The Sudbury South End Tunnel Project: Tried and Proven Methods in an Era of Mechanized Technology

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1. Introduction

From Brunel’s first shield in 1806 [1] to today’s fully automated multi-boom hydraulic jumbos the tunnel industry has seen a shift from hand digging and black powder blasting to fully mechanized earth excavation. TBMs dominate the tunnel industry today for their safety and rapid excavation. Long gone are the days of single jacking and double jacking; of Jonathan Crouch’s steam powered drills and the shovels that followed and the days were men like John Henry did battle with the iron machines. Fortunately one will never get rid of a jackleg and good a driller, nor will dynamite become a thing of the past in the construction industry. The following article illustrates techniques long used in the mines and still effective in today’s construction industry.

2. Contract Overview

With the growth of population in the South End of the City of Sudbury, and the existing sewer system operating at capacity, a 6.5 km tunnel was designed to replace the existing force main system. McNally Construction was awarded the contract in August of 2005, with an approved contract value of $26.4 million. It was determined during the bid stage that the contract could not be completed with a tunnel boring machine, due to the strength of the rock, subsequently traditional drill and blast methods were chosen. The project consists of four interconnected lengths of tunnel, three working shafts, six drop structures and three retrofitted lift stations, with corresponding underground chambers. The tunnel alignments were such, that they were driven below existing pump stations. The tunnels were driven from all three working shafts, with one site utilizing a ramp for access and muck haulage. Typically tunnel dimensions were 2.2 meters wide and 2.1 meters high and driven at a 0.11 percent grade. The tunnel received a concrete “v” invert to improve flow characteristics. The tunnel gravity feeds north to the existing Lockerby Tunnel and from there the sewer flows to the Sudbury Treatment Plant. (Fig. 1)
3. Geology

The project was located just south of the Sudbury Basin. The tunnel lies in Metamorphosed Precambrian Sedimentary Rocks, with the majority of the tunnel falling in the Mississauga Formation which consists of quartzite, arkose and greywacke. Generally the uniaxial compressive strength of the rock ranges from 100 to 250 Mpa, with the majority of the rock falling in the higher range of UCS values. The tunnel typically runs about 25 m below ground surface, with the least cover at 12 m. Minimum rock cover for the tunnel was anticipated to be approximately 5 m. Rock quality assessments based on GBR showed about 50 percent of the tunnel having a Q value of greater than 40 (requiring little support), 40 percent having a Q value between 4 and 40 (requiring pattern bolting), and about 10 percent having a Q rating of less than 4 (requiring pattern bolting, mesh and shotcrete).

4. Shaft construction

Two different construction methodologies were used for shaft construction. The Burwash Shaft site was located in the middle of the project at the intersection of the two main tunnel sections. A ramp was driven on an 18% decline to the tunnel depth. The ramp was driven utilizing a 1.9 m³ scoop for mucking and primarily jacklegs for drilling. The ramp has a dimension of 2.4 m high and 3 m wide. A shaft was then excavated off of the tunnel alignment to provide permanent access to the tunnel after the ramp was abandoned upon completion of the project. At both the Yale (27 m deep) and Green (29 m deep) sites at the north and south ends respectively of the
project, 5.4 m by 3.8 m shafts were sunk over the tunnel alignment for access. For both locations .1 m diameter holes were drilled on .45 m spacing around the perimeter of the shaft and four .15 m holes were drilled in the center from top to bottom utilizing down-the-hole hammer drills prior to shaft excavation. Approximately fifty 0.05 m production holes were drilled for each 3 m blast utilizing the center holes for relief, and blasting perimeter holes on the same delay. A mixture of dynamite and emulsion initiated with electric caps was used during blasting. The shafts were pattern bolted and shotcreted from the muck pile. Muck was removed with a 9570 Northwest Crane equipped with a 1.9 m$^3$ clam bucket and a 108 Link Belt equipped with a 0.6 m$^3$ clam bucket respectively. A mini-excavator and skip box were also utilized to clean around the edges and muck under the brow to minimize hand-mucking. Upon completion of the tunnelling operation a permanent concrete collar with removable caps were constructed to provide for access for future tunnel inspections.

5. **Tunnel Construction**

5.1. **Yale Site**

Headings were developed in both directions from the shaft at a width of 4 m to allow for a staging-switching area for the tunnel operations. This section of tunnel was driven utilizing jacklegs, an Eimco 630 overshot mucker, and a 0.96 m$^3$ scoop. Upon completion of this section rail was laid in preparation for mining of three separate headings. The shaft was separated into two compartments, one for mucking and the other containing the manway and utilities. All three headings were driven utilizing jacklegs, Eimco 12b overshot muckers, 5.5 ton Clayton battery locomotives, and 2.2 m$^3$ side dump muck cars. In the shaft a 30 m$^3$ box was installed below grade to receive muck. An air cylinder was mounted on the wall of the shaft that was then utilized for dumping the cars. A 9570 Northwest Crane equipped with a 1.9 m$^3$ clam was used to hoist the muck to surface. The mucking operation was performed with a camera system which allowed the operator to clamp without a signalman. Underground access to the shaft was controlled by a light system operated by the crane operator. Typical tunnel rounds were 1.8 m in length and required thirty-eight 32 mm production holes and three 64 mm "reamed" relief holes. Holes were loaded with anfo, and perimeter holes were loaded and traced with primer cord to produce a smooth wall, "half barrel". Nonel "easy drifters" were used for caps, and the round was initiated electrically from the station area. Ventilation was exhausted from each heading to surface utilizing 7.5 hp fans at the shaft with booster fans approximately every 300 m in the drift. Utilizing separate exhaust systems allowed each heading to blast independently, as all contaminated air was sucked thru the vent line and discharged on the surface. Two 0.35 m$^3$/s compressors coupled to a receiver tank, located on surface, were used to supply air to the tunnel.

5.2. **Burwash Site**

From the bottom of the ramp all three headings were developed utilizing the 1.9 m$^3$ scoop and jacklegs, to sufficient length to allow for rail installation. A sump and re-muck area was excavated at this time. All headings were mined using jacklegs, Eimco 12b muckers, 5.5 ton Clayton battery locomotives and 8.4 m$^3$ Hagglund cars. The Hagglund cars discharged into the re-muck area, where the 1.9 m$^3$ scoop loaded and hauled the shot rock to the surface. Typical tunnel rounds and methods were the same as the Yale site, although mining from this location encountered more water which necessitated the use of packaged emulsion products in place of the anfo. All air for ventilation was blown down the shaft; from the shaft about two thirds of the air volume flowed directly up the ramp. Each heading was equipped with an exhaust fan setup that drew fresh air from the station area to each heading and deposited it back into the ramp. This setup ensured that the station area was not contaminated when blasting occurred, allowing the headings to work independently. Compressed air was provided on surface utilizing two 0.35 m$^3$/s and one 0.28 m$^3$/s compressors coupled to a receiver tank.
5.3. Green Site

Both headings were developed from the bottom of the shaft utilizing a 0.4 m$^3$ scoop and jacklegs at a width of 4 m to allow for a staging/switching area. Upon completion rail and switches were installed, along with the sump/re-muck box and dump cylinder. The shaft was divided and a camera system identical to that at the Yale site was set-up. (Fig. 3) A 108 Link Belt equipped with a 0.6 m$^3$ bucket was used to muck. Fans were set-up exhausting from each heading, and a 0.35 m$^3$/s compressor coupled to a receiver supplied mine air. Tunnel rounds and methods were the same as at Yale, but again more packaged emulsion was used due to water ingress.
6. Drop Structures

There were six drop shaft structures and three retrofitted lift stations that were connected along the tunnel alignment. A local subcontractor was employed to construct the structures. At each structure, a separate drilling subcontractor placed 762 mm casings to rock with a foundation rig and then sealed each with cement to the base. A small Subterranean 003 raise bore unit was then used to drill a 200 mm pilot hole down to a cut-out on the side of the tunnel where a .6 m reaming head was then attached. Holes were then reamed back to the casing. A 400 mm, or 550 mm stainless steel liner was then inserted and grouted in place (depending on location). Each structure has two holes, one for venting and one for flow. The structures located on rock were constructed prior to drilling. Holes at these locations were drilled upon completion of the tunnel below. The three lift stations were retrofitted when the tunnel was completed. Each retrofit consisted of drilling the pilot holes and back-reaming while the lift stations remained operable. Outer casing were installed around the holes to be drilled to prohibit flows entering the drilling operation and tunnel prior to commissioning the tunnel.

7. Concrete Invert

As the drifts were completed ballasting of the tracks and final grading proceeded. Ballast was trammed in on a Hagglund car or a modified dump car and spread with a SK500 mini-skid steer. Elevations were established off of control points approximately every 200 m and transferred along the rail using a rotating laser. The tracks were left in place to facilitate the transportation of concrete into the tunnel. Concrete was brought in on a battery operated 3 m³ Maxon car. A Somero Power Rake and Screed were used to spread and level the concrete. The rake provided a rough grade while the screed followed providing the finished elevation. Each was fitted with a custom “v” shaped plow and screed at a 1:8 to meet flow conditions. Both pieces of equipment were fitted with laser targets and automatically adjusted to the proper elevation via the rotating laser set to grade. The skid steer and concrete screed equipment were all equipped with diesel engines. In order to grade and pour concrete with the equipment safely in the tight space of the tunnel all of the vent line had to be removed. As such the concrete operations could not proceed until at minimum of one drop/vent shaft was completed at the end of tunnel section to be poured.
At this time a fan was mounted to the hole and tunnel air was pulled from the drift and vented to the surface. Air doors were constructed as needed. The concrete operation started at the fan and worked away from it allowing fresh air to be supplied to the crews at all times.

8. Production

Shaft sinking was performed on a single shift and subsequently progress was slow. The main focus of initial work was driving the ramp at Burwash and commencement of production mining from the center of the tunnel. Each shaft took approximately 4 months and included excavation, support of excavation, and utility setup. The mine setup at each site included turning under the shafts, widening the tunnel/station area, excavating and installing the re-muck, and installation of rail switches and mine utilities. Average setup for each site took approximately 2 months with double shifts. Production mining was generally two shift operation except at the Green Site. A global tunnelling production rate was in the area of 2.42 meters per day with a best week of 19.5 meters. Grading of the tunnel averaged approximately 75 meters a day and was greatly impacted by high spots along the alignment. The actual concrete operation averaged 110 meters a day with a best day of almost 170 meters. Grading and concrete was generally done on a single shift basis.

9. Major Challenge

As is the case in most tunnelling projects, not everything goes as planned or without a hitch. On this particular project, one problem presented itself as tunnelling was approaching its end. Low rock cover in the most important section of the tunnel, the Lockerby Tunnel connection proved challenging. Geotechnical studies done leading up to the project show approximately 5.5 m – 9 m of crown pillar along the tunnel alignment near Lily Creek. Three boreholes with Q values between 4.4 and 20.9 were located in the vicinity. Due to access restrictions none of the boreholes were located over the tunnel alignment. Geophysical surveys were done across the creek and over the tunnel alignment instead.

In April of 2008 a fault zone was encountered at approximately 170 m from the Lockerby connection. Steel sets poured back with concrete were required to stabilize the ground. About 20 m worth of steel sets and concrete was necessary. (Fig. 4) Excavation commenced again in mid-June along the proposed alignment heading towards Lily Creek. Later in the month, while drilling probe holes, it was discovered that the crown pillar had significantly decreased to a range of 1.25 m to 1.5 m. The tunnel was some 30 m from the creek bed at this point. Tunnelling was immediately halted while an alternate plan was formulated.

Fig. 4
Using a borehole with known high rock elevations and projecting a new path towards it, a set of NQ-sized holes were to be drilled to prove ground conditions. Due to the necessity to drill over the new alignment, permission was granted to place a barge in the creek and drill from it. Four cores were taken in the creek and along its western bank. From the core data it was determined that the crown pillar was an estimated 2.3 m with a $Q_{equivalent}$ in the area of 12.9. Based on this information the tunnel was realigned and excavation proceeded with caution.

Instead of 1.8 m rounds, 1.2 m rounds were taken. As with the regular 1.8 m rounds, cushion blasting techniques were utilized. The back was shotcreted with 30 MPa dry-mix with 50 mm cover. Every 2nd round 4 probe holes were to be drilled at the face. One hole was drilled vertical, another hole was drilled at 45° to approximately 5 m or to bedrock contact, and two 'splay' holes at each shoulder were drilled out at 10° and up at approximately 10 - 15° to 3.5 m. Suggested safe roof thickness was 1.5 m. In addition to probe drilling and regular pattern bolts, 5 spiling bolts 2.4 m in length were recommended out in front of the face for added arch support. After a few weeks of mining, a roof thickness of greater than 1.8 m was achieved. Regular 1.8 m rounds were re-instated and the original pattern bolts installed.

Excavation continued as the tunnel began crossing under the east bank of the creek. One vertical probe hole at 1.8 m and one probe hole drilled at 45° out from the face to a depth of at least 2.6 m were drilled every other round. In mid-September, while probing out in front of the face, the bedrock contact was encountered at 1.5 m above the back. Minimal water inflow occurred, but once again the heading was stopped until further investigation could be performed.

This time the services of an underground diamond drilling contractor were employed with a Bazooka drill to probe +10 m out in front of the tunnel face. A number of holes were drilled out in front of the face and encompassing the back along the alignment. Bedrock contacts were noted; trajectories recorded and core samples taken during drilling. From this data a 3D model of the crown pillar was realized. It was determined that the worst area was directly above the last tunnel advancement and that the rock was sound.

A similar approach as the previous zone was used in advancing the tunnel. 1.2 m rounds were taken, spiling bolts installed, and probe holes drilled after every other round. Extra precautions were necessary being directly under the creek. Groundwater inflows were closely monitored. Trim powder was used in the perimeter holes to minimize overbreak and fracturing of the surrounding rock. Steel sets were erected and shotcreted completely in after every round to provide long term stability. After approximately 12 m the west bank of the creek was reached and the crown pillar increased dramatically. Normal mining and support systems were once again employed.

10. Conclusion

Tunnel excavation began in the fall of 2005 and the final break through into the Lockerby Tunnel was made in January of 2009. During peak production there were 8 different headings proceeding simultaneously day and night. As the commodity boom peaked during the South End Tunnel project, skilled labour was a difficult thing to retain. A sentiment shared by other contractors in the Sudbury region [2]. Without the skills of few seasoned mining foreman willing to pass these techniques along to the next generation of miners this project would not have been a success. Their time spent track drifting in the area mines, and their willingness to teach young miners these skills was invaluable. At the end of the day, approximately 50,000 m$^3$ of rock was removed, making way for the future expansion at the south end of Sudbury. Not bad for a couple of drills, an oversized shovel and a little compressed air made effective just under a century ago.