Tunnel Boring below Montreal: A Case Study of Urban Tunneling through Hard Limestone

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ABSTRACT

Montreal, Quebec, Canada's Rosemont Reservoir tunnel travels for 4.0 km below city streets, faulted rock, a disused quarry, and active subway. The story of the 3.0 m diameter Double Shield TBM's successful breakthrough involves a careful analysis of geology, TBM operating parameters, and ground consolidation measures. Over the years, geologists conducted two diamond-drilling programs totaling 65 borehole tests to depths ranging from 21 to 65 m below residential and commercial neighborhoods along the tunnel alignment. The core sampling program indicated the presence of medium to thinly bedded limestone, with some shale and intrusive rocks, mainly dykes and sills. While the limestone averaged 50 to 300 MPa UCS, rock in the intrusives ranged from 100 to 430 MPa. More than 80 dykes and sills as small as a few centimeters wide and as large as 8 to 10 m wide were mapped along the 4.0 km tunnel. Contractor Foraction, Inc. took measures including cement injection of vertical boreholes in two suspected fault zones from the surface to a depth of 50 m. Even with these measures, fractured rock and water inflows, which had to be temporarily deviated, slowed progress and required alteration of the boring parameters in some sections. The crew were ultimately successful and made their final breakthrough with the TBM in November 2015. This paper will analyze TBM boring methods and performance based on the changing geological conditions below Montreal. Special attention will be paid to sections in fracture zones and below sensitive structures including the inactive quarry site and active Montreal subway. The authors will analyze how preliminary studies, combined with operational techniques and on-going geological monitoring, resulted in an ultimately very efficient tunnel boring project in a dense urban area.

1   INTRODUCTION

The City of Montreal is currently upgrading its entire potable water supply strategy. The program is expected to reach its final phase in 2020. One of the main goals of the program is to restore the largest water reservoir (227,000 m^3 volume) on the island and put it back to supplying drinking water to the residents of Montreal, which would allow for a better balance of the water supply network across the island. It would nearly double the drinking water reserves, an essential need for a population that increased dramatically since the Rosemont Reservoir was built in the early 1960's. For the last two decades, the reservoir, still structurally in impeccable shape, was used to store water as fire service back up. The project thus involved the construction of a four kilometer long, 2.4-metre I.D. watermain linking the Rosemont Reservoir located in Étienne-Desmarteau Park to the existing high-pressure network, for which a water main line runs East-West along Notre-Dame street (**Figure 1**). It took 205 days of boring in limestone intercepted by numerous hard igneous dykes and sills, in a period of just over 300 days for the contractor ForAction (Les Entreprises Michaudville Inc.), equipped with a Robbins Double Shield TBM, to complete the boring

of the 3.0-metre diameter Rosemont Tunnel. Construction of the entry shaft by drill and blast took place in the seven months prior to the launch of the TBM in December 2014. The end shaft, located next to the reservoir in Etienne-Desmarteau Park, was constructed later, once the tunnel excavation was underway.

Figure 1   Location Map. Rosemont Tunnel, Montreal QC. (Modified from Google Maps 2016)

After the construction of a 100 metre-long gallery 32-33 metres below the surface, serving as garage and "launch pad", the tunnel the tunnel takes on a slope of 0,5% in the first 1,800 metres and then increases to 1,8% slope in the last 2,175 metres before the end shaft. Due to increasing

topography and surface elevation along the course, the tunnel depth is approximately 45 mbgs along the course.The slope differential had to take into account passing a respectable 14 metres below the Montreal Subway line: a passage that, thankfully, proved to be uneventful.

Details of the project in its initial phase as well as technicalities with regards to the shaft construction and methodologies as well as an overview of the geology expected to be broken through have already been presented by *Rancourt et al.* (2014) at a previous TAC Conference in Vancouver in 2014. The current paper summarizes the trials and tribulations associated with the building of a tunnel in a large urban area, below residences, businesses, heritage buildings, a subway line, and old quarries later filled with domestic as well as industrial wastes, not to mention the many challenges offered by the complex geological features.

2   GEOTECHNICAL INVESTIGATIONS

2.1   Borehole Programs

Geotechnical investigations prior to the tunnel construction were conducted in two phases. The first took place in 1976-77 when the first 38 boreholes were drilled. The original plan was to drill 56 vertical boreholes directly down into the proposed tunnel alignment. An interval of 60 to 80 metres between boreholes would provide enough information for the construction. The first 38 boreholes were completed vertically in open spaces. A different plan would have to be used for the boreholes located below residences, buildings, underground services and various infrastructure. Due to budget constraints and other priorities, the City of Montreal put the tunnel project on hold. The vertical boreholes, all equipped with standpipes for groundwater monitoring, were practically abandoned and left open. No laboratory testing was ever done on rock cores.

In 2012, Les Services exp Inc. was mandated by the City of Montreal to resume the geotechnical investigation initiated some 35 years earlier. After a thorough analysis of the 1976 data, exp produced a preliminary geological profile along the tunnel alignment and recommended lowering the depth of the tunnel axis from the original 1976 design. The rock mass crown pillar went from 2.5 m to 6 m at the southern entry point of the tunnel, where it is the thinnest.

The 2012 drilling campaign proposed by exp aimed to complete the work started in 1976 by providing detailed geological and geomechanical logging of the rock cores as well as all in-situ and laboratory testing necessary for the rock mass characterization. The 2012 geotechnical study would then supply a more complete database, particularly along sensitive zones such as:

- the start and end points of the tunnel and tunnel shafts where no data was available;
- areas where the 1976 boreholes did show high fracturing in the bedrock and the presence of breccia;

- the former quarry area, in order to confirm the maximum depth reached during quarry excavation and any effect the quarry operations could have on the rock mass quality at the depth of the proposed tunnel.

The 2012 geotechnical field work took place between October 11 and December 2, 2012 and included 27 NQ size diamond drill holes 40 to 60 metres in depth, including 22 inclined holes with core orientation. The cores were sampled to produce 135 laboratory tests including UCS, triaxial compressive strength, splitting and direct tensile strength, and abrasiveness determination tests. As part of the field work, Lugeon tests were carried out at the proposed tunnel elevations, and four of the boreholes were equipped with vibrating wire piezometers. Groundwater monitoring wells were installed at the proposed shaft locations. **Exp** also sampled and tested groundwater for corrosivity. A total of 1,251 metres were drilled, including 1,033 metres cored in the rock mass. Details of this latter investigation have been published in *Boivin et al. (2013).*

The testing of the rock properties yielded results that were carefully studied by the technical staff at Robbins in order to select the right equipment for the Rosemont Tunnel. High variability in rock hardness and strength was observed, with results varying from as low as 40 MPa UCS in argillaceous limestone to as high as 430 MPa UCS in some intrusive dykes.

Groundwater was another important factor in the making of the tunnel. Some irregularities were observed, particularly in two areas during the investigations. The contractor proceeded to improve these areas with random boreholes and grout injection--an operation with limited success.

Following some of the recommendations of the 2012 investigation, the City of Montreal recommended additional work, including seismic controls on buildings in the vicinity of the shafts during construction; 3D-modelling; analysis of the rock mass in the vicinity of the subway tunnel; and seismic monitoring of heritage and old buildings located directly above the tunnel corridor during passage of the TBM. Groundwater monitoring was also carried out during the boring, particularly in fault zones and in the vicinity of the ancient quarries. A secondary drilling investigation comprised of three new boreholes was also carried out to locate precisely the second fault zone, south of the old quarries.

2.2   Geological Setting

The tunnel profile, shown in Figure 2, traverses a Paleozoic sequence of sedimentary rocks of the Lower St-Lawrence Lowlands with near horizontal bedding planes, generally varying from 2° to less than 10° dipping South-East. Bedding planes varied considerably near fault zones (this was also one of the clues indicating we were approaching a potential zone of movement while boring). The tunnel is located on the east side of the Villeray Anticline, which plunges slightly to the Northeast (*Clarke, 1972*). Regional and local geology, including the lithological description of the formations, is well summarized by *Globensky et al* (1993).
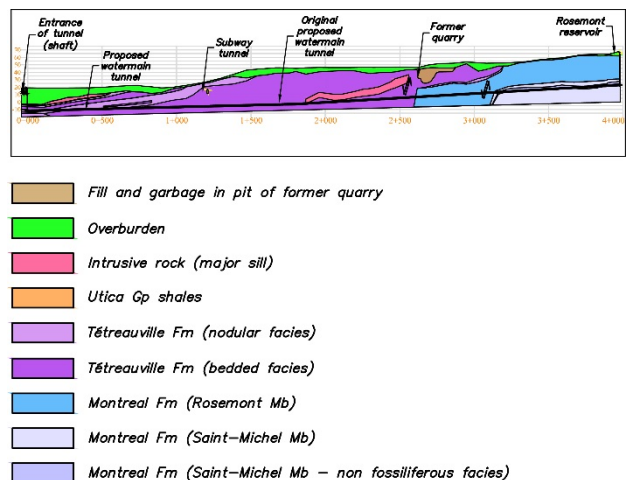
Figure 2. Simplified geological model along the tunnel alignment, based on the 2012 geotechnical fieldwork results (Boivin et al, 2013)

Along the tunnel, the underlying sedimentary rocks belong primarily to two formations of the Trenton Group, and, to a minor extent in the Southeast area, to the shales from the Utica Group. The latter was intercepted during the first shaft construction but not along the tunnel alignment. In addition to the sedimentary sequences, several igneous satellitic rock bodies (dikes and sills) associated with the Mount Royal intrusion were common throughout the tunnel. The Villeray Anticline is sectioned to the south by the east-west White-Horse–Rapids fault system, with the main fault located approximately half a kilometre south of the entry shaft of the proposed tunnel. Two other fault systems (Northwest-Southeast and Northeast-Southwest) are also present. Their apparent vertical movement vary from less than a metre to sixty metres or more. Geological structures associated with these major fault zones have definitely affected the boring of the tunnel in at least four different areas along the course.

The sedimentary beds are mainly composed of fine-grained dark grey to black limestone with argillaceous interbeds: The Tetreauville Formation was exposed along nearly two-thirds of the tunnel and was composed of three rock facies: a regular sequence of limestone made up of fine-grained dark grey limestone (beds 2 to 15 cm thick) interbedded with an almost black micrite (2-8 cm). The second facies is a "cloudy" textured, nodular fossiliferous limestone (calcareous mudstone) without regular bedding planes. These two facies offered a relatively low resistance to the TBM cutterhead. The third facies was a softer argillaceous limestone containing up to 70-80% argillaceous content and located lower in the Tetreauville stratigraphy. This particular soft rock proved to be a challenge to the contractor as will be discussed later in this paper.

The Tétreauville overlies the more regular Montreal Formation exposed in the last 1400 m of tunnel. The Montreal is made up of two distinct members. The Rosemont Mb is composed of thinly bedded crystalline limestones with wavy shaly partings. The limestones vary from finely to coarsely crystalline (micrite to sparite) and from pure to slightly argillaceous. Beds are lenticular, sometimes nodular and separated by thin argillaceous black shale partings and depict bioturbation. The presence of this rock unit along approximately 500 metres beneath a former quarry and further north is controlled by two normal faults (interpreted during the 2012 study) with strong vertical displacements.

The last normal fault along the tunnel exposes the Saint-Michel Mb composed of fossiliferous fine-to-medium grained crystalline limestone 10 to 40 cm thick separated by thinner black argillaceous and very fossiliferous micrite, with beds from 2 to 5 cm in thickness. It comprises a second, non-fossiliferous, very hard crystalline limestone facies that can be followed for the last 800 metres of the tunnel layout.

The intrusive rocks occur as dikes and sills and originate mainly from the Monteregian intrusions (gabbro and syenite), and other magmatic episodes (Clarke, 1972). They varied greatly in nature, strength and dimensions. During the final geological mapping of the tunnel, we numbered over 85 dykes and sills from felsic to mafic (several gabbros and a troublesome olivine pyroxenite), varying in size from a few centimeters to 8 to 10 metres in thickness (when angled across the course of the tunnel, these can extend up to 40 metres along the course of the tunnel). The thickest and most important intrusion, a sill that had been identified in several consecutive drill holes in the central area of the tunnel alignment, may have been crossed more than once during boring due to the normal fault systems occurring on the side of the anticline. In an area just south of the former quarries, the sill is cut by other intrusive rocks.

Larger intrusions have indurated the host limestones and shales to near marble and argillite states, sometimes obturating the bedding patterns. The resulting rock was fine-grained, massive, very hard, often developing a complex fracture pattern. A hard, siliceous intrusive breccia was also present in two occasions as a margin to other intrusions or as a single dike.

3   THE TUNNEL BORING MACHINE

Given the expected geology, a hard rock Open Gripper or Double Shield TBM (DS TBM) was specified by the City of Montreal. The contractor, ForAction (Les Entreprises Michaudville, Inc.), choose a Hard Rock Double Shield TBM from The Robbins Company based on its capabilities, price, and availability (Figure 3).

Figure 3. View of Robbins Ø3m Double Shield TBM used on Rosemont Project

A small DS TBM is based on the principle of open mode excavation using a machine belt conveyor for spoil transfer through the machine. Typically, DS TBMs or Shielded Gripper TBMs are used in geology that is unstable and blocky with fair to poor rock quality below 75%, or competent rock with low potential for squeezing or shield trapping. DS TBMs are also specified for tunnels through massive rock with fault zones where ground support is needed to prevent tunnel collapse.

For these geological reasons, a DS TBM is the tool of choice to install reinforced concrete segments behind the TBM, usually as the final tunnel liner. However, the logistics of moving small segments and supplies along with back-fill grout creates bottlenecks that slow production and reduce worker safety. In addition, pipe manufacturers can supply larger sizes and types of pipes from a variety of materials to match the application of the pipeline, all in a factory setting with high standards of quality. Therefore, it is very common for contractors to mine the tunnel as fast as possible and 'cast in place', or carry in and place the required pipe. On this project, ForAction (Les Entreprises Michaudville inc.) decided to "carry in and place" the final carrier pipe using a pipe carrier (Figure 4).

Figure 4. Pipe carrier with section of pipe

The machine is comprised of five main sections: 1) a Cutterhead and Forward Shield Assembly, 2) Telescopic Shield Assembly, 3) Gripper Shield Assembly, 4) Tail Shield Assembly with auxiliary thrust cylinders, and 5) Back-Up System – see Figure 5.
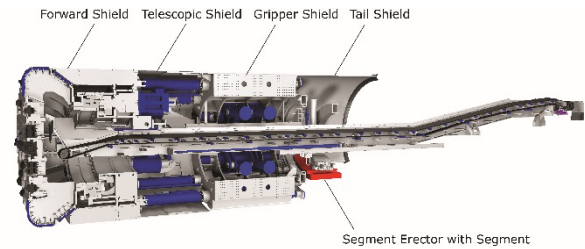

Figure 5. Cutaway view of a typical DS TBM

The rotating cutterhead assembly is a heavy-duty fabricated weldment with cutter saddles to mount alloy steel single disc cutters with high thrust capability to excavate hard rock. On the Rosemont TBM, the largest possible rear-mounted disc cutters, 17" diameter rings with 245 kN load rating, were used to maximize penetration rates and most importantly increase worker safety. Muck buckets, lined with abrasion resistant steel, are mounted on the periphery of the cutterhead and scoop up and transfer the rock 'chips' or spoil to a hopper. Gravity moves the rock chips onto a belt conveyor that runs thru the machine and back-up system to a track-bound muck train for removal to the starter shaft and haulage to the surface.

The cutterhead is supported by a high-capacity main bearing assembly mounted inside the forward shield. To rotate the cutterhead, the TBM uses four variable-speed electric drive motor and gearbox assemblies that drive a ring gear and cutterhead adapter, which rotates the cutterhead. Power cables run from these motors to variable frequency drives (VFDs) located in an electrical cabinet positioned on the TBM back-up system. To stabilize the cutterhead from oscillating eccentrically, the TBM operator uses a set of stabilizer pads mounted along the periphery of the forward shield to hold the forward shield in place so the cutter discs on the cutterhead follow the same concentric circles or 'Kerf' for each rotation (see Figure 6).

Figure 6. Example of the cutterhead "kerf" or cutting pattern

The forward shield is attached to one end of a set of thrust cylinders that provide the force necessary to push the cutterhead into the rock. The other end of the cylinder is attached to the gripper shield. Between them is a telescopic shield comprised of two overlapping shields, an inner shield and outer shield. These shields telescope, one over the other, as the thrust cylinders are extended. This provides worker and equipment protection from rock falls.

To prevent the telescopic shield from 'rolling' relative to the forward shield, large and short stroke torque cylinders are attached to torque arms. The torque arms are a pair of heavy steel plate weldments. One end is mounted to the rear side of the forward shield, and the other end to a robust rear bulkhead on the gripper shield. The gap between these torque arms is filled with a torque cylinder – one on each side of the machine belt conveyor - which basically runs through the center of the machine. The operator adjusts the pressure on these cylinders to keep the machine on a level plane.

The rear bulkhead of the telescopic shield is mounted to the gripper shield assembly. This shield contains a set of horizontally aligned gripper pads (one on each side of the TBM) that are contoured to match the bore diameter. Gripper cylinders are mounted to each pad and extend both pads onto the bored tunnel wall when the cutterhead is rotating and the thrust cylinders are extending to counteract cutterhead torque and prevent the complete TBM from rolling.

The tail shield assembly is attached to the gripper shield. It contains platforms for roof drills (Figure 7), roof support, and auxiliary thrust cylinders. If the geology changes from competent rock, where no ground support is needed, to blocky or fractured rock, the contractor will have to install steel ring beams and boards or wire mesh. The ring sets must be built with a 1-inch thick flat bar section along the bottom 90° of the ring set to allow the TBM back-up assembly room to pass through the ground support. If the grippers are rendered ineffective by soft rock conditions, the telescopic and gripper shields can be reset by the auxiliary thrust cylinders.

Figure 7. View of roof drill and work platform

The TBM has a rolling back-up system comprised of five rolling decks and seven skids. All electrical and hydraulic TBM support systems, including the operator's cab, are located on the rolling decks. The back-up skids primarily support the TBM spoil transfer belt conveyor but also contain space to store the main power feeder cable and the tunnel ventilation duct storage cassette. The back-up skids allow room or length for a muck train to accept two pushes of spoil, or approximately 2.5 m of advance per mucking cycle.

Due to strict environmental oversight by the City of Montreal, ForAction (Les Entreprises Michaudville inc.) used only bio-degradable oil for all lubrication and hydraulic fluids in case an accidental spill occurred.

To steer the TBM along the tunnel alignment, an automatic guidance system was provided by the TBM supplier.

To provide fresh air to the working area around the TBM, ForAction used an Ø800mm bagline to pump fresh air from the starter shaft and small intermediate shaft to the heading. The TBM included ventilation ducts and axial fans to provide fresh air supply at all times. Dust from the cutterhead and spoil conveyors was sucked into a separate set of air ducts and diverted to an air scrubber to remove dust particles from the air behind the TBM.

4 TUNNEL ADVANCEMENT: DECEMBER 2014 TO NOVEMBER 2015

4.1 Scheduling

The contractor Foraction had plans to run two 9-hour shifts on the TBM with a third 6-hour maintenance shift in the middle of the night, 5 days per week, and so they did. The average advancement projected was on the order of 20 linear metres a day.

After a few days of trial runs in December 2014, they began as planned. The first month proved to be one of shake-down and adjustments to the conditions. Production was slower than optimal as only a few metres a day were achieved (up to 10 metres/day) in near-ideal rock conditions. This was expected.

By February, all was running well, with an average 21,8 metres/day, with two or three days just below 30 metres/day. The production in March was very good, with an average rate of 23.9 metres/day, with a few days above 30 m/day, until the end of the month, when a break at the head of the conveyor slowed the progress. The TBM ran for three weeks in April including several days between 30 and 40 metres/day. The month of May was a full run and averaged nearly 24 metres/day. By early June, the tunnel is at the 1.8 km mark and this is where the geological factors start intervening in the process.

The rest of the journey was a little more challenging, with fault zones, excessive groundwater inflows, bedrock anisotropy providing uneven rock resistance, and a short-term deviation from the course. Success was finally achieved on schedule, before year end. After the slow-down of June, it was decided that, in order to meet the deadlines, a sixth day (one shift) had to be added to the weekly schedule. With a record setting October (a 700-metre sprint), the TBM reached its end shaft, bull-eye, on November 12, 2015 (see Figure 8).
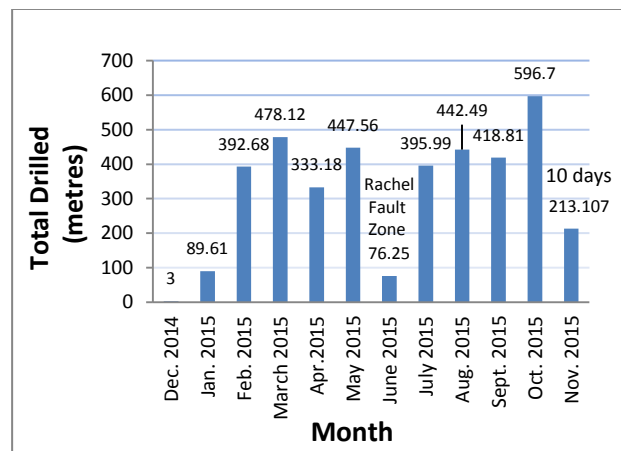
Figure 8. Monthly advance rate data

4.2 In-Situ Reality Check: Hard Rock, Soft Rock, Faults, and Groundwater

The geological interpretation along the proposed tunnel route contained in the geotechnical investigation proved to be surprisingly accurate, but a few questionable zones remained unknown despite recommendations for further investigation. However, even with further investigation of the suspected fault zones, it would be hard to accurately predict how the rock mass, competent or not, could behave and hold together during the passage of the TBM. Some precautions could be taken, but despite prior investigatory boreholes every 60 to 80 metres along the proposed tunnel course, what could happen between the boreholes was still an unknown. Adapting to these unforeseen conditions was what Foraction did with success.

There were several questions left unanswered by the time the TBM was launched: How did the large 8 to 10 metres-thick sill observed above the tunnel profile disappear so abruptly from the map? What is the in-situ condition of the rock, in the suspected fault zones? Could we face over-break of the crown? How wide are the fault zones? How much groundwater are we going to encounter? What is the quality of the rock below the quarries? Are there any deep fractures leading to contaminated waste water seepage?

All of the above unknowns were faced and successfully overcome. The contractor was able to navigate these zones despite the varying rock strengths and unpredictable nature. Even with geologic challenges including some water inflows and over-break in small sections, the contractor was able to achieve advance rates averaging 20 m up to 38 m per day in two shifts of 9 hours each. Much of the ground was self-supporting, though the contractor installed rock bolts every 2.5 m (8.2 ft) into portions of the tunnel crown, while mesh, rock bolts, and steel sheets were used in the sections of unstable rock.

Regular bi-monthly visits from a geological engineer to check the rock bolting and other support techniques when necessary was essential, and having a geologist full-time on-site was no luxury. The geologist made daily visits, often more than once, to the front of the TBM to observe any change in the nature of rock, its structure, fissure patterns, groundwater inflows and so forth. A very good clue to any lithological change was the constant observation of the muck pile coming to the surface. Any change in its usual characteristics, such as the fragments, shape, size, color hardness and water content of the muck would raise a flag and signify to the geologist that the cutterhead was entering a different lithology. The contractor had the muck cars raised to the surface and piled up near the shaft. When traversing the principal limestone formation, the muck was composed principally of flat and elongated limestone pieces 2 to 10 cm in diameter with a proportion of fines. When a different rock body or structure was bored, the muck would change. This granted a visit to the front by the geologist. As the saying goes, "You can`t excavate a tunnel in rock without a geologist". This proved many times to be true.

The first fault zone located at approximately 1,900 meters into the tunnel, was the toughest one to navigate through. It involved a section of the large sill, which seemed

to "slip" downward into a normal fault. It is quite probable that the huge fallen block partly fractured the less resistant layered limestone beneath it, which had recrystallized afterwards but rather weakly with a calcite cement. The result: the force of the TBM through the nearly 30 metre long fault helped to create a major over-break and the collapse of approximately 1.5 metre in the crown, once past the intrusive block. The once-hard limestone was reduced to sand or fine gravel-size debris. The TBM was stuck in that zone for a couple weeks since it could not grip the tunnel wall. There was also a large water inflow from the south end of the fault that made all operations difficult. Finally, the crew was able to push the TBM through the zone a quarter push at a time, and secure the cavern with deep rock bolts as well as several layers of wire mesh. Once the entire TBM convoy was through this zone, the area was secured with a temporary steel rib system, later replaced by two layers of shotcrete.

Most of the fault zones gave a warning: a sudden change in the bedding angle, groundwater infiltration through fissures, increased joint frequency and increased random calcite veining, etc. The other suspected faults were encountered where expected. The contractor went through more successfully by carefully regulating the controls on the TBM, passing through at much lower speed.

The passage below the old quarries also offered its own challenge. After much of the rock was extracted from the quarries, they were later used as municipal waste landfills and contained both industrial and domestic waste. Some of the leachate from the landfill slowly infiltrated rock fissures in the fault zone located just south of the quarries and found itself in the tunnel. Fortunately, despite former blasting activity, the bedrock directly below the larger quarry was in excellent condition at the tunnel elevation and leakage was prevented, except for the early boreholes from the first investigation, which had remained open and provided a fast and easy way for the leachate to make its way into the tunnel. These were plugged as soon as practically feasible.

Groundwater forced its way another time into the tunnel when the TBM crossed a sector beneath an area between two ancient quarries. Despite having randomly drilled and grout-injected the area previously, an underground fracture in a minor fault zone was open and a water stream with the force of a fully open fire hose forcefully penetrated the tunnel, provoking another slowdown.

The boring rate was also influenced by the heterogeneity of the rock inside the tunnel diameter. A TBM will tend to push itself towards the path of least resistance, or may try to "ride" parallel to a strong crystalline limestone bedding surface. The crew had to manually exercise precise controls on the cutter discs in several instances when a hard igneous sill or dike would run semi- parallel but occur in only one half or side of the tunnel leaving the other half to much softer sedimentary rock.

Slowdown also occurred when a particularly argillaceous limestone facies was prominent. Hard consistent rock is somewhat easier to bore through than soft shaly rock, particularly when water is needed on the cuttehead. Water and shale produce mud, which would more often than not produce cause for a cleaning of the disc cutters, not to mention the difficulty of eliminating the fluid brought to the surface.

As for the human side, noise complaints from residents were numerous. Even at 40 metres below the surface, people inside their residences and work places could hear the slow progress of the TBM, and the starts and stops between the pushes. The noise of the cutters making their way through the rock could be heard inside building walls, particularly when the building foundations were sitting directly on the bedrock. A muffled "grinding" sound was heard mostly at the approach of the TBM, up to 50 metres before the machine reached the actual building location. When directly underneath and once passed, nothing was heard. The City of Montreal's communications department was well-prepared and citizens were well informed at least a week ahead of the arrival of the TBM below their residence. Each complainant was responded to and most were satisfied. A couple days of noise is a small price to pay, when compared to the inconvenience of several months of surface excavation. A local neighbourhood newspaper produced a centrefold article which simply described, in layman terms, everything the population needed to see to feel well-informed.

5   CONCLUDING TUNNELING

The TBM broke through November 12, 2015 at a large ceremony attended by the mayor of Montreal (see Figure 9). Less than 24 hours following the tunnel breakthrough, the contractor formed crews to various tasks: one for dismantling the cutter head at the end shaft, another team started pulling the conveyors and other pieces of equipment, and another team was power washing the tunnel wall with high-pressure water and removing and replacing the rail. The cleaning was essential to assure good adhesion of the grouting cement once the concrete pipes were inserted.

Figure 9. TBM breakthrough in November 2015

While all this was happening, the geologist began a survey and flow measurement or estimation of all the water inflows in the tunnel. The detailed geological mapping that

began closely behind the cleaning crew was essential for understanding the major structural systems in place below Montreal. The large amount of information recovered from the mapping undoubtedly constitutes a useful database for any future deep rock excavation in the Montréal metropolitan area.

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