Did the selection of TBMs for the excavation of the Follo Line project tunnels satisfy the expectations?

A.K. Kalager & B. Gammelsæter
Bane NOR, Oslo, Norway

ABSTRACT: At the Follo Line project, four hard-rock double-shield TBMs have been operating from one single access-point, excavating in total 36 km of tunnels. This paper will describe the requirements for the machines and the results of the excavation, including performance in “extreme hard-rock conditions”, in combination with continuous mapping of the geology and the performance of grouting in areas with water leakages. Other main activities, such as production of lining and depositing of excavated material, are performed within the rig area. The deposit of the excavated material is performed in accordance with specific procedures, with the intention of reusing it as a foundation for a future residential area. The paper will also address the challenges with structural noise and disturbances to neighbors during the construction of the tunnels.

1 THE FOLLO LINE PROJECT

The Follo Line project represents a unique project. The project is divided into different sub-projects, as shown in Figure 1. The main part of the project consists of the 20 km long tunnel sections, which is still under construction. The northern section has been excavated by drill and blast in combination with drill and split. The rest of the tunnel, 18.5 km is excavated by four tunnel boring machines, all of them operating from one single access point at the rig area at Åsland.

Figure 1. The Follo Line project is divided in four sub-projects. 18.5 km has been excavated by TBM

2 GEOLOGICAL CONDITIONS

The rock mass within this project area consists predominantly of Precambrian gneisses with banding and lenses of amphibolite and pegmatite. (Kalager, 2017) In addition, several genera-
tions of intrusions occur. Sedimentary shale occurs in the northern part of the tunnel, close to Oslo Central station.

Generally, the rock mass is quite homogenous and competent, with moderate jointing. Laboratory tests show that the rock is abrasive and strong. The gneisses have a variation of the uniaxial strength from 100 to 250 MPa and the amphibolite in the area between 250 and 300 MPa.

Fracture zones have during several glacial periods been more exposed to erosion, which has resulted in deep valleys filled with marine sediments, mostly silt and clay.

Some of these fracture zones intersect the tunnel alignment, and in these zones, leakages were expected during the excavation of the tunnel. In some cases, these zones form a network of fracture zones with different orientation, both vertically and horizontally, and influence a large area or basin of marine clay. To avoid settlements and damages on buildings and infrastructure in these areas along the tunnel section, the requirements for leakage into the tunnel, both during the excavation and after completion, were very strict.

The overburden of the tunnel varies between 5 and 170 meters.

3 EXCAVATION METHODS

It was at an early stage of the project decided that due to time criticality and location close to other sensitive infrastructures, the excavation of the tunnel system in the northern part of the 20 km long tunnel section should be excavated by drill and blast in combination with drill and split.

For the remaining 18.5 km of the tunnel section, different excavation methods were considered. (Kalager, 2017).

Due to environmental impact, it was decided to perform the excavation by using four hard-rock double-shield TBMs operating from one single access-point, excavating in total 36 km of tunnels. The alternative to TBM-excavation was to perform the tunnels by drill and blast operating from six different locations along the tunnel section. Many of them would have been located within densely populated areas.

For the TBM-production, a network of access- and logistic tunnels, including two large assembly caverns, were excavated by drill and blast before the assembly and the start-up of the four TBMs. Se Figure 2.

![Figure 2. Rig area, access- and logistic tunnels and the northern- and southern assembly caverns](image)

Two machines were assembled in the northern cavern and performed the excavation in the northward direction and two machines were assembled in the southern cavern for the excavation in the southward direction. The TBMs should excavate approximately 9 km of tunnel each. The four machines were ordered the 30th of March 2015. The first machine started up the 5th of September 2016 and by 30th November 2016 all four machines were in operation. Two years later, the 11th of September 2018, the two northbound machines had their breakthrough.

4 DESIGN AND CAPACITY OF THE MACHINES

Based upon Norwegian experience from TBM-excavation of hydro power tunnels in the past, the four machines were designed for excavation in what many will define as “extreme” hard-rock conditions. For hard rock tunnel boring, a stiff cutterhead as well as a large diameter and high capacity main bearing capable to withstand extreme eccentric cutterhead loads is crucial
for the tunnel boring operation. Some main design parameters for the TBMs is showed in Table 1 below.

Table 1. Some of the main design parameters for the four TBMs at the Follo Line project

<table>
<thead>
<tr>
<th>Item</th>
<th>Spec.</th>
<th>Item</th>
<th>Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBM cutting diameter</td>
<td>9,960 mm with new cutters</td>
<td>Weight of Cutterhead</td>
<td>265 metric ton equipped with cutters</td>
</tr>
<tr>
<td>Cutter size</td>
<td>19-inch wedge lock, back-loading</td>
<td>Cutterhead (CH) power</td>
<td>13 each VFD motors x 350 kW = 4 550 kW</td>
</tr>
<tr>
<td>Number of disc cutters</td>
<td>4 centers (x 2 discs) + 48 face + 15 gage = 71 cutting discs</td>
<td>Total power installed</td>
<td>Approx. 6900 kW</td>
</tr>
<tr>
<td>Load per cutter ring</td>
<td>315 kN</td>
<td>Nominal torque</td>
<td>11,115 kNm @ 3.67 rpm</td>
</tr>
<tr>
<td>Max. recommended CH load</td>
<td>71 x 315 = 22,365 kN</td>
<td>Max. overload torque</td>
<td>16,672 kNm @ 3.67 rpm</td>
</tr>
<tr>
<td>CH rotational speed</td>
<td>0 – 6.06 rpm</td>
<td>Water resistance</td>
<td>12 bar static</td>
</tr>
<tr>
<td>Main Bearing (MB)</td>
<td>3 axis roller bearing, 6,600 mm OD</td>
<td>Main bearing lifetime</td>
<td>&gt; 20 000 hours according to ITA-tech guidelines</td>
</tr>
<tr>
<td>Total weight, TBM + BU</td>
<td>approx. 2,300 metric ton</td>
<td>Total length, TBM + Backup</td>
<td>Approx. 150 meters</td>
</tr>
<tr>
<td>Probe Drilling Equipment</td>
<td>Two drill rigs with rod adding system for drilling up to 35 m long holes for probing and pre-grouting through 38 ports in gripper shield with 11-degree angle to tunnel axis and or through 8 openings in the cutterhead.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The experienced rates of penetration (ROP) and the advance rates, included time for probing and pre-grouting for the machines excavating in the northward and southward directions respectively are showed in Table 2 and 3 below.

Table 2. Rates of penetration by the end of August 2018

<table>
<thead>
<tr>
<th></th>
<th>ROP [mm/min] North</th>
<th>ROP (mm/min) South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>31,05</td>
<td>31,21</td>
</tr>
<tr>
<td>Maximum</td>
<td>52,93</td>
<td>62,43</td>
</tr>
<tr>
<td>Minimum</td>
<td>14,94</td>
<td>14,95</td>
</tr>
</tbody>
</table>

Table 3. Advance rates including time for probing and pre-grouting by the end of August 2018

<table>
<thead>
<tr>
<th></th>
<th>Average [m] North</th>
<th>Highest [m] North</th>
<th>Average (m) South</th>
<th>Highest (m) South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>14,1</td>
<td>31,0</td>
<td>12,7</td>
<td>32,1</td>
</tr>
<tr>
<td>Week</td>
<td>85</td>
<td>144</td>
<td>76</td>
<td>145</td>
</tr>
<tr>
<td>Month</td>
<td>364</td>
<td>568</td>
<td>330</td>
<td>542</td>
</tr>
</tbody>
</table>
5 HANDLING OF GEOLOGICAL CONDITIONS

5.1 Continuous and systematic geological mapping

As an important supplement to the geological information that had been collected before the start-up of the excavation, systematic geological mapping is daily being performed by experienced geologists.

5.1.1 Optical tele-viewing

Probe-drilling for detecting water ahead of the TBM and to prepare for systematic and continuous mapping by optical tele-viewing along the tunnel alignment, is performed every day during the maintenance-shift. (Fritsøe Lawton, Gammelsæter, Finnøy, Syversen, 2018). The detection of water is described below.

The results from the continuous fracture-mapping by optical tele-viewing (OTV) is used as input for the NTNU-model for compensation. This model is based on continuous fracture-mapping from an open TBM, where the rock-surface is available behind the cutterhead. (Bruland, 1998). For a shield-TBM, the rock-face is only visible through the cutterhead when the TBM is not excavating. To collect necessary and continuous information about the different fractures- and fissure systems along the entire tunnel section, 40 meters long probe-holes are drilled from behind the shield, forward ahead of the machines. An overlap of approximately 10 meters between the lengths are normally achieved.

The probe-holes are logged with Measure While Drilling (MWD), but this gives mainly information about weakness-zones and presence of water, and no precise information of the orientation or condition of the fractures. The MWD-data is therefore not suited for detailed fracture-mapping as required for the NTNU-model.

Instead, mapping of the probe-holes by an optical tele-viewer has given pictures with quite high-resolution scale, where fractures and their orientation can be mapped in detail. An example is shown in Figure 3 below.

The probe-holes prepared for OTV are bored upwards to achieve a drained hole. They are also flushed to avoid debris covering parts of the holes.

The OTV-logging provides a continuous geological data record along the entire tunnel section. The experience is that the data are detailed and of good enough quality to be used as input for the NTNU-model. The continuous OTV-logging provides a huge amount of information to be analyzed. To utilize all the data collected from the OTV, it is important that the analysis are performed by geologists with experiences from face-mapping and chip analysis as well.

![Figure 3: Analyzed picture from OTV where fractures are mapped](image)

5.1.2 Face mapping

The purpose of performing face mapping is to gather general geological information and to get input to assess the fracture factor $K_s$, which is part of the compensation model. Mapping is performed every morning during the maintenance shift by geologists from both the Client and the Contractor. Both parties sign the agreed mapping form before leaving the TBM.
Depending on the excavation rate, there are 15-20 tunnel meters in average between each face mapping.

Access to observe the face is through the manhole and to a certain degree through muck openings as well. The cutter-head is then retracted from the face to make it possible to get an overview of a larger part of the face.

The geological mapping of the face gives information about presence of rock types and eventually of hard and abrasive minerals like quarts or garnet. Signs of weathering are often visible. Other important information is the number of fracture sets visible and the space between the fractures. In some cases, the mapping makes it possible to observe the roughness of the fracture planes and eventually infilling or aperture. It is also possible to verify if fractures or weakness planes contributes to fall-out or over-break. Water seepage from the face can also be identified. Figure 4 shows an example of how photographing of the face contributes to supplement the geological mapping.

![Fractures with different orientation identified at the face](image)

Due to magnetism, it has not been possible to use a compass near the cutterhead. Only principal strike and dip orientation can be given.

### 5.1.3 3D Photographing at face

3D photographing of the face is performed regularly every day during the maintenance shift. Equipment and software from 3GSM are used. A camera is then mounted in the manhole of the cutterhead and a circular video is captured during one rotation of the cutterhead.

Advanced software generates scaled and oriented 3D images illustrating the various joint sets with their orientation from measurements taken. This is illustrated in Figure 5 below.

![A 3GSM photo, a “doughnut” with fracture set identification](image)

The width of the taken image is in the range of 0.5-1.5 meter depending on how far back the cutterhead has been retracted. The result is an illustration of the rock mass conditions. From the 3D images it is possible to identify over-breaks, perform geological mapping and to analyse fracture set orientation and to some degree fracture spacing as well.
5.1.4 Chip analyses

Chip analysis can be a valuable tool to obtain information on the rock breaking process and is therefore performed regularly. Normally 10-20 of the largest chips are collected from the TBM excavation and measured in three directions, x, y and z. The shape and size of the chip gives information or tendencies on fracturing factor, rock brittleness and hardness. The combination of chip shape and chip size can give tendencies on the efficiency of the boring process.

5.1.5 Core drilling

Every 250 meter of the tunnel excavation, core drilling is performed at the front of the TBM’s. Cores of four meters length are drilled perpendicular to the tunnel to get rock material for laboratory testing to determine Drilling Rate Index (DRI), Cutter Life Index (CLI) and mineral analysis. The DRI value is needed to be able to calculate the $K_{ave}$ as an input for the NTNU-model. For cutter life calculations, CLI and the mineral content is needed.

In addition, two meters long cores are bored for geological logging as a supplement to the geological information obtained from the daily tele-viewing, face mapping and chip analyzes.

5.2 Monitoring of the pore-pressure, ground-water level and settlements

A network of registration wells for measuring the pore-pressure along the tunnel section and in sensitive areas connected to the tunnel by fracture-zones have been installed. The groundwater monitoring system consists of a combination of piezometers or stand-pipes in soil and deep rock wells. The first piezometers were installed in 2009. Early installation of monitoring is important to obtain a history of natural seasonal variations in the pore pressure. (Syversen, Lawton, Finnøy, Gammelsæter, 2018). The wells have been installed in the rock, with connection to fractures, and in the soil, that mostly consists of marine clay, as well.

The monitoring of the pore-pressure is a continuous and ongoing process throughout the project, and after finalization of the excavation until the water-balance is stabilized as well. All sensors are logged automatically every 10th minute, and the results are uploaded to a web-based GIS portal with a frequency of down to 1 hour if deemed necessary.

In addition to the pore-pressure monitoring program, an extensive settlement program has been carried out. Nails have been mounted on the foundation of more than 2300 buildings. The nails are manually surveyed in due time prior to passing with the TBMs and after the TBMs had passed, and the readings are uploaded to a web portal. In addition to the manually measurement of settlements, a monitoring program utilizing satellite data (inSAR) from 2014 and up to date has been established to identify if settlements occurs on buildings along the tunnel section.

5.3 Probe-drilling and pre-grouting in areas with leakages

To fulfill the requirements regarding limited drop of pore-pressure and no damages to buildings or other infrastructure in the areas above or close to the tunnel, the tunnels are built as an undrained tunnel solution. Concrete segments with watertight gaskets are installed right behind the shield of the machine. When the lining is installed, the back-fill behind the lining is completed and the grout-ports are closed, the tunnel becomes water-tight and acts as an undrained tunnel.

Before the lining is installed, there is an open rock-face of approximately 15 – 20 meters between the tunnel-face and the last installed segmental ring. In a few areas where highly permeable fracture-zones intersects the tunnel, there has been some extensive leakages into the tunnel before the lining was installed. Such leakage usually follows the fracture-zones, and in the worst case a huge area within a distance of 1.5 km from the tunnel was seen to be affected.

The experience achieved in the beginning in areas with such leakages through fracture zones, was that the water ingress also resulted in outwash of the cement-based back-fill that was injected behind the lining. This outwash made it possible for continued water to flow behind the lining, which resulted in even more out-wash of material and in some cases a destabilizing of the lining as well. From an early stage of the excavation period, it was obvious that the contractor needed to improve their strategy and methods for handling the water as an integrated part of their construction.
On a daily basis, during the maintenance-shift, probe-drilling is performed in the rock ahead of the TBM to register the geological conditions, detect fractures with high permeability and identify if leakages can be expected. The number of probe holes depend on the sensitivity of the area above the tunnel and the expected geological conditions ahead of the TBM. The entire tunnel section is classified in different sensitivity-zones defined as small sensitive, moderate sensitive, sensitive and very sensitive. In general, one probe hole located on the top of the cutterhead or two probe holes in different locations related to the cutterhead are bored in areas defined as small sensitive. In moderate to sensitive areas, experience has showed that increasing the number of probe holes to four distributed in different positions around the cutterhead, gives quite reliable information about the geological conditions ahead of the TBM. In very sensitive areas the number of probe holes are set to six.

To reduce the amount of leakage before the lining is installed, pre-grouting is performed from the TBMs when identified as necessary, based on water ingress measurements from the systematic probe drillings. The trigger values of water leakage from the probe holes are based on the sensitivity class of the areas affected by the tunnel excavation. Based on experience achieved during the excavation, the trigger values for starting pre-grouting in the different sensitivity areas are set to 80 l/min from one probe hole in areas with small sensitivity, 40 l/min from minimum two probe holes in moderate to sensitive areas and 8 l/min in total from all the probe holes in very sensitive areas.

In some of the areas classified as high sensitive, mandatory pre-grouting is required. Each TBM is equipped with two rock-drills for probing and for drilling the holes that should form the umbrella for pre-grouting. The double shield machines are designed with 38 holes around the shield where it is possible to perform holes for probing and grouting.

Every 500 meters, the two parallel tunnels are connected by cross-passages. The experience has showed that opening of this cross-passages often results in additional leakages. Even though pre-grouting is done as an umbrella from the tunnel around the portal of the cross-passage, leakages after opening-up the lining occurs. The water seemed to come through channels in the back-fill material between the lining and the rock. After considering different methods to stop the water in this portal-area for the cross-passages, contact-grouting, with low pressure, of the back-fill area around the opening is identified to give the best result.

In areas defined as very sensitive, it was decided to do systematic pre-grouting from the TBM in the areas around the future portals for the cross-passages as well as contact grouting.

This methodology for identifying water and limit the leakage has been developed and improved during the excavation phase, and the results appear to be positive. The drop of the pore-pressures stopped and were re-established when the performance of grouting was tailor-made to the geological conditions.

5.4 Infiltration wells

To compensate for the water leaking into the tunnel, and by that avoid a drop of the pore-pressure and development of settlements on buildings within the influence area of the tunnel, temporary infiltration wells have been installed at different locations. The wells are operated from the surface.

Many of the wells have been operated with good results, but not all of them. The key to success seems to depend on the quality of the installation and the match with the geological conditions. The infiltration wells are usually drilled 20-50 m into the rock. The intention is that they should cross identified permeable fracture zones that preferably are inclined under soil deposits.

Water with some overpressure is infiltrated from the rock well trough the fracture zone, up to the soil. Pressure and flow are carefully controlled to avoid piping effects in the soil. The infiltration of water is mostly activated in combination with pre-grouting to control the water balance in the area affected by the tunnel excavation.

It is a requirement that these infiltration wells shall only be used as a temporary mitigation to maintain the pore-pressure while the TBM passes by. After the lining is properly installed, there should be no need for them anymore.
5.5 Experience by the TBM-operation in the Norwegian hard rock and specific ground conditions

Most of the tunnel excavation in the Norwegian hard rock has traditionally been performed by drill and blast methodology. Therefore, a decision to use TBMs to excavate the main part of the 20 km long twin-tube tunnel at the Follo Line project caused a certain degree of skepticism.

Lessons learned from the excavation of this tunnel section by four double-shield TBMs is that there are some key-factors that must be present for achieving a successful result, namely establishing a good knowledge of the general geological conditions along the tunnel section as a fundament for the contract, systematic mapping of the conditions ahead of the TBMs during the excavation, systematic measurement of the pore-pressures and settlements, improved and tailor-made mitigations to limit the amount of leakages and timely and appropriate decision-making for activating the mitigations.

The machines and the equipment must be tailor-made for the specific ground conditions. Last, but not least, the experience, competence and skills of the personnel, on both the Contractor’s and the Client’s side, and the communication and co-operation between them, is also in many ways crucial for achieving a good result.

The experience from the excavation of the two Follo Line tunnels is that the Contractor improved their skills during the construction. Their procedures and performance for probe-drilling, detection of water and pre-grouting became more efficient after a while, and in total, the excavation must be defined as being a success.

6 SEGMENT PRODUCTION

The requirements regarding no leakage into the tunnel, no drop of the pore-pressure or development of settlements above the tunnel, demanded a watertight and undrained solution for the tunnel-lining.

The lining is designed as a ring consisting of seven segments. The thickness of the segments are 400 mm and the length of each segment is 1800 mm. The segments are reinforced by steel-bars in combination with steel-fibers in the concrete. (Gollegger, Pinillos Lorenzana, Cavalaro, Kanstad. 2019) The ring, and the gasket between each segment are designed to handle a water pressure of 16 bar.

The inner diameter of the lining is 8.750 meters. The gap between the lining and the rock is filled with a cement based two-component material, injected behind the segments a few rings after installation.

The experience is that the back-fill grout didn’t work as intended in areas with high leakage. The result was that too much of the back-fill material was washed out. In some cases, this had influence on the stability of the rings as well.

By improving the procedures for detecting water and performing pre-grouting ahead of the face when necessary, the quality of the entire performance and delivery of the tunnel lining was improved. Ecco detecting equipment is used to check the quality of the back-fill, which makes it possible to identify whether the back-fill is homogenous with a good distribution or if there are spaces behind the lining that can act as drainage channels. If the quality is poor, additional contact grouting has to be performed.

Despite the lessons that needed to be learnt, the quality seems to be satisfying. One question to be raised is whether the problem with the fluid back-fill material could have been avoided if the material had consisted of more cement?

7 RE-USE OF THE EXCAVATED MATERIAL

Originally, it was a requirement that 10 – 15% of the excavated material should be crushed and used as aggregates for the concrete- and segment production. This re-use of the material was defined as an important environmental benefit for the project, but unfortunately this could not be achieved.
When analyzing the chemical composition of the material, 20% of the samples identified a higher amount of the unstable mineral Pyrrhotite that can be accepted in concrete when it occurs in combination with Sulfur. To achieve the required quality of the concrete, aggregates with no content of Pyrrhotite had to be procured from an external supplier.

Before the project started, there was some skepticism about the use of material excavated by TBMs. In close cooperation with geotechnical expertise, a procedure for alternating filling and compaction was developed and tested with good results. One of the experiences was that during heavy rain and with high water content in the material, it was difficult to achieve the expected result. Under such conditions, the excavated material is transported out for external deposition. Despite the limit regarding the water content, the major part, approximately eight million tons, of the excavated material is re-used within the rig-area as a basement for a future residential area. This limits the total transport volume during the construction phase and contributes to future gains connected to the development of the residential area and a saving in project costs.

8 ENVIRONMENTAL IMPACT AND COMMUNICATION

To achieve an efficient excavation of the tunnel and due to the schedule of the Follo Line project, it was required to have a 24/7 production for the TBM-drilling.

In some locations along the tunnel section, the two twin-tube tunnels are excavated under densely populated areas. In Norway there are restrictions regarding the level of the structural noise that the neighbors can be exposed to. The structural noise is measured in dB and defined as A-weighted sound pressure level, \( L_{p\text{Aeq}} \). The trigger-values are defined in Table 4 below.

<table>
<thead>
<tr>
<th>Building type</th>
<th>Noise req. daytime ((L_{p\text{Aeq}} 12h, 07-19))</th>
<th>Noise req. evening ((L_{p\text{Aeq}} 4h, 19-23)) or Sundays/public holidays ((L_{p\text{Aeq}} 16h, 07-23))</th>
<th>Noise req. night ((L_{p\text{Aeq}} 8h, 23 - 07))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential buildings</td>
<td>40</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Work space requiring low noise levels</td>
<td>45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Estimations for the expected values of structural noise depends on different parameters like the distances between the TBMs and the buildings, the geological conditions, the foundation of the buildings and on which level in the buildings people have their living rooms and bed rooms.

A prediction model has been built, and it is used as an important tool for the communication with the neighbours that are expected to be affected by structural noise from the tunnel excavation. This is a 3D-model including the tunnel alignment. The terrain above the tunnel section has been mapped and is combined with geographical data from official authorities like cadastre data and number of inhabitants at each address point. In addition, information of the geological ground conditions is also linked to the model. The TBM progress is updated every day and makes it possible to measure the real distance between the TBMs and the buildings along the tunnel section.

Based on the information from this model and the experience achieved about the migration of the structural noise through the different types of geological conditions, it is possible to calculate expected levels of structural noise that will affect the different buildings on the surface.

Before entering in to the different neighborhoods, it is quite clear which structural noise level the individual buildings will be exposed to. The general experience is that people living within a distance, horizontally and vertically, of approximately 70 meters from the TBM can expect to be exposed to structural noise exceeding 40 dB. People living between a distance of 70 and 120 meters from the TBMs can expect to be exposed to levels of approximately 35 dB and people living more than 200 meters from the tunnel and the TBMs will probably not be exposed to levels exceeding the trigger values. In addition to the distance to the TBM, the geological conditions, the foundation of the buildings and on which level in the building people are living, influence the calculated and the measured values of structural noise.

As a successful strategy for the Follo Line project, the neighbors are informed in due time be-
fore the TBM are expected to approach the different areas along the tunnel section. Those who will be affected to structural noise levels exceeding the trigger values, especially during night, are offered alternative accommodation, mainly in nearby hotels.

This strategy to excavate 24/7 and compensate the disturbances of the neighbors by offering them alternative accommodation has been accepted by the health authority in the affected municipalities. The argument is that it is better to pass the different residential areas as fast as possible, mainly within three weeks, instead of exposing the neighbors for structural noise over a longer period.

The experience so far is that in total a limited number of neighbors have accepted the offer to stay at a hotel while the TBM passes the area where they live, but there are variations. In areas where the distance down to the TBM are between 120 and 200 meters, less than 1% of the inhabitants have so far used the opportunity to sleep in more quiet environments. In some of the areas where the TBM passed within a distance of 30 to 70 meters, between 50 and 60% wanted to stay at a hotel while the excavation took place under their neighborhood, but in other areas where the TBM passed within this small distance, only 10% accepted the offer. The general experience is that in spite of the expected noise levels, most of the neighbors wanted to stay at home as long as possible.

9 Conclusion

The experience by performing the main part of the 20 km long tunnel at the Follo Line project by four double-shield hard-rock TBMs, operating from one centrally located access point has demonstrated that this project was tailor-made for this excavation method.

An important key to the success is that the machines were designed for the specific geological conditions. They have so far been working as expected, but experience also shows that the machines seemed to be operated conservatively within their design parameters, and it can be concluded that performance could probably have been even better.

When it comes to handling of leakages, the contractor improved its skills and methodology and the result is satisfactory. The impact on the environment is probably equal to or better than what could have been expected if the tunnels had been excavated by drill and blast.

The re-use the excavated material within the rig area, with its environmental and cost benefits, was an exclusive opportunity related to the TBM-excavation from one single access point. This would not have been possible if the tunnels had been excavated by drill and blast from six different locations.

Communication with the neighbors has been an important tool to pave the way for acceptance of a 24/7 excavation. The process has so far been managed efficiently and successfully resulting in very few complaints and no negative press coverage.

The conclusion is that the expectations for the drilling of the Follo Line tunnels by the four double-shield TBMs have been fulfilled.

10 References