored lining should reduce the costs of electricity for safer and more comfortable tunnel traffic. Different designs could be tested in a simulator (Jenssen 1998), which is a cost effect tool in evaluation of tunnel lining design. Another problem for tunnel drivers is the monotony driving in long tunnels. To reduce it, different lining patterns should be tested in the simulator.

12.2 Geology studies

The planning should keep the geological conditions in focus as a main constituent. Even if the demand for improved geology studies have been advocated for from the start, unexpected events tied to the unsolved geological conditions have left the contractor and client several challenges. Fortunately, these events have not led to severe accidents, but did have a serious bearing on the final, excessive costs for several projects. Examples demonstrate that core drillings have saved projects from disasters and, on the contrary, the lack of more detailed investigations has led to unforeseen troubles during excavation and for the maintenance. That was just what happened at the Bømlafjord tunnel, where a sub-horizontal core drilling above the projected tunnel crown revealed that it was heading towards a morainic deposit not detected by the seismic soundings. Consequently, the tunnel had to be dug steeper than originally planned.

It is important that all available resources should be used in the exploration of relevant geology, in particular, consulting geologists that have studied the geology in the project area (Grønhaug 2000).

12.3 The leakage problem

The leakage problem did not cause as much problem as previously feared. At the Muskø tunnel, extensive water leaks were met. Cement mortar injection reduced the inflow by 50%, and subsequently increased to the original inflow after ten years. To Norwegian tunnels, the opposite took place in that most parts of the tunnels have experienced a decreasing inflow in the course of time. However, seawater leaks cause corrosion of installations and excessive energy for pumping the water out. The costs involved should be weighed against the costs of pre-grouting for reducing the inflow. This effort should certainly have been an advantage for the Vardø tunnel, where the inflow is considerable with 1,000 litres per minute. In the Vardø tunnel, the water inflow has been shielded by frost insulated, corrugated aluminium arches, which are still in good shape. The old shielding has been successful because it was made of a special seawater resistant alloy and installed exactly according to specifications. In later years, fire resistant PVC fabric has replaced frost insulated aluminium shieldings, as being more advantageous (Grønhaug 1999).

12.4 The rock support problem

Many years ago, thin layers of shotcrete replaced manual scaling, rock anchors and, where needed, supplied with wire nets as heading support. This strategy is fast and handy during excavation, but has not been beneficial for the permanent support. Firstly, it is expensive because it is often applied continuously, also in sections where it is not needed. After excavation, the rock should have some time to settle, in particular where there is risk for rock falls. Rock falls in the wire net is a warning sign for a coming cave-in, and support should be installed immediately. By applying shotcrete, such locations may not be detected, as has recently occurred several times.

The performance of shotcrete in road tunnels has been studied (Grønhaug 1996), and it was found that it had performed inferiorly in leaking sections of the tunnels. Recently, finding has been made (Hagelia 2009) that seawater forms mineral changes, causing deterioration of the concrete. In leaking sections, concrete linings should be water protected by a continuous watertight membrane.

In poor and leaking bedrock, the tunnel should be lined with membrane protected, cast concrete. In rock where occasional rock bolting is needed, driving could be made more confident and comfortable with a lining of bright tunnel fabric (Grønhaug 1999).

13 SUB-SEA CROSSINGS A VERY SUCCESSFUL DEVELOPMENT

The development of the sub-sea crossings have been a huge benefit to many communities. Continuous roads have made it more advantageous for industrial development in the areas involved, and giving sparsely populated coastal areas the possibility of expansion to more flourishing and prosperous units.

In addition to this, the pioneer project at Vardø has promoted a rethinking connected to solutions for strait crossings other than sub-sea tunnels in bedrock. Solutions that have been studied are floating bridges and submersed floating concrete tunnels where crossings are too wide or sea is too deep.

14 FUTURE PROSPECTS

However, the prospects for the remaining sub-sea crossings in Norway may not be so encouraging for several reasons. One is the economy in connecting sparsely populated regions by a total and per capita very expensive crossing. Another is the new European tunnel specifications that may not take the low traffic situation and the Norwegian low cost and standard tradition into full consideration. Consequently, the increased costs involved may put the brakes on further strait crossing development. However, generally speaking, it is certainly an alternative strait crossing that should be recommended for many international projects.

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Abbreviations
PR: Public Road Works
PRA: Public roads Administration
NRRL: Norwegian Road Research Laboratory
NRRL Int rep nr: Norwegian Road Research Laboratory Internal Report no