

CHALLENGES AND SUCCESSES OF LARGE DIAMETER TBM TUNNELING AT CANADA'S NIAGARA TUNNEL PROJECT

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ABSTRACT

The presentation will cover the history and reasons as regards what type of machine to be used. The geology was reasonably well understood and the TBM did not perform well in some of the formations and this matter is addressed. A unique approach of Onsite First Time Assemble (OFTA) was used and the TBM started boring in 12 months after order and this controversial approach to TBM supply is elaborated upon. The main features of the TBM are presented and some of the auxiliary components needed fairly substantial modification; especially the ground support equipment, and this is presented in some detail. Another unique part of the project was Boring and Final Lining (without segments) was conducted simultaneously. This presented numerous complications in muck removal and access to the TBM and how such complications were overcome and effected performance are addressed. The presentation concludes by addressing what could have been done differently to improve the overall performance if had to do it all over again.

1 INTRODUCTION

The construction of Canada's epic Niagara Tunnel Project is now coming to a close. This 10.4 km long, 14.4 m diameter tunnel was a significant technical challenge and achievement. The original schedule called for completion by 2009 and the current schedule is to complete all construction and bring the project online in 2013. The original contract price was for CAD \$985 million, while the current projected cost to complete has increased to CAD \$1.6 billion. What caused the delays and cost overruns, and what could have been done differently.

From a manufacturer's point of view, this tunnel certainly presented a number of interesting situations:

- how selection of TBM type was made at time of tender;
- how to reduce the construction schedule;
- how misjudgment of the geology caused progress delays and cost over runs.

This paper will expand on each one of these topics, and will address TBM mechanical problems encountered during actual boring as well as design changes that would be incorporated if the entire project were to be repeated.

2 PROJECT BACKGROUND

In the Canadian city of Niagara Falls, power generation commenced in 1892. By 1922, the largest hydro power station of that time, commonly known as the Sir Adam Beck 1, was brought into service and, in 1954, a second power station, Sir Adam Beck 2, including its two large water supply tunnels, was placed in service.

Recent upgrades at the Sir Adam Beck complex have increased the efficiency and discharge capacity, and allowed the new Niagara Tunnel Project to proceed into the construction phase, which when completed will divert an additional 500 m³/s of water to the existing Sir Adam Beck generating facility (see Figure 1).



Figure 1. Original Route of the new Niagara Tunnel

2.1 Geology

The new tunnel passes under the St. David's Buried Gorge, at roughly 140 m below ground surface, crossing down through the Lockport to Whirlpool Formations and into the upper 60 m of the Queenston Formation before making its ascent back toward the surface.

The Niagara Tunnel Project presents a unique opportunity to observe the Niagara sedimentary strata and allow for a more detailed understanding of the geological behavior and interaction of the heterogeneous rock units above and into the Queenston Formation (Perras & Diederichs, 2009). These rock types consist of limestone, dolostone, sandstone, shale and mudstone. The rock strength ranges from 15 to 180 MPa UCS, with most of the rock in the 40 to 100 MPa range. With the exception of sandstone, the geology is basically non-abrasive (see Figure 2).

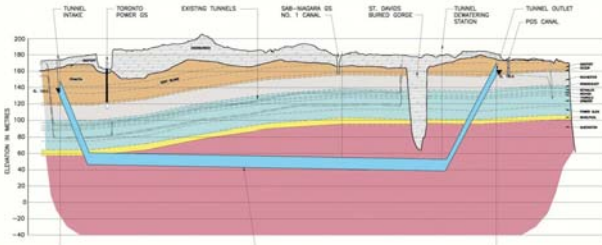


Figure 2. Geology and Original Vertical Tunnel Alignment

The new tunnel was planned from the downstream end starting on OPG property at Queenston with an original alignment consisting of a - 7.82 percent decline for a length of approximately 1,400 m. Here, the tunnel proceeded with a relatively horizontal plane for a distance of approximately 7,800 m. The alignment included several 1,000 m curves. The tunnel excavation ended at the Intake in the Niagara River at the International Water Control Dam located 1.6 km upriver from the Horseshoe Falls with an incline gradient of +7.28 percent over the final 1,200 m.

3 SELECTION OF THE CORRECT TBM AT TIME OF TENDER

On most projects, the selection of the correct type of TBM at time of tender is not usually entirely the TBM manufacturer's responsibility. This was the case on the Niagara tunnel when the TBM selection was made by contractor.

During the tendering process there were three tendering consortiums or contractors and each of the consortiums had their viewpoint of how best to excavate and line the tunnel. The two unsuccessful Contractor Joint Ventures elected to tender using a shielded TBM and the erection of precast concrete segments within the tail shield. As a TBM manufacturer, Robbins quoted Shielded Rock TBMs to these tendering companies. The successful tendering company elected to bore the tunnel with a 14.4 m diameter Open-type TBM using temporary ground support, while placing a final water proof liner and continuous concrete pour simultaneously behind the TBM excavation. Robbins quoted for this type of TBM as well. From the manufacturer's perspective, it is not within our scope of responsibility to decide on what type of lining method is best suited for any particular tunnel.

Despite the differences in proposed TBM type, there were several TBM features that would have been constant no matter what was chosen (Single Rock Shield, Double Shield or Open Main Beam type). Below, the features are addressed that are common to all the proposed TBM types.

3.1 Cutters and Cutterhead Design

For each type of machine we would have recommended the same cutter size, cutter load, cutter spacing and bucket arrangement. In the Niagara case, 20-inch diameter cutters were chosen, setting the machine cutterhead thrust and other requirements (see Figure 3).

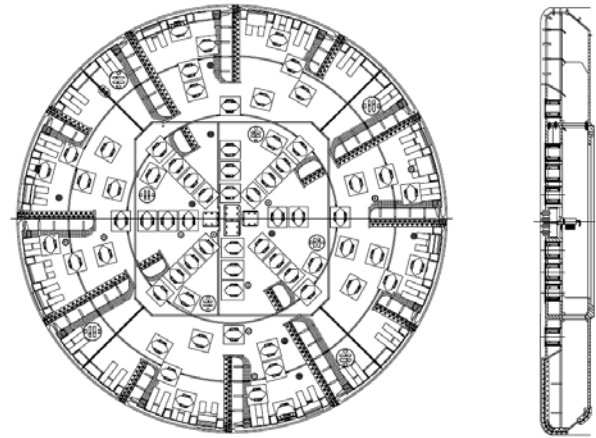


Figure 3. Niagara TBM Cutterhead

3.1.1 Cutterhead Thrust and Power Requirements

Again regardless of machine type the power to load the cutters and rotate the cutterhead remains the same. In the Niagara case, we selected 20-inch cutters rated to 311 kN per cutter, requiring 18,462 kN of cutterhead thrust and a torque of 18,800 kNm. While it was possible to use smaller 17-inch diameter cutters and get acceptable advance rates, larger diameter cutters were chosen because of the large number of cutters, making it important to reduce the down time related to cutter changes. Today it is generally accepted that 20-inch cutters can give approximately twice the life of 17-inch cutters.

3.1.1.1 Cutterhead Speed

Again the cutterhead speed would have been the same regardless of type of machine. The cutterhead speed selection was an interesting challenge. It was selected to use variable speed with constant torque from 0 to 2.4 RPM and reduced torque from 2.4 to 5.0 RPM. At 4 RPM, the cutters have a peripheral speed of ~180 m/min, which through our experience is in the upper limit to maintain good cutter life.

It was anticipated there could be some face fallout in some formations and when passing from one formation to the next, so a fairly high torque was designed for these situations.

In the harder sandstones that tested up to 180 MPa, it was understood there would be low disc penetration and, therefore, to get reasonable advance rates we designed a relatively high maximum speed of 5 RPM. The higher speeds of 3.5 to 4.5 rpm was sometimes used, particularly as the tunnel alignment was changed and a much higher percentage of harder sandstones were bored rather than in the original alignment, where 80% of the rock would have been shale.

4 TBM ASSEMBLY & LAUNCH

In order to comply with the aggressive construction program outlined by OPG/Strabag, the supplied TBM system had to be designed, manufactured, assembled and made “ready to bore” within 12 months after contract award.

The project team achieved this by the pre-assembly of the major critical components in a workshop and final assembly and commissioning of the complete machine at the project site.

This practice of jobsite assembly, known as Onsite First Time Assembly (OFTA), will be detailed in Section 8, “Actions Taken to Reduce the Construction Schedule”. The machine was launched in September 2006 (see Figure 4).



Figure 4. The 14.4 m diameter Main Beam TBM at the time of launch

4.1 Misjudgments and “What If’s”

Many of the parties involved at the time of selection of type of lining and machine type (including Robbins) were under the misconception that the Queenston shale would temporarily self-support for the majority of the tunnel length if it was mechanically excavated. There was also a contractual requirement to not have any loose rock behind the final lining.

This was not the case, however. When the Queenston shale was bored immediately above the cutterhead, over-break began to occur due to inherent rock stress. This initial over-break was ingested into the cutterhead opening, causing more room for over-break, which was in effect the result of the rock de-stressing (see Figure 5).



Figure 5. Over-break above the TBM, with room for a worker to stand on top of the roof shield.

Once the over-break occurred then the contractual requirement of no loose rock behind the lining came into play. The TBM was not set-up to scale down loose rock over the cutterhead or to place ground support outside the periphery of the bore. The ground support system was modified while excavation continued, from essential access by platform system to access by man bucket system (see Figures 6-7).

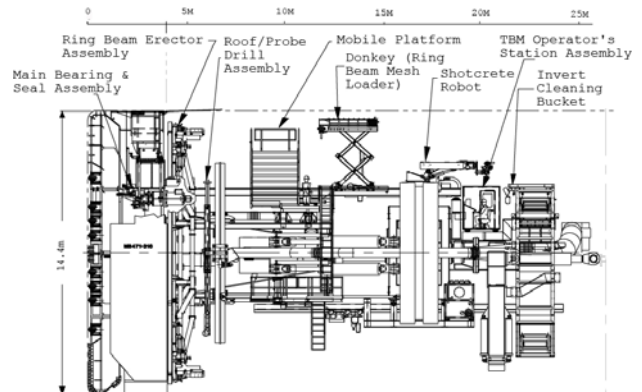


Figure 6. Original ground support set up on the Niagara TBM



Figure 7. Revised ground support system

In addition to the ground support modifications, the owner and contractor also opted to alter the vertical alignment of the tunnel. The alignment was raised by 45 m to bring the tunnel out of the Queenston shale and into more competent rock, in order to reduce over-break (see Figure 8).

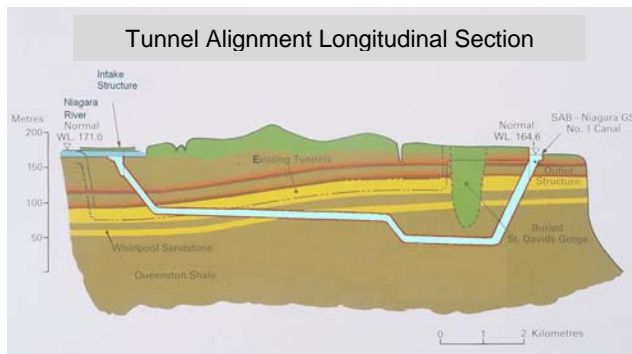


Figure 8. Revised Niagara Alignment (Wallis et al. 2011)

Several "What If's" regarding ground behavior as it relates to machine design have come up as a result of these events:

- Would over-break have occurred if a shielded TBM had been used? The answer is yes, the over-break would have occurred as it commences at the face, and extends above the crown in the gage area. The cutterhead on a shielded TBM would have ingested this over-break as it did with the Open TBM. The over-break would have filled the gap between the cutter overcut and the shield O.D., and would have eventually filled the gap between the overcut and segment O.D.
- What would daily advance have been if a Shield TBM was used? The answer to this question is a little more complex. If loose rock above the lining was allowed, the daily advance rate with both types of TBMs would have been similar. It was certainly possible with the Open TBM to hold all the loose rock in place and maintain TBM advance rates by

the use of wire mesh, the McNally Support System, shotcrete, rock bolts, steel straps, etc. In the Shielded TBM case, the segments would obviously hold the loose rock in place.

- What thickness of segments would have been necessary if a pre-cast segment system was used? This is the most difficult question, as there was uncertainty about the behavior of the shale after excavation. There was concern that swelling or high stress would develop after excavation which has highly loaded the segment. It can be assumed whatever size of segment there would have been doubt about the 100-year life capability that was specified for this project especially if there was loose rock behind the segments.

5 GROUND SUPPORT LESSONS LEARNED AT NIAGARA

The need for improvement of ground support on large diameter TBMs was one of the most valuable lessons on this project, admittedly as a result of misjudgment on how well the Queenston shale would stand up after boring.

The initial ground support consisted of:

- A 360-degree Ring Beam Erector, which was capable of erecting two different sections of ring, rotating the sections into position and then expanding the complete ring against the wall.
- A series of platforms around the cutterhead area that allowed access for bolting the joints of the ring beam.
- A movable donkey to allow placement of straps and wire mesh in the crown area.
- Movable and stationary work platforms above the main beam for man access to assist in placing rock support.
- Rotating rock drill system with two Atlas Copco drills and booms.
- Hand-held temporary shotcrete directly behind the cutterhead area.

The final rock support system consisted of essentially:

- Two man basket booms capable of carrying men and material (wire mesh, bolts) and shotcrete nozzleman.
- Modified original rock drill system. Full 360 degree ring beams were used in the initial decline boring; a total of 100 rings were set. The use of full 360 degree ring beams was abandoned for the following reasons:
 - They were effective if the tunnel remained round. After scaling the tunnel profile was only 60 to 70% round.
 - The ring erector device needed to be structurally strong to support the weight of the beam, and this took up too much valuable real estate immediately behind the cutterhead. Such space was needed for the more effective ground support systems.
 - Ring beams themselves are difficult to move and position in large tunnels. It is difficult to get good

rock contact. In the author's view, ring beams should only be used in ground where there is a need for a base structure to pass through completely non-self-supporting material like clay or fault zones. The ring beams can be useful if spiling or forepoling are necessary to advance through soft material.

5.1 Ground Support as it Should Have Been in Queenston Shale

If the project had been allowed to "keep the broken rock in position" several modifications to the TBM would have been implemented to allow good daily advance such as:

- Restricting and modifying the downward movement of the roof shield.
- Going to a "McNally System" combined with wire mesh.
- Reducing the distance between the gage cutter and the roof shield.

The basic concept in ground support is that when loose rock exists the rock is held in place with as much support as necessary, as soon as possible. Prior to allowing "fall out" the loose rock should be made to form its own natural arch until the stress can be maintained. In the Niagara TBM case, high stresses were causing loose rock to occur in the gage area and near the gage cutters. The loose rock had space to fall out from the gage cutter to the front of the roof shield. This caused a greater loose rock volume than necessary. The distance from the gage cutter to the roof shield was greater than necessary due to the way the retraction of the roof shield was designed (see Figure 9). If we were to redesign the TBM for similar rock, we would modify the movement of the roof shield.

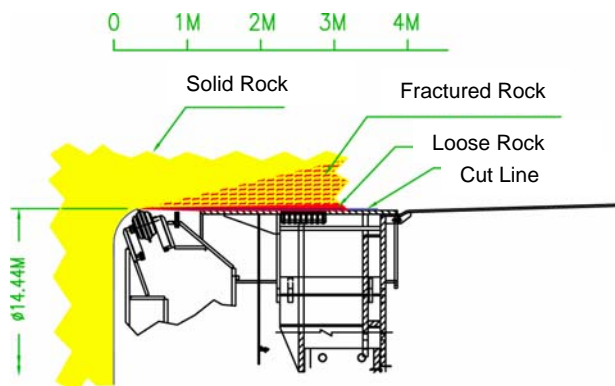


Figure 9. Setup of the gage cutter relative to the roof shield, which allowed some loose rock to fallout

5.1.1 Ground Support in General

On large diameter TBMs there has to be a lot of attention to ground support. What we have learned from the Niagara project and other large bore projects is the following:

- Face fall out is a regular occurrence because rock jointing, fissures, jointing etc. and the combination of loose rock at the face on a large area

exasperate the condition. It can be expected that rock fall out will extend beyond the periphery of the tunnel in the cutterhead area.

- The rock support system needs to be flexible and adjustable for various types of rock support. The final rock support system at Niagara accommodated this requirement.
- If acceptable, hold loose rock in place. This can be done by rock bolting and the McNally System or a combination of this and other systems (see Figure 10).
- New shotcrete type systems with non-rebound shotcrete material are available that are user friendly and TBM friendly and effective in the cutterhead area.
- Think of an NATM approach for rock support, even though the TBM is in the tunnel.

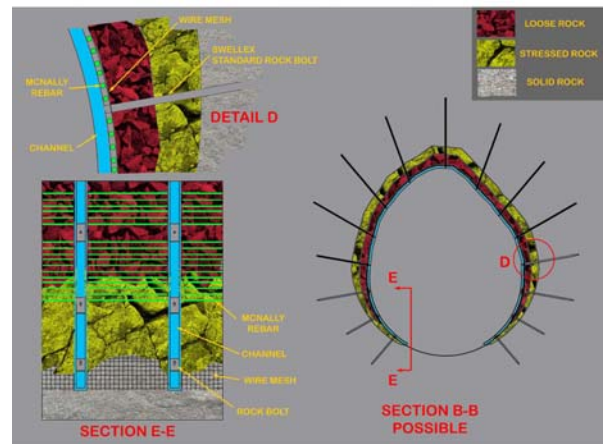


Figure 10. Various ways to effectively hold back loose rock.

6 Cutter Performance

The actual TBM performance on this project was considered quite good, with the machine achieving a world record for TBMs over 11 m in diameter in July 2009. The following advance rates were achieved during excavation (Niagarafrontier.com) see table 1.

Table 1. Summary of Advance Rates

Best Shift	Best Day	Best Week	Best Month
14 meters	25.4 meters	153.2 meters	467.8 meters

The cutter life was also considered to be good. The total number of cutter changed was 788, or 2,100 cubic meters per cutter. There were some problems with the cutters in the upper rock formations, however. The cutters were prematurely blocked due to the cement-like effect of the fines and water. The wet rock fines and

water packed around cutters as is normal, but special problems arose because of the consistency of the fines and the chemical content of the rock. Within a few hours of downtime, the fines hardened into a cement-like mixture, causing cutters not to turn when the cutterhead rotation was restarted. A foaming system was prepared as a corrective action but the situation eventually self-corrected as the machine moved into another rock formation.

A time consuming activity related to cutters on these large TBMs is the actual time for preparing the cutterhead for inspection and crawling around the cutterhead to inspect 85 cutters. To this end, the contractor allowed Robbins to experiment with a new remote cutter monitoring system (see Figure 11).

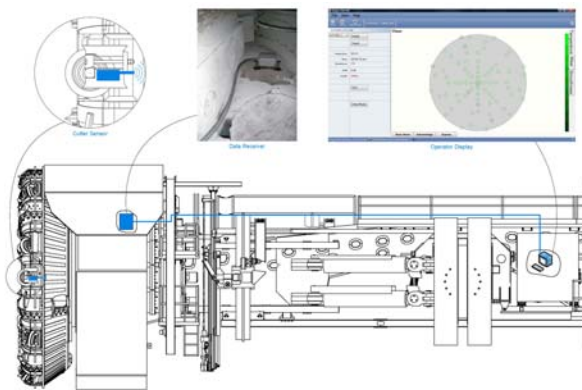


Figure 11. Cutter Monitoring System Setup

This remote monitoring system used smart chips with signaling on the cutters and cutter housing to send data remotely outside the rotating cutterhead to a receiver in the cutterhead support. The relative wear is measured by the rotating speed of the cutter (as discs wear, rotating speed increases). If the cutter is not rotating this fact is also picked up through the same device. Cutter heat build-up is also detected, giving indications of bearing and lubrication conditions. Each cutter's instantaneous load is also detected to indicate blocky ground (in order to caution the operator to reduce cutterhead rotation speed and load).

The system was not made fully functional at Niagara but the project allowed Robbins to make good progress on this very necessary and useful technology.

7 OVERALL MACHINE PROBLEMS

There were no major mechanical problems with the TBM. There were no major interventions for cutterhead repair, and there were no main bearing or main gear problems as a result of design. Most gear reducers lasted the complete project. There were some problems with the variable frequency drives in the early stages of boring. Due to some erratic steering in difficult ground, the main

beam was overstressed and at one point had to be repaired.

The machine mined for 6,700 hours and, considering it was inundated with scaled down rock for approximately 3,000 meters, the equipment had very good availability.

8 ACTIONS TAKEN TO REDUCE THE CONSTRUCTION SCHEDULE

Because of the decision to bore the tunnel as one operation and line as a second operation, there was considerable emphasis on new techniques to reduce the total time. Two innovative concepts were used with good success: one from Robbins' initiative and one from the contractor side.

8.1 Robbins-proposed use of On-Site First Time Assembly (OFTA)

The OFTA process involves not full shop assembly but sub-assembly of the various TBM components, with final assembly and testing once at site. Since Strabag and Robbins had previous experience working together at the Manapouri project in New Zealand, this process was accepted. Normal delivery would have taken a minimum of eleven (11) months to shop assembly and test, two months to disassemble and deliver to site and three months to site assembly, i.e. a total of sixteen (16) months. Robbins took responsibility for site assembly and the TBM was boring within twelve (12) months of the contract signing. There was some field rework that would have been picked-up in shop assembly and the process of assembly does take longer than if the machine had been shop-assembled. There was more downtime in the first few 100 meters of boring than there would have been with full shop assembly and testing. This differential in time was scheduled in and this OFTA process was considered a success.

8.2 Boring and Final Lining

The contractors initiated the design and implementation of boring and final lining concurrently. Because of the numerous processes this was no simple task. Between the TBM and back-up system, continuous shotcrete was also being applied by robotic shotcrete system, which worked very well.

Behind the TBM and back-up, the water proof lining was attached to the tunnel walls. Several thousand meters behind these operations there was a crown restoration concrete operation. The final lining was done in two operations several thousand meters apart: first the invert pour and then the final pour. The complications were in moving the conveyors, ventilation and service line through the forms and the logistics of traffic. The contractor did an admirable job of planning and implementing these simultaneous processes (see Figures 12-13).



Figure 12. Waterproof Lining Installation



Figure 13. Concrete Lining Arch Form

9 CONCLUSIONS

From the machine manufacturer standpoint, the Niagara project was only partially successful. No matter what the reason, no TBM manufacturer likes to be part of a project that is over budget and behind schedule. As TBM manufacturers, we are well aware our equipment is often key to the success or financial failure of the project.

We can take some consolation that there were no major mechanical breakdowns and the equipment obtained the advance rates predicted in various rock conditions. We can also take some responsibility for not paying sufficient attention to the interface of rock boring and rock support.

Tunneling is a combined effort between the owner, consultant, contractor and TBM supplier. In the Niagara case, the parties worked as a team and adjusted to the conditions they encountered. There was throughout most of the project a very cooperative effort for adapting and improving the tunneling system. The Niagara tunnel will remain a large chapter in the tunneling industry history books.

10 REFERENCES

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