Design and Construction of the Montreal Largest Transit System

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ABSTRACT: Once completed, the Montreal Réseau Express Métropolitain (REM) will be the fourth largest automated transportation system in the world. The REM represents the largest transportation infrastructure in the region since the Montreal metro inaugurated in 1966. The proposed solution fosters environmentally sustainable transportation and represents a construction cost of approximately 7.0 billion Canadian dollars. The project consists of 67 km over four branches of twin track and includes 26 stations with 3 underground stations in downtown Montreal. One of the underground stations was built using the NATM method with thin permanent shotcrete initial and final liners separated by a sprayed on waterproofing membrane. The project also includes the rehabilitation and enlargement of the 100-year-old double track Mont Royal Tunnel which is about 5 km long. The REM also consists of 3.6 km new TBM tunnel connecting downtown to the Montreal International Airport through saturated soft ground and karstic rock.

Keywords: TBM Tunnel, NATM Station, Deep Shaft, Tunnel Rehabilitation, Shotcrete Permanent Liner.

1 INTRODUCTION

The Réseau Express Métropolitain (REM) is an electric and fully automated, light-rail transit network designed to facilitate mobility across the Greater Montreal Region in Canada (Nasri et al. 2022). This new transit network will be linking downtown Montreal, South Shore, West Island, North Shore and the airport (Figure 1). The REM system will connect with existing bus networks, commuter trains and three lines of the Montréal metro (subway).

The project is currently under construction by a joint venture of SNC Lavalin, AECON, Dragados, EBC, and Pomerleau and the final design was performed by a joint venture of SNC Lavalin and AECOM. Its construction will be completed at the end of 2024. To deliver this major project, several underground works are undertaken. This paper presents the major underground developments of the REM and the solutions used for the successful achievement of the underground construction objectives which include ensuring safety and stability of the opening during construction and for its full-service lifetime, minimizing impact and disturbance to the surrounding environment, meeting

Owner's technical requirements, and minimizing cost, duration, and risk of underground construction.

2 GEOLOGICAL CONTEXT

Montreal geology consists of a variety of sedimentary horizons dating from the Precambrien, Cambrien and Ordovicien periods. The main associated lithologies are limestone and shale. Intrusive rocks dating from the Mesozoic/Cretaceous period are also encountered throughout Montreal, intersecting the sedimentary packages.

The strata are generally relatively sub-horizontal layers of sedimentary rock. However, events such as faulting, folding, glaciation and isostatic movement have shaped the strata differently in certain region of the island. Faults are generally considered inactive in the region.

Solutions that were put forth for the successful completion of the REM underground works were selected to best match project constraints and local ground conditions. Located in different parts of the city, intersecting different strata, a total of four different types of underground works are undertaken.

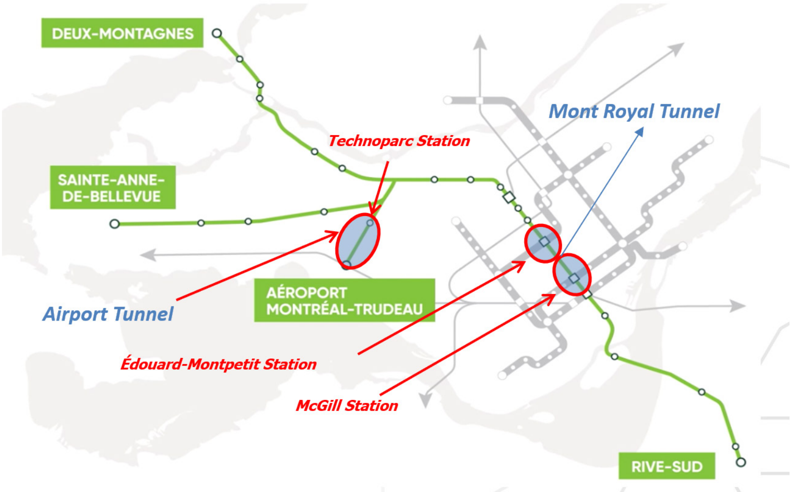

Figure 1. Map of the REM corridor / branches.

3 UNDERGROUND DEEP STATION

To connect the deeply sitting REM track to an existing metro station located closer to the surface, an underground station accessible by an approximately 70 m deep vertical shaft was designed using NATM (Edouard Montpetit Station, EMP). Figure 2 shows the 3D model of the station with the main entrance shaft, the side platforms constructed by enlarging the existing Mont Royal Tunnel, concourse tunnel, ventilation tunnels and shafts and vertical circulation tunnels and shafts (Nasri 2021). Figure 3 shows the excavation of the main entrance shaft and tunnels. This station configuration was optimized to minimize the rock excavation volume. With practically no overburden present in the area, the interchange station is almost entirely located within the Trenton formation which consists of interbedded limestone/shale packages and argillaceous limestone. The station is also located near the intrusive Mont Royal formation which consists of gabbro, monzonite, and breccia, resulting in a significant number of hard dikes and sills in the area.

In this area, probably resulting from the contact metamorphism due to the proximity of the Mont Royal intrusive, the sedimentary rock package shows hard rock properties, with uniaxial compressive strength (UCS) varying between 125 and 180 MPa and Young's modulus varying between 75 and 88 GPa. Because of the nature of the work, the quality of the rock and the lower initial cost of the technique, controlled drill and blast method was selected to sink the deep vertical shaft and excavate the underground station.

The excavation took place in a densely populated area with major infrastructure in the near vicinity. Among those infrastructures is one of the main University of Montreal pavilions. This building houses classrooms and laboratories including a recently completed state of the art and highly sensitive acoustic laboratory located within only a few meters of the excavation. Hence, several engineering control mechanisms were put in place to minimize impact and disturbance including line drilling technique along the full entrance shaft excavation perimeter and for its entire depth, use of a maximum blast round length of 2.5 m, blasting sequences and patterns designed for low impact (specific blast hole, loading and delay patterns). The line drilling was performed using a DTH drill with the holes diameter of 140 mm placed at 250 mm center to center. The holes center is put at 200 mm from the excavation line to account for the vertical deviation of the drilling operation. To complement this effort, a comprehensive monitoring plan, counting over 150 instruments, was used.

Permanent CT bolts and shotcrete reinforced with steel fiber (Dramix 3D) were used as both initial and final liners for all shafts and tunnels. A layer of 5 cm of flashcrete was applied first for safety, the bolts were installed, spray on waterproofing membrane (BASF Masterseal 345) was added, and then another 5 cm of steel fiber reinforced shotcrete was applied. The liner was designed for a 125-year service life per the contract requirements. During development of the underground excavation, rock mapping was undertaken after each exposure of the final wall. Permanent rock bolting pattern was adjusted based on the ground condition and the need for additional rock bolting was assessed on site to ensure the overall stability of the excavation. In addition to durability, the shotcrete mix was designed specifically for the cold weather application in Montreal. By using the drained concept, a thin layer of fiber reinforced shotcrete for initial and final liner, permanent bolts and spray-on membrane significant reduction in the station cost, schedule and carbon footprint was achieved. Figure 4 shows the side platform enlargement of the existing MRT allowing one track to remain in operation.

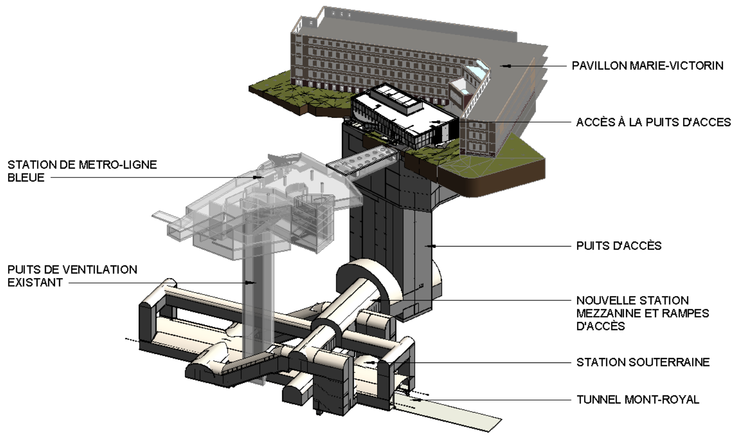

Figure 2. 3D model of the EMP deep station.

Figure 3. Excavation of EMP Station entrance shaft and tunnels.

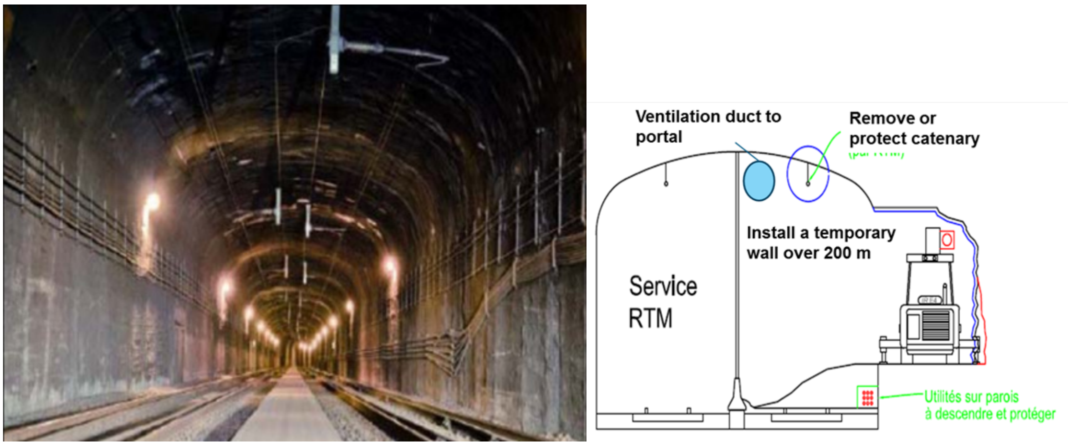

Figure 4. Enlargement of MRT to EMP Station side platforms.

4 MONT ROYAL TUNNEL REHABILITATION

The Mont Royal Tunnel is a railway tunnel in operation since 1918, third longest in Canada, which connects the city's Central Station (Gare Centrale), located Downtown Montreal, with the north side of the Island of Montreal and Laval, passing through Mount Royal (Figure 5). The REM project used this existing double track horseshoe tunnel (5060 m long, 9.6 m wide and 4.4 m high, and a constant 0.6% grade) and two of the project stations were built inside this tunnel by enlarging it from a double track tunnel to side platform station at the location of these stations. To accommodate the new track system and to ensure the tunnel is to current safety standards complying with NFPA 130 fire life safety requirements, the existing tunnel conditions were assessed. Various solutions including the installation of a center wall and boring a parallel egress tunnel on one side of the existing tunnel and connected to the existing tunnel through cross passages at regular spacing were evaluated. Adding a center wall to the existing double track tunnel was selected as the preferred solution.

To accurately evaluate the current conditions and define the tunnel enlargement needs based on the new train envelops, a high-resolution laser and optic scanning was performed by Dibit. Using this information, the current conditions of the existing tunnel and accurate clash analyses and interfaces requirements assessment was performed. Results from such analyses were used for the development of the optimal solution to minimize the volume of enlargement excavation.

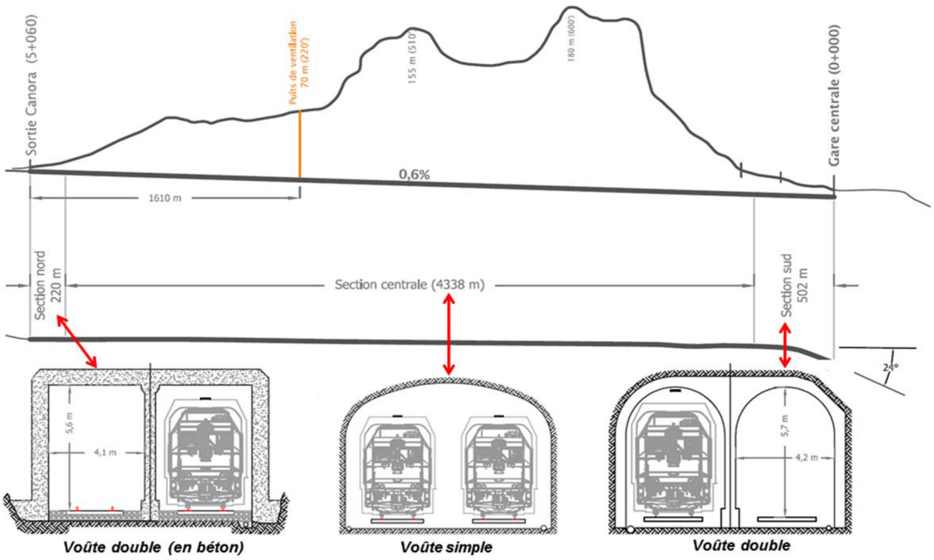

Figure 5. Existing Mont Royal Tunnel.

5 CUT AND COVER STATIONS

To connect the financial district of Montreal to the REM tracks located approximately 15 m below grade, a major station was planned on McGill Avenue (Figure 6). In this area, due to previous underground works for building the MRT and the Montreal Metro Green Line, the first 15 m of ground consists of backfill. The rock located below this layer of backfill was observed to belong to the Tétrauville formation, which consists of an interbedded limestone/shaly limestone.

Given the local stratigraphic column and low water table, the soldier piles and lagging wall solution was selected as the support of excavation for this station. Drilled soldier piles were socketed into the rock and steel fiber reinforced shotcrete were used for the lagging. The soldier piles and shotcrete lagging support of excavation walls were considered as the permanent station walls. Once the rock is reached, controlled drill and blast took place to cut the rock to the design level.

The station is located between two major high-rise buildings and is connected to shopping centers inside these buildings. An existing underground commercial passageway connecting these two high-rise buildings is just above the station and were kept in place during the station construction. The station is at the intersection of McGill Avenue with two of the most important streets in Montreal and therefore the maintenance of traffic and utility relocation were among the main challenges of this station construction. In addition, the site limits of this station were at the edge of the adjacent buildings and the existing metro tunnel and therefore robust design of support of excavation in soil, controlled drill and blast in rock, and comprehensive instrumentation and monitoring program were required to prevent damage to the neighboring structures (Ramirez et al. 2022).

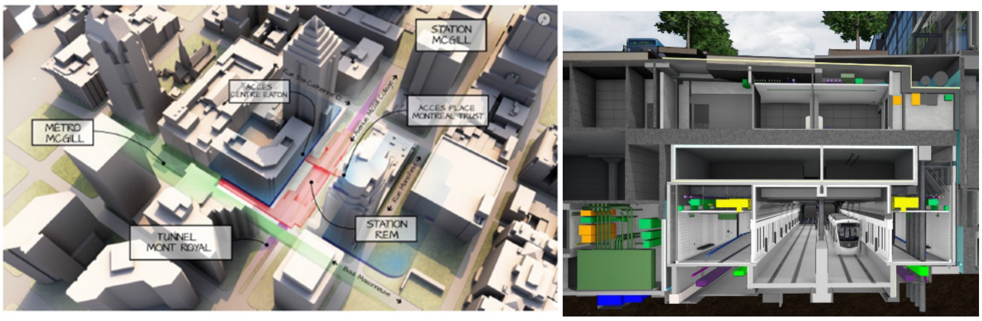

Figure 6. McGill Station in Montreal Financial District.

The Technoparc Station, located at the northeast corner of Alfred-Nobel Boulevard and Albert-Einstein Street, is an underground station on the Airport branch. A method of construction using secant piles for the sidewalls was selected for this station that serves as both temporary and permanent support of the excavation (Figure 7). Wide-flange permanent roof beams act as struts during excavation. This method was used for the approach ramp, the cut-and-cover tunnel, and the Station. The secant piles were drilled to rock and socketed into it. The excavation was drained during the construction and the final structures were tied down to the bedrock for buoyancy control during the permanent condition. 0.5% verticality was assumed for the construction tolerance of the piles.

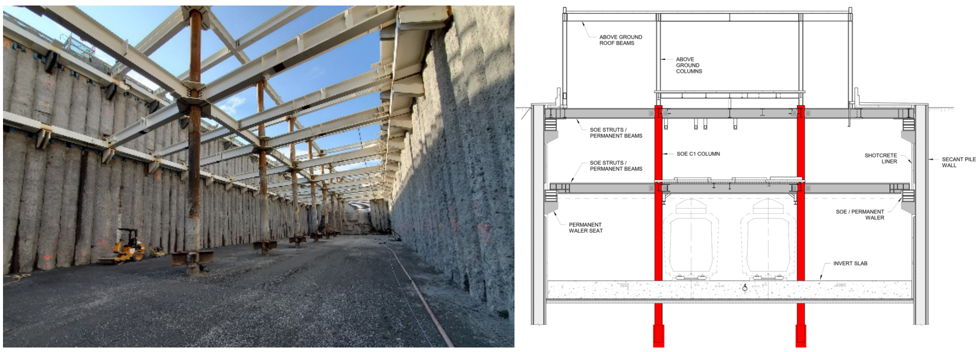

Figure 7. Permanent secant pile at Technoparc Station on the Airport Branch (Lee et al. 2022).

6 AIRPORT TUNNEL

The REM connects downtown Montreal to the airport, requiring the development of an entirely new tunnel that runs below the international airport airstrips. The overall underground stretch consists of approximately 3.6 km. Along the tunnel alignment, bedrock elevation varies significantly, and a constant grade is observed at surface, resulting in a varying overburden thickness. The overburden consists of layers of backfill, granular material and glacial till, going from grade to bedrock. The bedrock consists of interbedded limestone/shaly limestone, belonging to two different formations: the Tétrauville formation and the Montreal formation.

Within the Tétrauville formation, two different members are expected to be intersected by the underground works. The upper horizon would consist of a good quality micritic shale with UCS values varying between 75 and 185 MPa, and Cherchar abrasivity index varying between 0.8 and 1.8. The lower horizon would consist of softer shaly limestone with UCS values varying between 60 and 80 MPa, and Cherchar abrasivity index varying between 0.3 and 0.6. Within the Montreal formation, only the Rosemont member is expected to be intersected. This member is expected to be of good quality with UCS values varying between 55 and 145 MPa, and Cherchar abrasivity index varying between 0.8 and 1.8.

Given the significant constraints related to developing a tunnel underneath an international airstrip, the main portion of the underground works were performed using a hybrid TBM. From the surface, the REM starts its descent and enters a cut and cover underground station (Technoparc Station). Heading out of the station, the cut and cover portion continues and widens to serve as the TBM launch pit.

The hybrid TBM was launched in the overburden material and continued its descent and progress in this material for about 300 m. The ground was improved at the break-out over the first 10 m of the drive to allow watertightness and TBM control at the launch. Once the TBM reached the bedrock, it continued its descent over a course of about 300 m, down to 40 m below grade. From there, it progressed at this constant elevation, totalizing approximately 2.7 km of excavation within the rock. The hybrid TBM was able to progress within the overburden loose material in Earth Pressure Balance (EPB) mode and in open mode during its progression through competent rock.

As the TBM was advancing, precast segmental lining was installed, ensuring the stability of the opening and the safe development of the tunnel. Routine probing ahead of the face was also performed to assess ground mechanical and hydraulic conditions prior to advancement. Depending on ground conditions, pre-excavation grouting performed ahead of the face was required to improve mechanical and hydraulic properties of the ground before the TBM excavation.

CONCLUSION

This paper presents the design and construction aspects of the underground elements of the REM mega project in Montreal. It discusses the details of one of the underground stations built using the NATM method. It also explains the rehabilitation and enlargement of the existing Mont Royal Tunnel and the construction of the airport TBM tunnel. Several innovative and cost-effective design and construction methods used for the REM project were discussed in this paper.

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