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Subsea tunnel linking Föglö with the main island in Åland

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Abstract. The paper describes a well considered subsea road tunnel in Åland, Finland which will hopefully start in the very near future. The paper describes partly the socio-economics and public benefits of such a project in Åland and partly some technical aspects of designing and constructing road tunnels under the sea to connect land masses. The tunnel is expected to be constructed along the lines of similar rock tunnels being constructed and entered into successful operation in many of the Scandinavian /Nordic countries. More important though is the vital role such a project will serve for the society in Åland. The project is not one that serves millions of people in busy mega cities – still it is a pleasure to see a mega project for a small community mature, starting from a sketchy plan made by individual enthusiasts to a solid plan for a multi-million Euro investment.

1. Introduction

The Åland Islands are self-governed and consist of around 6500 islands in its archipelago. Mariehamn is the main centre of activities in Åland hosting the parliament and other vital offices in the islands, whilst the many surrounding islands are basically either agriculture land, fisheries, tourism, and shipping industry or being the home to people who commute to Mariehamn.

A subsea tunnel under planning will connect the island of Föglö with the main island where the city Mariehamn is located and allow vehicles to pass around the clock no matter the day in the week.

To provide a reliable, cost effective and open at all times link between the island of Föglö located to the East of Mariehamn a subsea road tunnel has been suggested. A route finding has been ongoing for about 15 years where the tunnel alignment been moved up and down the fjord between the two islands, and the length of tunnel has varied from around 5-6 km to the present length of 10,5 km.

The tunnel is planned to be built in well suited rock mass conditions, granitic rock mass which is certainly on the hard rock side and well proven for tunnelling. The concept of subsea road tunnel has so far been following close to what has developed in Nordic countries like Iceland, the Faroe Islands and Norway, a concept well fit to low traffic tunnels.

A main driver for the initiation and motivation for the tunnel is to enhance the social aspects of life in the islands.

2. The current situation

The archipelago is connected through several small car ferries. The ferries carry both cars and passengers, and have a cruising speed of ca 20 km/h. The many ferry lines make this traffic system very costly, with OPEX exceeding 16 MEUR yearly. The current structure also creates a long travel time, up to five hours one-way to some destinations.

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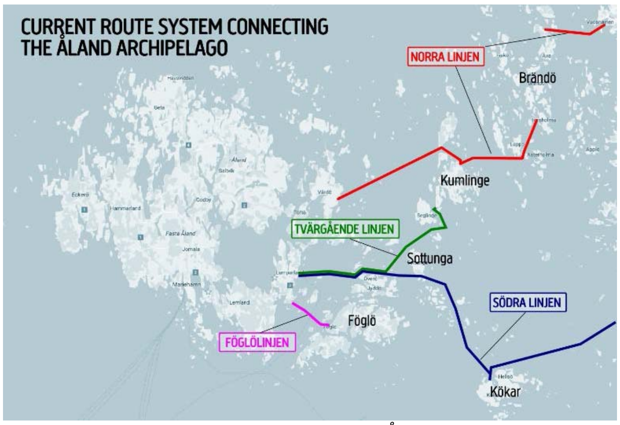

Fig. 1 The different ferry lines in Åland's archipelago (FS Links Ab 2018)

The current ferry lines as described in Figure 1

- The Northern Line (red), connecting the northern part of mainland Åland with the Islands of Kumlinge and Brändö, continuing to the Finnish mainland.
- The Transverse Line (green), connecting the southern part of mainland Åland with the Islands of Föglö and Kumlinge
- The Southern Line (blue), connecting mainland Åland with the islands of Föglö, Sottunga and Kökar, and continuing to the Finnish archipelago.
- The Föglö Line (magenta) connecting the Föglö island to the Åland mainland.

3. A restructured traffic system

The planned tunnel would entirely replace the ferry services on the Föglö Line, making the island of Föglö an extension of the Åland mainland. This also allows for restructuring most of the traffic system connecting the eastern archipelago.

By using extracted rock materials from the tunnel excavation, a new harbour on reclaimed land will be built on the eastern side of Föglö island. By eliminating the Föglö Line, and re-routing the Transverse and Southern lines further to the east, up to 7900 running hours and two entire crewed ferries can be saved annually while maintaining the current traffic frequency. The cost savings from this operation will be enough to fund the construction and maintenance of the tunnel over a 30-year period.

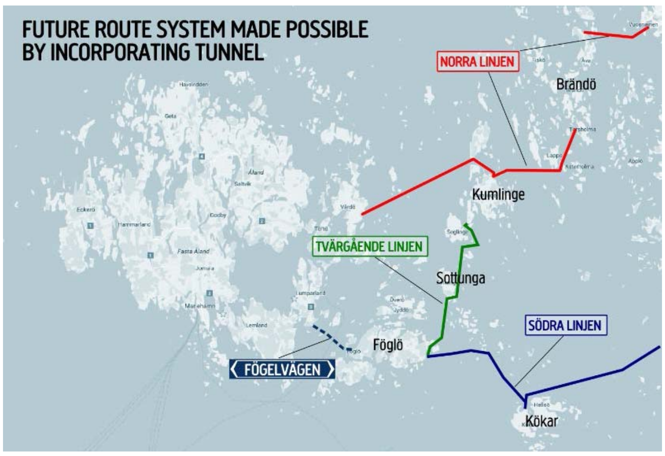

Fig. 2 The tunnel and the subsequent restructured ferry lines (FS Links Ab, 2018).

The tunnel road is shown by the name 'FÖGELVÄGEN' and dotted line in the southern part of Åland is the tunnel alignment in brief.

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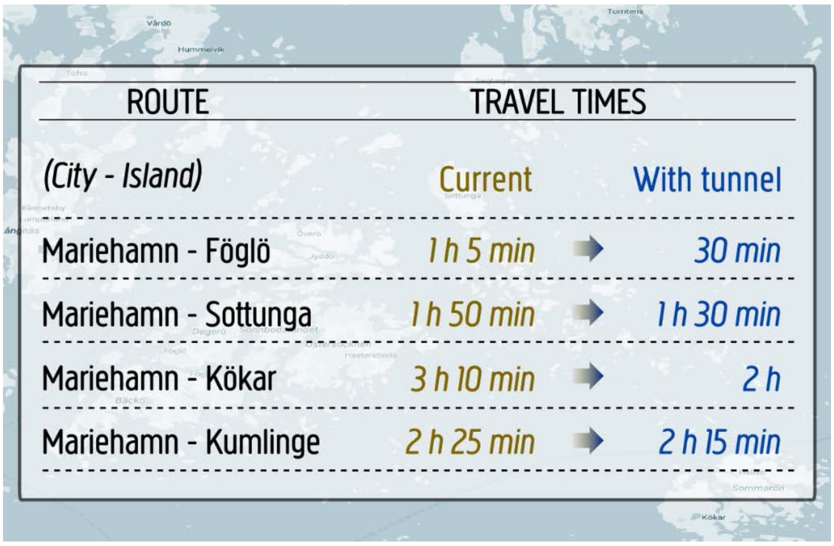
4. Demographic challenges

All of the 10 small municipalities on mainland Åland have shown a relatively stable population during the last four decades. Contrary to that, all the island municipalities have shown a declining population. As in most places affected by urbanization, the commute time to an urban centre seems to be the most important factor that decides whether the population increases or decreases.

With a restructured ferry system, the shortened routes will not only cut travel time by up to fifty percent. -It will also allow ferries to depart on a schedule that adjusts better to passenger's needs. Departure time is better adjusted to passenger flow. Current time tables are very limited by the long turnaround times of up to six hours.

Expected travel time from the city of Mariehamn to some of the island municipalities after the tunnel is given below:



ROUTE (City - Island)	TRAVEL TIMES Current	With tunnel
Mariehamn - Föglö	1 h 5 min	30 min
Mariehamn - Sottunga	1 h 50 min	1 h 30 min
Mariehamn - Kökar	3 h 10 min	2 h
Mariehamn - Kumlinge	2 h 25 min	2 h 15 min

Fig. 3. Shortened travel times (FS Links Ab 2018)

During the Environmental Impact Assessment (EIA) process, a survey was included where the general public could answer a set of questions and also add their own comments. Some findings from the survey are that 84% agreed that the tunnel project is a corner-stone for the archipelago's future survival. 89% of respondents thought the archipelago would be a more attractive place to live in if the tunnel is built, and 88% thought that services offered in the archipelago would be improved when a tunnel is in place.

Despite the limited number of people who are involved in this infrastructure development in Åland, there is a need today, in 2020 to find solutions which are providing robust and reliable connections for the public.

5. Progress and milestones of the project

A private consortium, FS Links Ab, initiated this project. The project has received strong political backing, with a majority now working towards making this a reality. So far, these steps have been completed:

- Identification of problems to be solved, solution alternatives and relevant stakeholders that need to be consulted (2017, FS Links Ab)
- Preliminary assumptions of route and financials (2017, FS Links Ab)
- First round of measurements for potential routes, including bathymetry and boomer surveys (2017, FS Links Ab/GTK)
- Technical feasibility study and cost estimates (2018, SINTEF)
- Financial models, estimates (2018, Skanska/FS Links Ab)
- Land owner dialogue and subsequent route adjustments (2018, FS Links Ab)
- Second round of measurements of two alternate chosen routes, refraction seismic survey (2018, Geomap/Geovista)
- Environmental Impact Assessment (2019, Ramboll)
- Enhanced alternative for tunnel design (2019, SINTEF)

6. The Tunnel

Work has been ongoing for a subsea road tunnel across the Föglöfjärden between the 'Fasta Åland' and Föglö for a number of years, at least 15 years under the auspices of the Åland Landskapsregering and then in most recent years by the FS Links Ab. Many different tunnel alignments have been considered and discussed for the crossing of the Föglöfjärden between the islands to the east and the 'Fasta Åland' or Mainland Åland.

The most recent alignment lies between the former northernmost and southernmost alignments, as shown in Figure 4. The southernmost option was investigated quite thoroughly around 2009 and some seismic surveys were also carried out. Some of the findings may be of benefit to the option to be considered in the current alignment option as well. The northernmost alignment dates back to an even earlier time, probably around 2005.

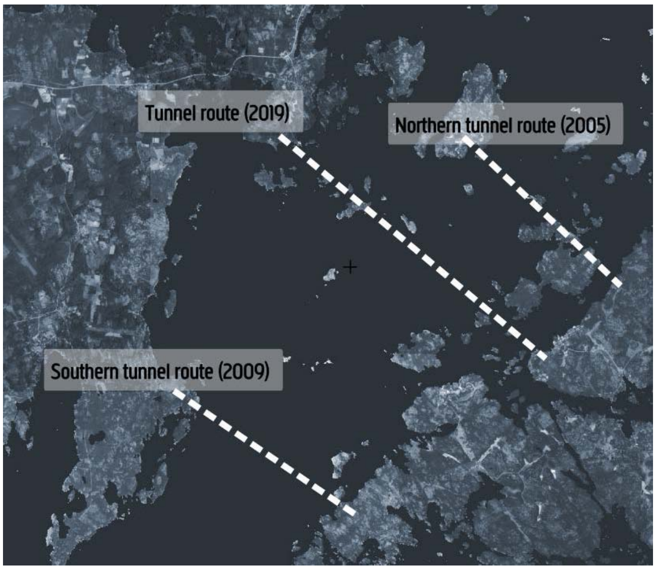


Fig. 4. Approximate locations of 3 different alignments/routes at three different times in the project development

The suggested tunnel alignment may not necessarily provide the shortest crossing between Föglö and the Mainland Åland across Föglöfjorden. However, it provides a direct connection between Svinö and Degerby, the centre of Föglö, with short road connections at both sides, the tunnel could practically connect directly to the road network on both sides.

Further, the tunnel as shown is quite long but without any other elements in between the two landing points at each side, other proposed alternatives have included a suit of elements like bridges, embankments etc. in addition to a tunnel. A long tunnel would require a longer construction time as it allows only two tunnel faces being applied, one from each end. There is no intermediate solution for an adit or access tunnel, thus the excavation will be by one tunnel face from each side, compared to an alignment that holds various elements that can be constructed simultaneously.

The suggested tunnel alignment is 10,5 km long and has its entrances at 15 meters above sea level (masl) at Föglö and at 5 metres above sea level at Svinö.

A pumping station and water collection magazine has to be established at a low point in the tunnel. The logical location of these facilities appears to be at the low point towards Föglö, right north-west of the small island of Ekholm. This will give the shortest length of water drainage to the surface through the tunnel and to clean and discharge the water at Föglö and back into the sea. It could also be a possibility to discharge such water through vertical shafts at Ekholm or Färnsholm. This has to be looked further into at later detailed design stage.

As shown above, the crossing of the channel between Färnsholm and Föglö (Färnsholm sund) is the critical point at the Föglö side. As the water depth is quite low at this point it was suggested to waive the 50 meters rock cover requirement and use 30 meters at this point. From this point there is approximately 1000 meters to the portal in the suggested alignment, whilst there is a need of 740 to 1040 meters, pending on the inclination and with the portal at 15 masl.

One possibility would be to increase the inclination and reduce the tunnel length if a

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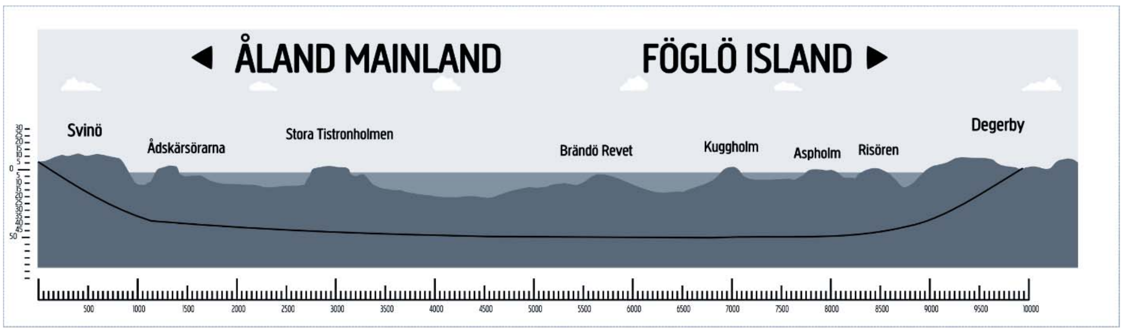
reasonable portal area can be found and the horizontal curvature can be maintained. A very small potential exists to reduce the tunnel length if a portal location is found to fit the above geometry based on the current alignment.

Fig. 5. Current tunnel alignment in reddish colour between Föglö and the mainland Åland, subject to slight modifications along the development of the project

At the Svinö side, between Kulvikudden and Rönnören it has been suggested to possibly reduce the rock cover to 35 meters. The length from the low point to the portal according to the suggested tunnel alignment is around 1,2 to 1,4 km. Using the EU-requirement of 5 % inclination goes well in balance with the available length in the suggested proposed alignment. Increasing the inclination to 6% and even steeper to 7% could include some savings on the tunnel length (a few hundred meters) if a suitable portal is found. By reducing the rock cover, all inclinations are within reach, and the alignment could be reduced by even another few hundred meters if a suitable portal location is found. Note that the current maximum level of inclination is at 5% for the project in line with the EU-regulations.

Fig. 6. Longitudinal section of the Föglö tunnel



The above are comparisons to demonstrate the sensitivity when modifying the rock cover at the critical points at both sides and the maximum inclination. It is obvious that a combination of steeper inclination and waiving the 50 meters minimum rock cover requirement would enable different solutions that could include potential savings. From the low point at Svinö (at level appr 35-40 mbsl) a gentle decline will be needed to reach the low point of the tunnel at level around 80 mbsl, which over a length of appr. 6 km produces a gradient of around 1%. See the longitudinal section in figure 6. Water drainage by gravity of that level of decline may not be desirable. The Guidelines in Norway states that if the gradient is less than 1% the drainage pipes shall be installed with 100% overcapacity to mitigate clogging by bacterial growth. There is a possibility to lower the tunnel to e.g. around 100 mbsl to give a steeper gradient and above 1%. This will give approximately 4 % declined tunnel to the low point under Färnsholm sund from Svinö side, consequently there is still some flexibility to determine the tunnel elevation at the low point west of Ekholm.

The tunnel is planned to be built as a single tube with two-way traffic. Appropriate measures will be taken to secure that the tunnel is a safe place for road users.

7. Geological and structural geological conditions

The geological description at this early stage of the project relies quite extensively on information that can be found in existing sources, one such is the Google Earth that provides good overview pictures, other sources are from the Finnish Geological Survey, and in addition SINTEF holds some information from some earlier works in Åland. These latter were specifically done for the southernmost alignment that was evaluated around 2008/2009. The current tunnel alignment is located North of the tunnel alignment which was studied in 2008/2009.

The dominating rock type at Fasta Åland and most of the tunnel alignment is a variety of Rapikivi granite (red color on the map in Figure 6). The Rapikivi granite is coarse-grained and has a typical reddish color. Typical joint spacing on Fasta Åland side was 2-3 m or more according to the report by SINTEF from 2008. On the Föglö side the rock type is granodiorite and quartz diorite, locally gneissose (orange color on the map). Typical spacing on the Föglö side was somewhat smaller than at the Fasta Åland side with 1-2 m as typical joint spacing.

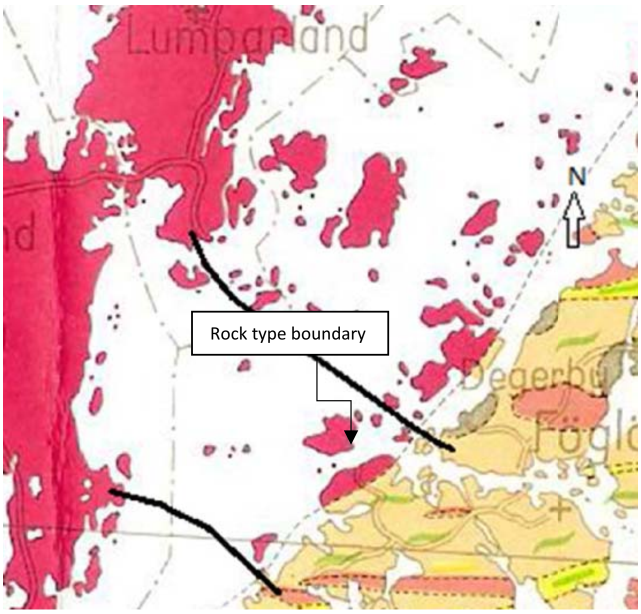


Fig. 7. Geological map of the around Föglöfjorden

There are no regional fault zones or weakness zones in the area other than described above. There is, however, a rock boundary between the Rapikivi granite and granodiorite close to the Föglö-side. This rock boundary has not been studied in details, but it will be necessary at a later stage as it could represent a weakness plane with respect to tunnelling through.

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Fig. 8. Traces of weakness (red lines) in the area of tunnel crossing the Föglöfjord

From Figure 8 it can be seen that several lineaments orient themselves in a NE-SW-direction both at Fasta Åland and Föglö side. This also coincide with the main orientation of the fjord. At Fasta Åland NS-oriented lineaments can be seen. While at Föglö some lineaments seem to have a NW orientation. The lineaments found from the 3D map in Figure 8 most likely is coinciding with weakness zones and are expected to govern the orientation of joint sets also in the subsea tunnel.

According to the geological mapping done in 2008 two joint sets were dominating on both sides of the fjord, see Table 1.

Table 1. Registered joint sets on both Fasta Åland- and Föglö-side.

Joint set	Fasta Åland- side (all measurements included) Strike / dip	Föglö-side (all measurements included) Strike / dip
Joint set 1	N50-80°E / 60-90 S	N40-60°E / 70-90°SE
Joint set 2	N150-170°E / 70-90 E and W	N110-130°E / 70-90°S(W)

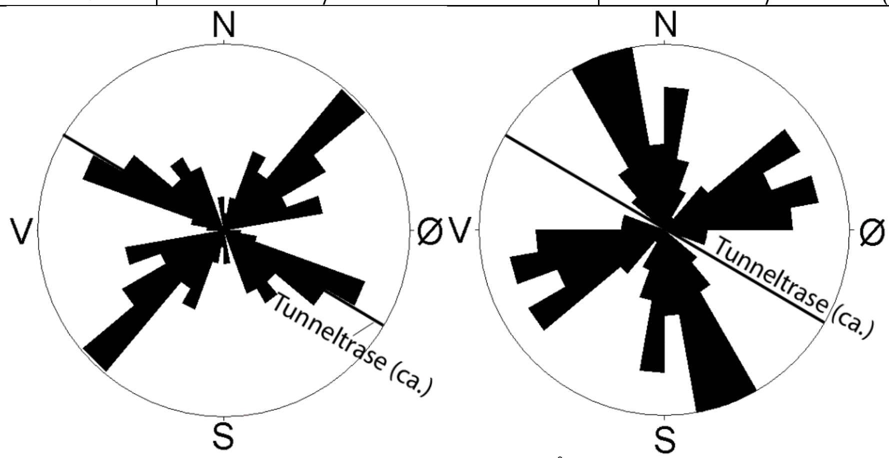

Fig. 9. Joint rosettes, to the left joint rosette Fasta Åland, and to the right joint rosette Föglö.

Comparing the joint rosettes in figure 8 with the lineaments found by studying the 3D map of the area for the current tunnel alignment the joint sets seem to fit very well.

It is expected that the rock mass quality will be medium to good (Q-values between 4 and 40) with average joint-spacing of 1.5 to 2 meters. However, a few weakness zones with Q-values of lower quality rock mass can also appear in the tunnel alignment.

8. Project technical and operational specifications

In Norway, if Norwegian Guidelines are to be used for the Föglö-tunnel (issued by the Norwegian Public Roads Administration), there are various design classes (Dimensjonerings-klasser) for road tunnels as shown in Table 6. These are relevant for national main roads. (ÅDT = Annual Daily Traffic Density (AADT), Fartsgrense = speed limit, and Tunnelprofil = tunnel profile). SINTEF have inserted the actual classes for the Föglö-tunnel and shown it as a rectangular box in red outline below.

Table 2 below shows the different design classes for the tunnel, in the left hand side column, then the Annual Average Daily Traffic is shown (< 4000 vehicles in total), the design speed limit (km/t = km/h) and finally the tunnel cross on the far right hand side column.

Table 2. Tunnel profiles for various design classes (Ref. 5).

H2	< 4 000	80 km/t	T9,5
H3	< 4 000	90 km/t	T9,5

Based on the above, it was decided to choose Design Class H3 for this project with the background in the expected AADT in 2028. This design class will allow a design of 90 km/h whilst it is fully up to the authorities in Åland to use 70 or 80 km/h as signed traffic speed. The AADT of less than 4000 vehicles would in any case give a cross section area equivalent to T9,5. A tunnel profile with relevant measures are provided in the following. Relevant measurements for tunnel profile T9,5 is given in Tables 3 and 4.

Table 3. Geometrical measures for tunnel profile T9,5 (table 3.3 in N500).

	T9,5
Total width (B_t)	9,5m
Total width carriageway (Bk)	7,0m

Table 4. Tunnel cross section data for profile T9,5 (table 3.4 in N500).

	T9,5
Teoretical excavation areal (A_S)	66,62m^2
Teoretical excavation curved length (B_S)	21,04m

On the basis of the expected AADT on the current route, the tunnel is classified as a Class B tunnel according to the Norwegian Road Tunnel guidelines. Tunnel classes determine the geometry and safety measures to be taken into account. Class B has been used throughout in the subsequent description of geometry and installations.

In Scandinavia 1 subsea tunnel has been constructed in Iceland, there will be a total of 4 subsea tunnels (maybe 6 in the long term) in the Faroe Islands and 34 tunnels in Norway at present. These are all tunnels excavated fully in rock. For all of these projects the excavation method has been by conventional drill&blast.

At the time that the Föglö-tunnel will be materialised the concept of the Föglö-tunnel is similar to the ones mentioned above, to be fully excavated in rock. The rock mass will be the main material to handle the stress distribution, the water inflow and possible deformations that the tunnel might experience, therefore also the considerations of the minimum rock cover.

This implies that the rock reinforcement would typically be fully grouted rock bolts of double corrosion protection in combination with sprayed concrete. Probe drilling and pre-excavation grouting will be the main tools to 1) do exploratory drilling ahead of the tunnel face to investigate the ground conditions and thus reduce the need of pre-construction investigations which in this case are expensive and not necessarily very accurate in delivering geological information, and 2) reduce the water inflow to the tunnel to the required Maximum allowable inflow rate. Drain pipes and water pumping systems will handle the inflow water and discharge it to either of the tunnel portals, whilst a large magazine will be excavated in the low point to collect water in case of break-down of the pumping system.

There are a couple of subsea tunnels in Denmark and also between England and France a subsea tunnel crosses the English Channel. These projects are all excavated using TBM's (Tunnel Boring Machines), whilst these tunnel alignments are shallow and the ground conditions along these alignments are in soil/sediments or weak sediment rock types. They are also fully lined with pre-cast concrete segments for ground reinforcement and water proofing.

The cons with respect to TBM versus a horse shoe shaped drill&blast cross section is the excessive room that is created in a TBM, whilst the major draw-back is related to the much larger cross-section that would be needed to encompass sufficient width of the tunnel.

During the feasibility study phase for the Rogfast project in Norway SINTEF was preparing a report on excavation method to consider TBM for that particular project. We were looking at the possibility of excavating the Rogfast tunnel with TBM, including identifying pros & cons, cost and time etc. The main reason at that time was that it was realized that the tunnel alignment after lots of investigations would face several zones of weakness with very poor to extremely poor rock, thus a Double Shield TBM is likely to be recommended which can operate with pre-cast segment lining where needed and without if not required. The result of the comparison was as follows:

- Even with the particularities of the Rogfast project TBM-tunnelling was feasible
- TBM tunnelling was significantly shorter in excavation time
- TBM tunnelling was costlier mainly due to concrete structures to be installed
- TBM produces a circular tunnel profile that makes the excavation volume higher than a conventional horse-shoe shaped profile that is blasted

Consequently, TBM was abandoned as excavation method for the Rogfast project. For the Föglö-tunnel, early studies indicate that it is difficult to see the need of making significant investigations to evaluate the excavation method. Conventional Drill&Blast has certain pros when it comes to construction of subsea rock tunnels which make it the preferred method. The main pros associated with Drill&Blast for subsea tunnelling are as follows:

- It is a flexible tunnelling method which allows a change in advance based on the actual encountered geological conditions
- It allows different types of equipment (shotcrete jumbo, grouting jumbo, cast-in-place formwork to locally stabilise the tunnel face and cast concrete lining) to easy access the tunnel face in case of particular needs caused by adverse ground conditions and subsequent instability in the tunnel
- It allows various investigations to be done ahead of the tunnel face if needed (core drilling, probe drilling using percussion drilling etc)
- A predefined maximum inflow rate will be established and pre-excavation grouting will be applied to balance the inflow level to the maximum allowable level

The preferred excavation method for the Föglö tunnel is consequently Drill&Blast and using traditional rock reinforcement as rock bolts and sprayed concrete, in adverse ground conditions various other methods can be applied, whilst probe drilling ahead of tunnel face and pre-excavation grouting are the first line of defence for water control.

9. Construction time estimate

A rough time estimate of the construction time suggests that from construction starts with access roads to the portal, construction of the portals and then the tunnel works, somewhere between 45 and 65 months are required. This is as it is stated a rough estimate and a far more detailed estimate needs to be established at a later stage in the project development.

A detailed construction time analysis has not been done for this study and our estimate is based on reference to experience and projects elsewhere where we have information on construction time. There are several parameters that influence the construction time, and at present we do not have the necessary input to make such an estimate with a high level of details. At later stage in the development of the project further details have to be nailed and thus an update and improvement of the time schedule can be made.

Out of these 45 to 65 months, some 2-3 months are required for access roads and preparation of the portal itself. Then 2,5 to 3,5 years are needed for the construction of the tunnel and all works related to rock reinforcement and rock mass grouting. Finally, somewhere between one year and two years are required for all the installations works, testing and commissioning. The total construction time is also reflecting the possibility

This estimate may be slightly more conservative but it reflects the uncertainty in time scheduling for such a project on a rather limited basis. We have used the Eustyrøy-Sandøy Tunnel-project (EST) in the Faroe Islands as basis and also considered other projects we are involved in with respect to discussions on time scheduling. The two subsea road tunnels in the EST-project is slightly longer, but at this stage it is wise not to be over-optimistic, but also see the possibility of a time effective construction period. Tunnelling is very much a matter of managing logistics and doing this in the best possible way. Figures exists on high advance rates in tunnel excavation, tunnelling under the sea with an indefinite source of water that potentially could fill up the tunnel and literally drown it requires careful procedures and thorough considerations for every step on the way, thus we are using conservative figures for our construction schedule estimates.

There will always be situations and issues related to the ground conditions that are encountered, but this is an inevitable risk that is associated with tunnelling works. Important in such situations is to have a contact that works, a contract that actually allows decisions to be taken at the tunnels face, it is flexible and includes regulations and pay items that could be applied in various situations.

Further works on investigations, studies and design. As per today one project specific investigation has been made for the studied tunnel alignment, namely a single geophysical line. Whilst the earlier locations of alignments had both surface geological mapping on land combined with aerial photo studies and geophysical investigations were undertaken. We have included some of the information available from these investigations, where applicable for this study.

However, it must be expected that in the future, as the project develops additional investigations must be undertaken. It is important to perform such investigations step by step, in accordance with the progress of the design details. In the following the need of various investigations for current tunnel alignment is discussed.

10. Effect on greenhouse gas emission

The EIA found that the tunnel would result in a net reduction of greenhouse gasses. It was calculated that the entire tunneling project, including shipping away excess rock mass to the Baltic States, would result in 25600 – 31000 tons of CO_2e emissions. The restructured traffic system would entail in net savings of around 6000 tons of CO_2e yearly. It is possible to further reduce the greenhouse gas footprint by using more of the rock mass locally and by replacing diesel powered construction machinery with electric powered versions.

11. Conclusions and summary

The Föglö tunnel will be the first of its kind in Finland and in Åland. However, it is planned to be designed and constructed according to a well established, and proven concept for subsea road tunnels. The expected rock mass conditions suggest that the tunnelling concept is fully adaptable to the Föglö-tunnel and the means and methods available for rock support and rock mass grouting are all well tested and documented. And tunnel excavation by conventional drill&blast has shown to be superior to TBM-excavation for these kinds of tunnels. The tunnel will be a basic tunnel with a safety level that fits to the traffic density of the project.

The possibility to make very detailed per-excavation investigations for a subsea tunnel project like this is not a viable alternative, it would be associated with a cost and time consumption that would not pay back in terms of cost reduction during construction. Consequently, the use of probe-drilling ahead of tunnel face is a mandatory method to be used during construction to obtain information of the first 25-30 meters ahead of the tunnel face. This is more accurate and a lot cheaper than pre-excavation methods.