The return of TBMs to Norway at Røssåga HEPP – TBM operation through extremely hard rock, unstable rock mass and other challenges

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ABSTRACT: The breakthrough of the TBM at the Røssåga HEPP on 10 December 2015 signaled that the first TBM breakthrough in Norway in more than 20 years was a fact. The Robbins TBM was delivered as an Onsite first time assembly (OFTA) in January 2013 and was ready to bore less than 11 months from when the contract was awarded. During the excavation the TBM encountered extremely hard rock (over 280 MPa), which posed an extreme challenge for both the TBM and the cutters. During the excavation a highly efficient main bearing replacement was also performed in the tunnel. Even though the project encountered some challenges the TBM performance increased steadily to a level of about 200m/week towards the end of the project. After completion, the TBM was walked back through the tunnel and disassembled at the surface.

1 INTRODUCTION

The Røssåga hydroelectric project was originally constructed in the 1950s to supply power to iron and aluminum works in the nearby municipalities. The original Røssåga hydroelectric plant had a capacity of 250MW and in addition to the metal works it provided electricity to 19 nearby municipalities and made it possible to electrify the Nordlandsbanen rail line. The plant consisted, among other works, of an 8km long headrace tunnel from Norway's second biggest lake, Røssvatnet, to the power station close to the outlet o the Røssåga River and took more than ten years to construct.

In the early 2010s the project owner, Statkraft, initiated a refurbishment of the power plant to increase the capacity to 350MW and replace the original turbines. This would increase the yearly production of the power plant by about 200 GWh, resulting in a yearly production of 2150 GWh. As a part of the refurbishment it was also decided to refurbish the headrace tunnel with a parallel tunnel to the existing headrace tunnel. This also allowed the power plant to be under full production during construction of the new headrace tunnel. As a side note the tailrace tunnel was also relocated further up in the river to increase the length of the very important salmon-producing part of the river, thereby allowing an increase in power production with positive effects on the environment. (Statkraft 2016)

The tunneling works consist of 7400m long main headrace tunnels. In addition, it was decided to bore the access tunnel at a decline of 10% and a curve radius of 500m. As well, the project including building a new underground power station and other tunneling works related to the new power station.

The geological report for the project showed rock types that were favorable for mechanized excavation, including Schists, Mica Gneiss, marble, limestone and one zone consisting of granites (see Figure 1).

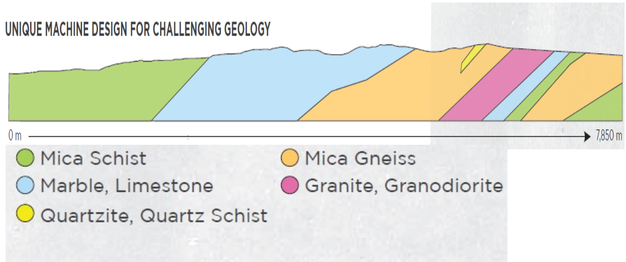

Figure 1 Baseline geological profile (Robbins 2013)

The experience from the previous excavated tunnels and observations from the surface indicated water ingress problems as well as the presence of moderate karstic features.

The project tendered as a drill and blast project in May 2012. The contractor, Leonhard Nilsen og Sønner (LNS), had by then worked with the TBM supplier Robbins to offer a TBM solution as an alternative construction method. After considering and negotiating the tenders the TBM alternative was found to be the best economical option. There were several important factors behind this decision. The option saved several kilometers of adit tunnels; they could reduce the cross section by almost 40% due to the increase in water flow in the TBM tunnel; and there was reduced risk of damage to the existing structures--including the existing headrace tunnel that was in full production--by avoiding blasting in sensitive areas. The contract between Statkraft and LNS was signed in November 2012 and marked the return of TBMs to Norway after more than 20 years since the last TBM project.

2 TBM DESIGN

LNS signed an agreement with the Robbins Company for delivery of a 7.23m Main Beam TBM (MB-TBM) and conveyor system in January 2013. AS LNS did not have previous experience with TBM operation Robbins committed to an extensive service and support agreement for the project.

2.1 *The TBM Specifications*

The refurbished Robbins MB 236-308 was chosen for the project. The TBM had been proven in a cold climate, having previously bored more than 10km of tunnels for the Kárahnjúkar Hydroelectric Project in Iceland. The TBM obviously thrived under cold conditions, as it set several production world records, including best day and week production in its size class: 115.7 m and 428m, respectively. (Robbins 2010)

Table 1. TBM Specification of MB 308

TBM Specs	
TBM Diameter	7,23m
Cutters	46*19” BL Cutters
Max Thrust	14 342 KN
Max Torque	3,490 kNm@ 8.3 RPM 6,275kNm@ 4.62 RPM
Cutterhead power	10 a 315 kW
Cutterhead Rotation Speed	0-8.7 RPM

The TBM was designed according to Robbins HP principles with large cutters, high power and a strong base structure. These features were deemed essential in the potentially hard rock conditions of the tunnel alignment.

2.2 *Design for rock support and water control*

The TBM was equipped with two rock drills on 180-degree movable rings for rock bolting as close to the forward shield as possible, as well as one probe drill on a 360-degree ring. In addition, the McNally roof support system was integrated into the forward shield for efficient installation of rock support. The main rock support methodology consisted of rock bolts and McNally slats for primary support (see Figure 2). A shotcrete robot was installed at the bridge and there was an option to apply manual shotcrete in the L1 area if heavier support was needed.

Figure 2.McNally slats in the shield and probe drill (Log)

To prepare the TBM for detection of the karstic conditions, Robbins and the Norwegian company Bever Control developed a specially designed Measurement While Drilling (MWD) program for the TBM. This was installed on a Montabert HC 110 probe drill with feeder supplied by Andersen Mekaniske Verksted (AMV). The TBM also had the capability to install an additional probe drill if needed. The Measurement While Drilling (MWD) system provided electronic visualization of probe drill data in the operator cabin.

The MWD data was automatically analyzed in the office and interpreted with the TBM performance into a geological model as given below in Figure 3.

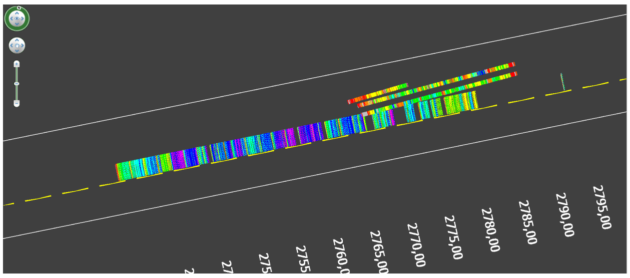

Figure 3. Screen print from the MWD system provided by Bever Control (Bever)

2.3 *Conveyor system*

Robbins also supplied the first continuous conveyor system to be used with a TBM in Norway for the project. The conveyor system consisted of the 7850m tunnel conveyor, which also needed to haul muck through the access tunnel and to a stacker unit. The prospect of starting the conveyor in a decline of 1/10 with a curve radius of r=500 is challenging for any conveyor system and likely to cause excessive damage to the belt. To avoid this Robbins utilized the patented self-adjusting curve idler. The curve idler and conveyor system performed well on the project and limited the downtime of the conveyor system to a minimum, contributing greatly to the good production on the project.

3 ON-SITE FIRST TIME DELIVERY

Due to the limited construction time for the project it was decided to utilize OFTA (Onsite First Time Assembly) methodology. OFTA was developed by The Robbins Company based on experiences from a significant amount of projects around the world. Instead of the traditional methodology of shipping all components to one location for a full workshop assembly, the OFTA methodology is based on doing the major sub-assemblies in a workshop and shipping smaller components directly to site for the first complete assembly at site. The methodology has been used on dozens of projects globally and has saved significant time and labor costs.

For the Røssåga TBM the sub-assembly was assembled in Italy and sent to site. The first major parts arrived at site on 30 August 2013.

A good team consisting of Robbins experts and LNS labor made an efficient assembly despite weather and snow challenges during the assembly (see Figures 4 and 5). The TBM and backup gantries was assembled and ready to bore by mid-December 2013.

Figure 4. OFTA assembly at Røssåga (Gibson 2013)

The Røssåga TBM was ordered in late January 2013 and the machine was in principle ready to bore at site in December 2013. Effectively, the machine was ready to bore less than 11 months after contract signing.

Figure 5. Assembled TBM in the snow (Solhaug 2013)

4 PROJECT RESULTS

4.1 *Production*

The initial plan for the project was to assemble the TBM on the surface and walk it down to a starter chamber at ch.450. After initial consideration it was decided to bore the 450m long access tunnel from the surface. The combination of unexpected hard rock, curvature, training of the personnel, and adjustments of the TBM and conveyor and civil works (installation of conveyor cassette and excavation of a 300m D&B tunnel from the TBM tunnel), caused the production to be slow. More stable operations did not occur until the machine was at the start of the headrace tunnel.
After the initial start the production stabilized in the very hard rock with some months of reduced production due to unforeseen incidents (see Figure 6). These included a damaged gripper shoe and repair in December 2014, main bearing replacement in March/April 2015, and heavy water inflow in November 2015. All these three happenings will be described later in the paper. It is also worth mentioning that July, December and March/April have less operation hours because of the Norwegian holiday periods.

After the initial very hard rock, boreability improved in October 2014 and this, together with a more skilled crew, contributed to more efficient operation. After this period the production stabilized at 500m and above in production months, with monthly highs of above 800m.

It is worth mentioning that the high production was possible due to skilled laborers and the good cooperation between Robbins and LNS personnel at site. The efficiency is clearly illustrated by impressive daily and weekly production records, 52m and 250m respectively, in a very hard and challenging rock mass.

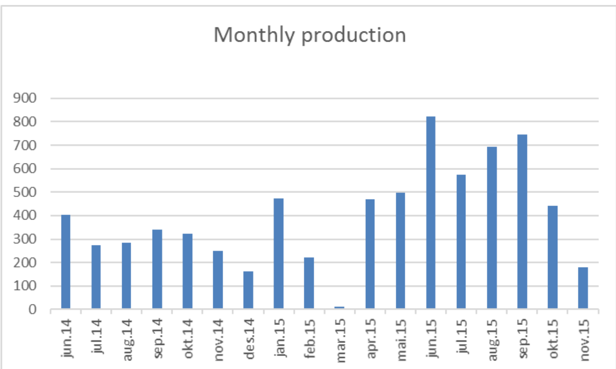

Figure 6. Monthly production at Røssåga (Log)

4.2 *Extremely hard rock*

Immediately after the TBM started boring, extremely hard rock with average rock strengths of above 200 MPa and some zones with strengths above 280 MPa were encountered (see Figure 7). In addition, the rock was massive with very limited fracturing, with NTNU fracturing classes below St. I- and highly abrasive with Cutter Life Index (CLI) values ranging from 4,5-11 and averaging just above CLI=5.

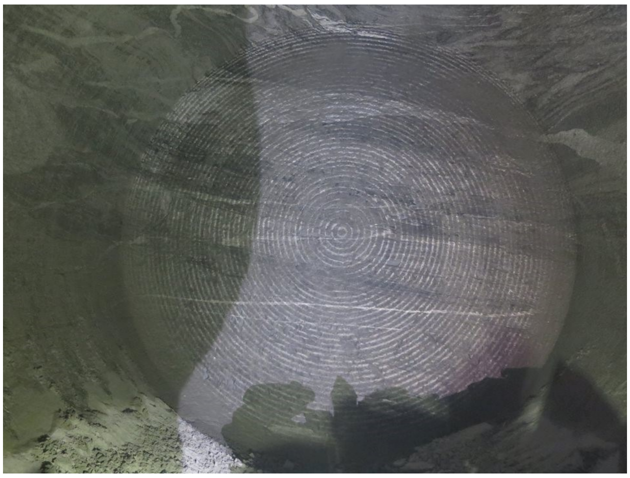

Figure 7. Extremely massive and non-fractured cutting face (Anderson)

The combination of curvature, decline, and the extreme rock properties signified some of the most challenging boring conditions for any TBM and would put any TBM and any cutter to the ultimate test. The extreme conditions caused low cutter life (approximately 100-150m^3/cutter), which again affected the production of the project. To improve the situation, the Robbins cutter department got involved and did a detailed analysis of the geology, machine performance, cutter wear and cutter failure mechanisms. Based on the findings of the analysis the cutter department worked together with the steel supplier and heat treatment shop to optimize the cutter ring properties to the geology encountered. The Robbins company's vast experience and years of experimenting on steel alloys and heat treatments, allowed the cutter department to do qualified considerations and developing some different cutter rings with properties that could enhance the cutter life. After initial trials with several different materials/heat treatments which performed well, one of the versions, XHD4, stood out and showed a very promising reduction of the destructive wear of the rings. The XHD4 cutters utilizes the same alloys as the world famous Robbins HD rings, however there are changes in the heat treatment process which improves the properties of the ring in extremely hard rock, as on Røssåga.

The improvement of the XHD4 cutter rings is hard to quantify on the project because of gradually introduction of the new cutters and changes in the geology, but it seems likely that the performance in the very hard sections has improve by a minimum of 25%. The benefits of the XHD4 is also likely to explain the superior cutter life for the remaining of the project, also in the relatively softer ground.

The geology on the entire project was generally massive, very hard and abrasive for the majority of the tunnel. Based on rock testing and mapping of the first 5200m of tunnel performed by NTNU it was observed that 80% of the tunnel had CLI values below CLI=10 and more than 30% had CLI values below CLI=6. For reference these are typical values that you see in very hard rock types such as un-weathered granites or quartzite. In addition to the rock testing, NTNU performed geological mapping for the project. Particularly the first 5200m shows a very consistent fracturing range from KS=0.43 to KS=0.59, (Macias 2014) which correlates to an average spacing between discontinuities of more than 100cm. For the first 2km the rock was consistently around 200 MPa and above, while between 2km -5km the rock was between 100-200 MPa with some sections above 200 MPa. The remainder of the tunnel was tested to be about 100MPa and above.

Based on the rock testing and geological mapping the NTNU-model estimated a net penetration rate on the project of 1,37 m/h and cutter life as low as 88 m^3/c on the first 5200m of the project (Bruland 2015). This illustrates to a certain degree the extremely challenging nature of the rock mass encountered. For the same length of the tunnel the actual net penetration rate was 2.12 m/h and the cutter life was 284 m^3/c. When also including the last 2km of the tunnel the net penetration rate increases to 2.22 m/h and the cutter life to 306 m^3/c.

The big deviations in the estimated and actual performance are likely to be explained by the test samples not being completely representative of the encountered geology and that the NTNU model might underestimate the performance of modern hard rock TBMs. It is, however, apparent that the TBM and cutters performed tremendously well in the geology encountered.

4.3 *Main bearing replacement*

On the evening of 14 February 2015 crews identified contamination in the main bearing cavity, which could have indicated main bearing damage. The TBM was immediately stopped for further analysis, including probe camera inspections. The inspections gave no conclusive answers and the owner, contractor and manufacturer needed to consider either doing an efficient main bearing change or continuing to bore with the risk of further damage to the TBM and potentially a complete failure of the bearing. After thorough considerations it was decided to change the main bearing. The decision was supported by the likelihood of an efficient replacement, due to the fact that there was a replacement main bearing available. LNS is an experienced D&B contractor with equipment and personnel available at site and Robbins had an experienced field service team available that would reduce the risk of any delays in the works. The decision was taken on Thursday of that week and the preparation for sending a replacement bearing to site and blasting a niche commenced immediately. A detailed and aggressive plan for the replacement was made: It was scheduled to finalize the replacement in six weeks and to be boring by the end of March, before the Easter holidays.

Figure 8. Workers during Main Bearing replacement (Anderson)

The procedure of a main bearing replacement for a Main Beam TBM in the tunnel is as follows: 1) Blast a niche with 25m length and 3.5 m height in the crown behind the TBM and install lifting equipment. 2) Unbolt the current cutterhead and bolt it to the tunnel face. 3) Bring in new main bearing and hang it up in the niche. 4) Walk TBM back to the niche. 5) Change main bearing and hang the old main bearing in the niche. 6) Walk TBM up to the tunnel face and bolt on cutterhead.

7) Remove all main bearing components and reconnect TBM. 8) Ready to bore.

The main bearing was transported by truck from Germany and was already ready at site on the 2 March, less than two weeks after the decision to replace the main bearing was made. This was two days before the niche was finalized and the lifting equipment installed (see Figure 8).

Due to the great cooperation between the skilled LNS tunnelers and experienced Robbins Field Service personnel, with the input of senior Statkraft personnel, the main bearing was replaced and the machine started boring on the 30th March, less than six weeks after the decision to replace the main bearing was taken. To the authors' knowledge, this is one of the fastest main bearing changes ever performed on a TBM of this size.

4.4 *Efficient rock support methodology*

Even though the rock is described as massive with limited fracturing previously in the paper, there was still zones of the tunnel that needed rock support. The rock support methodology on the project was proven to be highly efficient. The McNally system was utilized with rock bands and bolting, which allowed for continuous advance of the TBM under supported rock (see Figure 9).

Figure 9. Example of efficient use of the McNally system (Log)

Due to the highly efficient rock support methodology there was very limited downtime for rock support on the project. The rock support scheme also supported the findings of previous TBM in projects in Norway, that the need for rock support is dramatically reduced in TBM tunnels compared to D&B tunnels. The experience data from the previous TBM period in Norway, documented by NTNU (Bruland 2015) mentions a reduction of 40-90% of rock support and the installed rock support on Røssåga seems to confirm these numbers. In total there were just above 7000 bolts installed and less than 40m^3 of shotcrete for the total excavated 7800m. The shotcrete volume also includes filling up a void after the gripper shoe pushed out a wedge from the tunnel wall in a fractured zone. The incident caused severe damage to the gripper shoe, which needed immediate repair before the TBM could advance. The incident happened when the TBM was excavating through a zone consisting of mica gneiss or mica schist with some clear mica fractures. After excavating parts of the zone successfully the gripper shoe was thrusting towards a stable rock wall, which afterwards turned out to have two mica fractures forming a wedge in the tunnel wall. The wedge gave way under high loads so that only half the gripper was in contact with the stable rock wall. This caused tremendous loads to the other half of the gripper shoe and the studs were sheared off immediately, causing damage to the gripper shoes and the gripper shoe itself to fall into the invert.

Beside this incident there were very limited problems in relation to the rock support, despite the fact that the geology on the project could be called treacherous with large zones of extremely stable rock, weaker zones and well-hidden fractures. The good handling of the rock conditions at site are likely to be explained by the well-experienced Norwegian tunnelers on the project.

For the majority of the tunnel there was less water ingress than expected and the water that was encountered was typically in relation to known weakness zones. When approaching such weakness zones probe drilling was already instructed by Statkraft, and if water was encountered it was efficiently grouted off. The only major grouting work performed was, as expected, when approaching the intake. Since the cover was limited, the adjacency to the existing operational tunnel was limited and, as there was already equipment at the location for the intake structures, it was decided to grout from the surface at the same time as grouting from the TBM. In hindsight the grouting from the surface did not prove to be very efficient, but the grouting from the TBM was good enough to let the TBM through.

4.5 *Breakthrough and walk-back*

The TBM broke through into the intake shaft on 10 December 2015 in one of the most picturesque breakthroughs in Norwegian TBM history. After a proper breakthrough celebration, the work of disassembly and walking back the TBM commenced. The majority of the equipment was disassembled and removed through the breakthrough shaft prior to the machine starting walking back (see Figure 10).

The walk-back procedure was highly efficient with shift distances averaging between 150-200m per shift for the headrace tunnel, walking continuously when not re-gripping. There were some smaller sections with limited or no gripper pressure, and for these zones a push frame bolted to the invert was utilized.

Figure 10. Breakthrough! (LNS)

5 CONCLUSIVE REMARKS

The breakthrough in December 2015 was the conclusion of the first TBM project in Norway for more than 20 years. The project experienced several challenges, especially related to the hard rock encountered and the relative lower production caused by this. It is however apparent that the contractor, project owner and TBM manufacturer have cooperated well together and from a technical level performed better than expected with the conditions that were encountered.

The experience from the project also highlights the importance and need of having a good geological baseline and a well-written contract for any TBM project.

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