4 Dubbelsköld TBM maskiner för hårt berg i bruk på Oslo Follo Line projektet – Projektutmaningar och TBM lösningar

4 Double Shielded Hard Rock TBMs in use for the Oslo Follo Line – Project challenges and TBM solutions

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ABSTRACT

Until recently, all rail tunnels in Norway were excavated using drill & blast technology. The Follo Line project is a new 22 kilometers long double track rail line that is currently under construction between Oslo Central Station and Ski. Four double shield hard rock TBMs with an excavation diameter of 9.96 meters excavate a total of about 36 kilometers of predominantly Precambrian gneisses with banding and lenses of amphibolite and pegmatite.

The tunnelling concept is based on using four TBMs, two of each operating in opposite directions from two access tunnels that are located near the midpoint of the alignment in a remote, rural location. When finished, the tunnel will be Norway's longest and largest rail tunnel. The paper highlights the project challenges in particular the abrasive and strong rock mass, the large diameter in combination with the possible risk of high water pressures (12 bar) that require a well-adapted TBM concept.

1 INTRODUCTION

The Follo Line project is currently the largest transport project in Norway and includes the country's longest railway tunnel (22km). It will form the core part of the InterCity development southwards from Oslo. When completed the new railway line will offer a direct line without stops between the Central Station of Oslo and Ski with the benefit of shortening travel time by half – from 22 minutes to 11 minutes.

The twin-tube, single-track tunnels between Oslo and Ski were designed to be excavated by TBM with a precast concrete segmental lining. Mechanized tunnelling was chosen to protect sensitive urban areas and infrastructure from being affected by the tunnel construction underneath. Also, water control and environmental concerns about maintaining groundwater levels to protect the quality of potable and storage water aquifers supported the decision in favor of the mechanized tunnelling method.

The Acciona Ghella JV was awarded the contract for the construction of this major project by the project owner Bane NOR, the Norwegian railway agency, in May 2015 with tough requirements on quality, costs and schedule. The construction of the 35km tunnel is being realized with four Double Shield TBMs that were designed and manufactured by Herrenknecht in Germany. The four machines arrived on site in spring and summer 2016 and tunnelling works started in September 2016.

Tunnelling between Oslo and Ski was expected to face generally rocks of good quality and is subject to strict groundwater leakage requirements. The latter demands comprehensive probing and pre-excavation grouting in order to avoid lowering of the groundwater table and possible subsidence. This paper provides an overview about the project challenges such as geology, site constraints and logistics that influenced the TBM design and TBM solution.

2 TUNNEL DESIGN

2.1 Geology

Precambrian gneisses of high to very high strength and abrasiveness dominate the geological conditions along the bored tunnel sections of the Follo Line project. In general, the rock mass is described to be quite homogeneous and competent with moderate jointing except for some faults and fractured zones. The overburden along the tunnel alignment varies from about 20 to 170m.

The maximum ground water level is close to the surface and in some areas this is about 150m above tunnel crown. In the fractured zones, potential of drainage channels are present that could result in water leakage into the tunnel. Ground water in the rock mass is mostly restricted to joints and weakness zones where higher pressures in the range of 12bar may act on the tunnel.

2.2 Existing infrastructure

The new 22km long Follo Line passes through populated areas demanding consideration of social and environmental restrictions. There are also challenges in respect of avoiding disturbance to the existing infrastructure, but these did not have an impact on the TBM design. The challenges include crossings beneath existing road or sewer tunnels. The main road tunnel has to be crossed under with minimum clearance between the top of the Follo Line tunnel to the invert of the existing road tunnel of only 4 to 4.5 meters.

2.3 *Tunnel lining design*

The predicted geological conditions and water pressure along the alignment determined the design of the tunnel lining. It consists of six precast concrete segments plus a key segment having an inner diameter of 8.75m and a thickness of 400mm with sealing gaskets to mitigate the risk of water ingress.

The annular gap between the outside of the segmental lining and the excavated surface of the ground is backfilled as the TBM advances to provide the bedding of the lining and to prevent subsidence. Also, the backfill protects the segments and the shield tail from ground water inflows. The backfill material employed at the Follo Line project is composed of a two-component grout and is injected through grout lines incorporated in the tailskin at the rear of the shield structure.

The two-component grout provides quicker stabilization of the ring, which is possible due to shorter setting times and optimized working times. The processing properties and the pumpability of the two components are not affected by downtime or advancement speeds.

3 FOUR TBMS SPECIFICALLY DESIGNED FOR THE FOLLO LINE PROJECT

The four Double Shield TBMs (diameter 9.96m) for the construction of in total 35km of bored hard rock tunnel for the Follo Line project are specifically designed to deal with the conditions and requirements to be faced during the excavation works such as:

- Strict groundwater leakage requirements
- Potential of high pressures (12bar)
- High to very high rock strength (UCS in the range of 90-270MPa)
- Very abrasive to extremely abrasive rocks (CAI in the range of 2.7 to 5.1)
- Quartz content in the range of 5-80%

3.1 Pre-excavation grouting

For the weak or fractured zones that are expected along the alignment a risk of high water ingress was anticipated. Specifically, local water inflows of up to 8.3l/s are considered based on experiences from tunnelling works in the same type of rock mass.

Figure 1. Probe drill equipment on independent carrier (360°)

An emergency dewatering system was installed on the two TBMs that are operating towards Oslo that will probably face weak and fractured rock mass. The system comprises three pumps having a total capacity of 300m^3/h. For dewatering, the water is pumped out of the tunnel through a 300mm dewatering line.

In those areas with possible water ingress or leakage or in areas exposed to subsidence, it may be necessary to pre-grout from within the TBM shield. Therefore, the machine is equipped with sophisticated permanent installations for drilling and grouting. Each TBM is designed with three blow-out preventers, 38 inclined probe holes and ten horizontal probe holes through the face. Two core drilling units are installed in the shield for drilling at 0° and 90° and two probe drill units are located on a 360° carrier beam (horizontal + 8° gripper shield).

3.2 Cutterhead design

The cutterhead design included a heavy structure and stiff support to address the strength and abrasiveness of the rock mass. For full-face hard rock excavation by TBMs, the use of disc cutters as excavation tools is today's industry standard and for the Follo Line machines 19-inch back-loading disc cutters are used. The increased disc cutter diameter increases the lifetime of each ring and allows an increased maximum cutter load to be applied which results in a higher pressure in the crushed rock mass below the ring. A total of 67 19-inch cutters are installed of which 4 disc cutters are centre discs, 48 face discs and 15 gauge discs.

Figure 2. Wear protection features and details on the original Follo Line cutterhead Wear protection on the cutterhead: ⇨ Wedges to protect the cutters; ⇨ Wear plates for the face; ⇨ Wear protection at cutterhead periphery; ⇨ Grillbars to protect the cutterhead periphery; ⇨ Calibration-bars to protect the scrapers from big blocks and control maximum block size to enter the cutterhead

The cutterhead's wear protection was designed to be highly robust in face of high CAI values indicating an extreme abrasiveness of the rocks. It comprises disc cutter protection wedges, hardox grillbars protected with Vautid L-pieces in the gauge and domite wear protection plates in the cutterhead face.

3.3 Disc cutter monitoring

All four Follo Line Double Shield TBMs are equipped with a Disc Cutter Rotation Monitoring (DCRM) system to optimize the maintenance intervals of the disc cutters on the cutterhead. During tunnelling the DCRM system monitors continuously the rotation and temperature of the disc cutters that are equipped with the DCRM units. Blockages of disc cutters are immediately indicated. In summary, the system's monitoring and alarm functions reduce TBM stoppages to a minimum:

- Minimization of service and maintenance work by the failure detection and track identification in real time (e.g. gradual bearing damage, abruptly blocked disc cutter)
- Detection of instable, blocky tunnel face conditions and thus possibility to adjust cutterhead rotation speed (rpm) and thrust force to avoid disc cutter overload
- Efficient mechanized tunnelling due to decrease of non-operation periods, optimization of disc cutter lifetime.

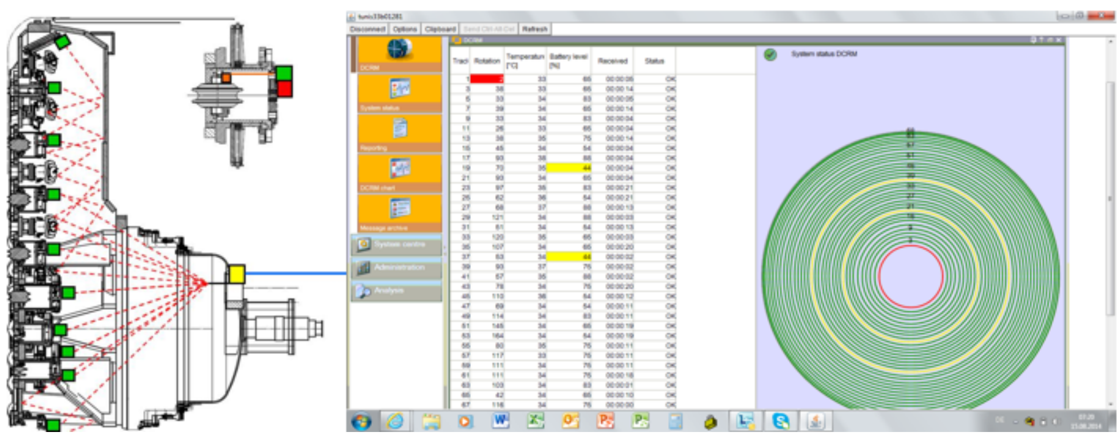

Figure 3. DCRM system; real time cutter temperature and detection of cutter blockages

3.4 Cutterhead drive

Due to the Follo Line's predicted ground conditions, the decision was taken in favor of an electrical drive with a main bearing size of 6.6m with frequency converters and an installed nominal torque of 11,415kNm. Special care was necessary for the main bearing seal systems since they have to withstand a maximum static pressure of 12 bar. The inner and outer seals are a 3-lip sealing plus an inflatable seal for the static case.

3.5 Muck handling

The extraction of the excavated material from the TBMs excavation chamber and transport out of the machine and the tunnel using belt conveyors is defined by its shape and size, chips in this case. The rock chips that are generated by the Double Shield TBMs' excavation process are collected from the bottom of the tunnel face by eight buckets that are equally distributed at the cutterhead periphery.

The material passes via muck chutes to the muck ring loads the material onto a machine conveyor belt. From there, a tunnel belt with a capacity of 850t/h transports the material through the tunnel to common conveyors taking the muck from all four TBM operations. The common conveyors with a belt width of 1,400mm have a capacity of 2,000t/h and transport the excavated material to the surface.

Continuous conveyors are more economical to transport the excavated material for longer tunnels such as the Follo Line. They can cope more easily with peak performances of the TBMs and are independent from the other tunnel logistics.

Moreover, the tunnel belt conveyors solution to transport the muck out of the tunnels has the advantage that vehicle and traffic movements in the tunnel are reduced which is of special importance due to the layout of the construction site where all of the traffic in and out of all the tunnels must go through the access tunnels.

Figure 4. Systems in the TBM tunnels

4 LOGISTICS OF TBM SUPPLY

Large-scale infrastructure projects with multiple TBMs operating at the same time, like the four Double Shield TBMs for the Follo Line, are always challenging in terms of organizing an efficient tunnel logistics, and the transport of material and personnel in and out of the tunnel. An effective and efficiently operated logistics system is one of the key factors in the success of such a large-scale construction project throughout all project phases.

For the Follo Line project the tunnel logistics have to pass through two 1km long access tunnels at the midpoint of the alignment. The access tunnels through which everything must pass have an inner diameter of 8.75m and incorporates the conveyor belt for muck transport to the surface, ventilation duct (Ø2.8m), grout lines for two component grout and lines for water supply, dewatering and cooling.

The tunnel lining elements (segments) and invert segments are supplied to the Follo Line TBMs with multi-service vehicles (MSVs). The invert segments are installed to provide road surface for the MSVs. Each MSV is 45m long and has a load capacity of 125t so that it can transport two complete tunnel rings plus the invert segments.

5 EXPERIENCES DURING TUNNELLING

The assembly of the four Double Shield TBMs, designed and manufactured by Herrenknecht, took place underground in assembly caverns, one each for two machines with assembly times of around three months per TBM. The caverns were built in the junction area between the access tunnel and the running tunnels. Two machines started towards the North in direction of Oslo Central Station and the other two TBMs started excavation towards the South towards the city of Ski. The assembly caverns are used as logistic hubs for the tunnelling processes.

5.1 Variable geology

In general, the geology is very variable, sometimes changing within one meter from hard rock to disturbed rock mass with presence of water. At the beginning of the tunnel operations, the rock encountered at the tunnel face were characterized by differing in strength.

After about one kilometer, the two TBM drives towards Ski faced disturbed geological conditions and high water inflows (locally up to 70l/s, with a pressure of 10 bar) resulting in reduced performances compared to the two northern TBMs operating towards Oslo Central Station. After about three kilometers of tunnelling the two northern TBM drives also faced consistently disturbed rock mass, which is partly highly water bearing.

5.2 Structural modifications

Tunnelling operation in rocks of high to very high strength (UCS values up to 270MPa) and of high to extreme abrasiveness puts a high demand on cutting tools, cutterhead structure and operation. Dynamic effects due to cutterhead operation and rock excavation process can lead to high fatigue loading resulting in structural cracks. This has also occurred in the front shield of the two TBMs excavating towards Oslo and lead to modifications at the front shield of the two TBMs in order to decrease stresses at the respective weld and to secure the load bearing capacity by additional stiffeners. Preventive improvements works were done on the other two TBMs tunnelling towards Ski although they did not show any indications of crack developments.

5.3 Pipe roof umbrellas

Instructions from the owner Bane NOR regarding water bearing fault zones require to drill a pipe roof umbrella with a length of 30-35m for the reinforcement ahead of the tunnel face. Only then can tunnelling continue for the next 30m before the next pipe roof umbrella needs to be drilled. Drilling the pipe roof umbrella takes about 30 to 36 hours and additional 12 hours for the injections before authorization is given to continue with tunnelling. Dependent on the prevailing geological conditions and water inflow this procedure can take up to 1-2 weeks. Similar conditions are expected for the remaining tunnelling sections for all four TBMs.

5.4 Disc cutters and disc cutter refurbishment

For the Follo Line TBMs, 19 inch disc cutters are used with operating bearing capacities of 315kN. The higher cutter load results in an increased penetration with possible improvement in TBM advance rates. In respect of tunnelling performance, average excavation speeds of 12 to 15 meters per day were planned for the Follo Line drives. The average performance of all four TBM drives from tunnelling start and dated to the end of July 2018 comprises about 80 meters per week with maximum performances of up to 239 meters per week. Tunnelling operations take place on 6 days per week with two tunnelling shifts and one maintenance shift with a day off on Sundays.

Due to the predicted very hard and abrasive gneiss a main focus was on the disc cutter performance, disc cutter consumption and disc cutter repair works. It was predicted that up to 1,000 disc cutters need to be repaired per month during tunnelling. Based on this it was already clear in the early design phase that an efficient cutter shop would be required.

Therefore, the machine manufacturer set up a completely new cutter shop at the headquarters in Schwanau in Germany with 20 disc cutter mechanics. The logistics for transport between the jobsite in Norway and the cutter shop in Germany is done by trucks with optimized pick up and unloading to keep the trucks driving in a loop.

During tunnelling, changing geological ground conditions have led to different kinds of disc cutter wear patterns and disc cutter replacement criteria. The machine manufacturer is in permanent communication with the Joint Venture to adapt the disc cutters to the geological ground conditions encountered. During the excavation of the first 14,000m several different tests have been carried out to ensure the highest performance of the disc cutters. For this approach several cutter rings, bearings and seals were tested. The actual disc cutter lifetime is about 250 m^3/cutter which is about 10% higher than the initially theoretical calculated lifetime of 235 m^3/c. All disc cutter related documentation is prepared jointly by Acciona Ghella JV and Herrenknecht.

Upon completion of TBM tunnelling through a total 36km in Norwegian rock formations, comprising gneiss, amphibolite and pegmatite, comprehensive information on disc cutter consumption and wear patterns are available. This documentation includes also information about the cutter refurbishment works with the benefit of being able to offer in future a more optimized product handling and cost-efficient refurbishment.

6 CONCLUSION

The Acciona Ghella JV was awarded the contract for the mechanized excavation of the Follo Line railway tunnels, a major project with a strictly defined framework of quality criteria, budget plans and time schedule. The owner Bane NOR put out the project to tender using mechanized tunnelling technology and thus brought back state of the art mechanized tunnelling technology for major infrastructure schemes to Norway. The Acciona Ghella JV ordered from Herrenknecht four Double Shield TBMs (diameter 9.96m) which are currently excavating a total of 36km of tunnel in toughest rock conditions for the 22km long single-track rail tunnel between Oslo and Ski.

The Acciona Ghella JV is accomplishing an extraordinary feat with tailor-made large-diameter TBM technology from Germany and logistics solutions for this major project in terms of high-performance tunnel construction in very strong and extremely abrasive rock mass with minimum impact to population and environment. The efficient management of this major project with high and reliable tunnelling performances can be expected to play the role of a door opener for future tunnelling opportunities in Norway and the Nordic countries in general.