Design and Construction of the Deepest North American Underground Station - Station Édouard-Monpetit, Montreal, Canada

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ABSTRACT: With the increased need for public transportation in densely populated areas, new transit projects start including more and more interstations and tunnel rework. To facilitate mobility across the Greater Montreal Region (Canada), The Réseau Express Métropolitain (REM) includes a deep underground station which connects the deeply sitting reworked tracks to the University campus located above. The tracks being located at approximately 70 m below surface, the Édouard-Montpetit station is expected to be the deepest in North America, surpassing the famous Forest Glen Station. This paper will present the design and construction of this deep underground station and the various challenges and solutions put forth for its successful completion. The objective of this paper is to serve as a valuable example for future deep excavation performed in urban area, in the close vicinity of highly sensitive structures.

KEYWORDS: Tunneling, Deep Excavation, Hard Rock, Underground space, Durability

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 (Canada). This new transit network will be linking downtown Montreal, South Shore, West Island, North Shore and the airport.

Spanning over 67 kilometers once completed, the REM will be one of the largest automated transportation systems in the world after Singapore, Dubai and Vancouver (Nasri, 2019). The REM system will connect with existing bus networks, commuter trains and three lines of the Montréal metro (subway).

To deliver this major design-build project, several underground works are undertaken. One of the major and challenging underground works of this project is the Édouard-Montpetit Station. The Édouard-Monpetit Station is an interchange station that will connect the deeply sitting REM tracks laid within the century old existing Mont-Royal tunnel to the existing metro station of the same name located closer to the surface.

The tracks being located at approximately 70 m below surface, the Édouard-Montpetit station will be the deepest in North America, surpassing the famous Forest Glen Station. This paper will present some components of the design and construction of this deep underground station and the various challenges and solutions put forth for its successful completion.

2. CONTEXT

2.1 Localisation and project description

In the area of interest, the REM tracks will be going from Montreal financial district to the University of Montreal campus area through an existing tunnel located underneath the Mont-Royal mountain.

To accommodate the new track system and to ensure the existing tunnel will be brought to current safety standards, the existing tunnel conditions were assessed. To accurately evaluate the current conditions and define the underground work needs, a high resolution DIBIT scan was performed. Using this information, accurate clash analyses and interfaces requirements assessment were performed. Results from such analyses were used for the development of the optimal solution. Various solutions including the division of the tunnel in two by adding a center wall or the development of a parallel egress tunnel were evaluated.

The Edouard-Montpetit Station was designed to be aligned with this existing Mont-Royal tunnel to connect to Montreal's subway blue line station of the same name, linking the University campus with the network at the intersection of Vincent D'Indy Avenue and Édouard-Montpetit Boulevard. At this intersection, the REM tracks are at an approximate depth of 70 m below surface.

Figure 1 shows the architecture of the Edouard-Montpetit Station at depth as well as the surrounding underground infrastructures. The station is located within a densely populated area, in the close vicinity of major sensitive infrastructures, resulting in major constraints including design and urban integration, smoke control management, connection to existing infrastructures, complex passenger flow analyses, reduced construction site limits and environmental impacts management (e.g., traffic, dust, noise, vibration control).

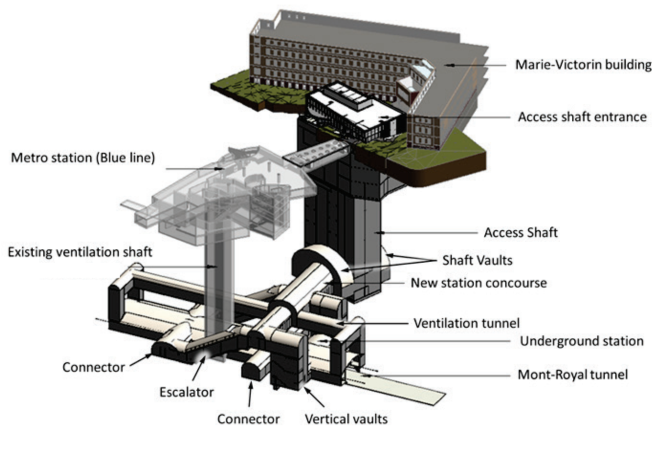

Figure 1 Edouard-Montpetit Station

2.2 Geological Setting

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 layers.

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. Figure 2 shows the geological map of

Montreal, after Clark (1972). The approximate trajectory of the REM is also projected onto the map, for reference.

The various major faults that were mapped in the region can also be identified in Figure 2. Different orientation can be seen, but the main fault system has an Est-West trending orientation. Faults in Montreal are characterized by fractured rock zones of centimeters to hundreds of meters. Faults are generally considered inactive in the region.

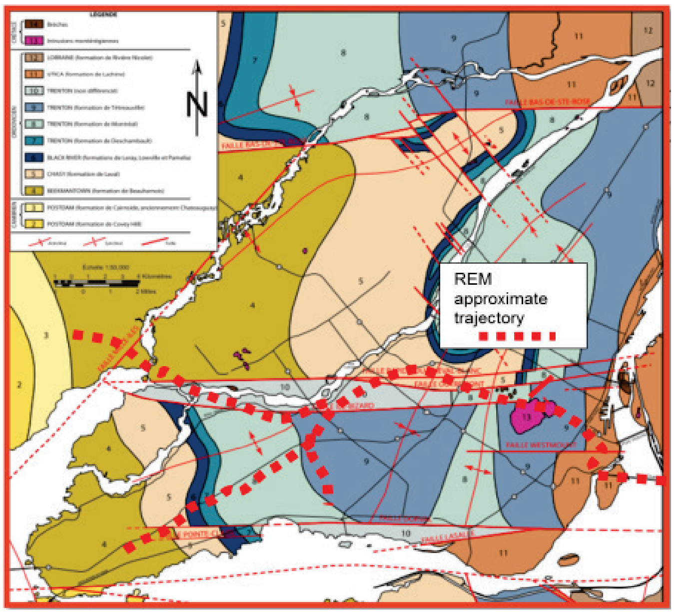

Figure 2 Montreal regional geology (after Clark, 1972)

With almost no overburden present in the area, the Edouard-Montpetit interchange station is almost entirely located within the Trenton formation which consists of interbedded limestone/shale packages and argiliceous limestone. The station is also located near the intrusive Mont-Royal which consists of gabbros, monzonite and breccias, resulting in a significant amount of hard dikes and sills in the area of interest.

In this particular area, probably resulting from the contact metamorphism due to the close 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.

3. DESIGN

The station is designed for a 125 years life span and considering a passenger load superior to 6000 passengers during the 3 hours peak period. Also, the station located below grade is to be accessible by elevators only, while being designed to ensure safe and timely evacuation in case of an emergency.

The design was developed for the successful achievement of the following objectives:

- Ensuring safety and stability of the opening during construction,
- Ensuring safety and stability of the opening for its full service lifetime,
- Minimizing impact and disturbances to the surrounding structures,
- Meeting Owner's requirements,
- Minimizing cost, duration and risk of construction.

The main design constraints and driving components of the design are presented in the following sections.

3.1 Station Architecture

The urban integration of the station is ensured through a signature architectural design. The underground station will be accessed by high speed elevators through an entrance connecting the street access and the metro line access. The entrance will be defined by a clear transparent volume, which creates a strong relation between the entrance and its setting, maintaining a clear visual axis between the street and the existing surrounding building.

The station will be located near the tracks, at depth, and will be accessible through highspeed elevators which will be located within the access shaft. In addition to the deep excavated tunnels and shafts challenges, the main components influencing and governing the overall design and underground space of the station are the passenger flow requirements and the tunnel ventilation system and philosophy.

To adequately and efficiently design the station, the entire design was developed using Building Information Modeling (BIM), allowing continuous optimization and clash detection where over 11 engineering disciplines were working on the design of the station. Figure 3 shows the multidisciplinary application of BIM in the design of Edouard-Montpetit Station.

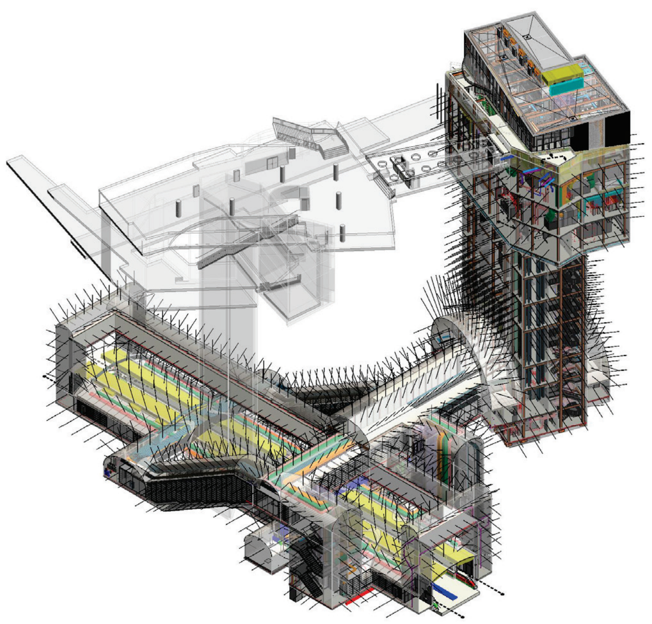

Figure 3 Edouard-Montpetit Station Multidisciplinary BIM Model

3.2 Ventilation

In addition to creating a direct and fluid intermodal access between the subway line and the REM, the Edouard-Montpetit Station will serve as a ventilation plant for the Mont-Royal tunnel in case of an emergency and for operational purposes.

In this particular configuration, the Edouard-Montpetit Station is used as a fan plant to operate in pull, push or pull-push mode to generate a longitudinal flow along the existing Mont-Royal tunnel. The project technical requirements asks for a mechanical longitudinal ventilation system be provided in order to sweep the smoke and heat from a tunnel fire along the existing Mont-Royal tunnel to one side of the fire and maintain tenable environment as defined by NFPA 130 on the other side of the fire, where the tunnel occupants will be evacuating the tunnel, making the Edouard-Montpetit Station a potential emergency exit.

The longitudinal ventilation system was designed to provide sufficient air quantity to produce the Critical Velocity upstream of the fire to prevent back layering of smoke over the top of the evacuating tunnel occupants. Based on formulas provided by NFPA 130, the quantity of air to generate the Critical Velocity for the REM Mont-Royal tunnel was calculated to be 130 m^3/s. This airflow is provided by fan plants in stations at the end of each tunnel segment, i.e. station Edouard-Montpetit.

3.3 Passenger Flow

As mentioned earlier, the station is expected to be a high traffic station with a passenger load superior to 6,000 passengers during the 3 hours peak period. In addition, the station will be accessible by elevators only during regular service, requiring a significant additional amount of analyses to be carried out to identify the elevators specifications in terms of capacity, speed, doors opening, and acceleration, to ensure all passenger flow requirements are met.

These various constraints make the passenger flow requirements and analyses a critical item in the design of the station. An iterative process was put forth to make sure that the various passenger flow requirements were met as the station design was being optimized. The basic steps of this process are described below.

First, a static analysis is carried out to determine the global dimensions of the station that are required. Second, congestion zones are investigated in terms of location and required flow and the zones are being optimized. Third, a sensitivity analysis is carried out considering a missed headway. Finally, an emergency exit scenario is performed to ensure the safe exit of all passengers in a timely manner can be ensured.

3.4 Excavation and Support

Because of the nature of the work, the quality of the rock and the lower initial cost of the method, controlled drill and blast technique was selected to sink the deep vertical shaft and excavate the underground station.

The excavation takes place in a densely populated area with major infrastructure in the near vicinity. Among those infrastructures can be found the highly sensitive University of Montreal acoustic laboratory located within meters of the excavation at shallow depth. Hence, several engineering controls are put in place to minimize impacts and disturbances (Sepehrmanesh, 2014), including:

- line drilling technique,
- definition of a maximum round length of 3 m,
- blasting sequences and patterns designed for low impact (specific blast hole, loading and delay patterns).

To complement this effort, a comprehensive monitoring plan, counting over 150 monitoring instruments, is designed.

During development of the underground work, rock mapping is undertaken after each exposure of the final excavation wall. Permanent rock bolting patterns dependent on the ground conditions are put in place and the need for additional rock bolting is assessed on site to ensure the overall stability of the excavation.

Prior to bolting, a first layer of 5 cm of steel fiber reinforced shotcrete designed specifically for cold Montreal temperature is sprayed onto the rock. The rock bolts are installed on top of this first layer. This layer of shotcrete and the bolts represent the initial support.

Once the rock bolts are installed, a spray on waterproofing membrane is applied on top of this first shotcrete layer and the rock bolts end hardware. This is later covered by an additional 5 cm of steel fiber reinforced shotcrete. Figure 4 shows the details of the initial liner bolt and shotcrete, spray on waterproofing membrane and the shotcrete final liner.

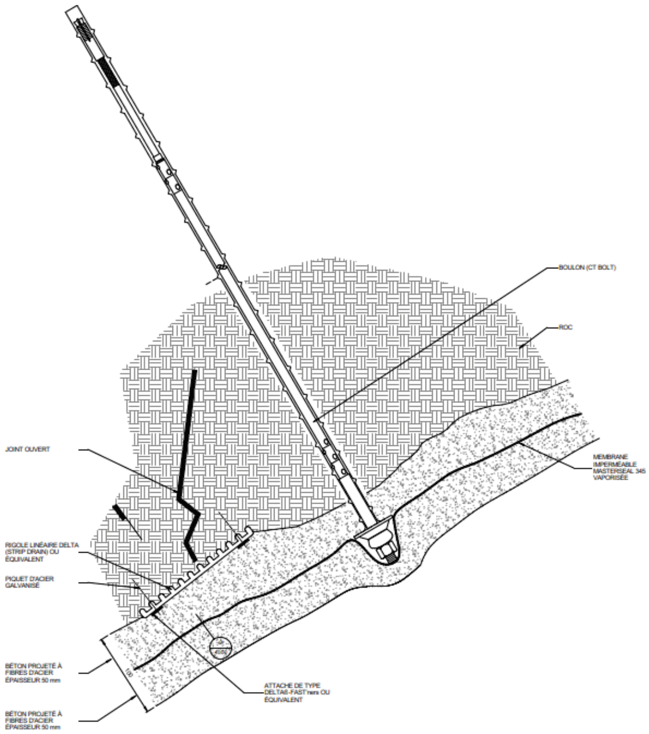

Figure 4 Initial and Final Liner System

With the spray on waterproofing membrane, the designed support system represents both the initial and the final liner. This configuration was first used in North America for a pump station cavern in Indianapolis, but it is the first time this approach is used for a major transit station in North America.

The advantages of this configuration are numerous both in terms of design and constructability in comparison to the typical approach which would consists of an initial temporary support, a sheet membrane and a permanent final liner.

Effectively, using the spray on waterproofing membrane aims considering the initial liner which would typically be considered only as temporary support as both temporary and permanent as this configuration allows load transfer from the initial lining to the final lining, reducing the overall lining thickness when compared to the typical design.

In terms of constructability, the use of a sprayed on waterproofing membrane instead of the typical sheet membrane represents labour saving, less logistic and is much easier to work with particularly where the excavation shape configuration varies. However, it should be noted that the current spray on membrane is not well suited for the cases with high water inflow and large water head.

3.5 Durability

Durability has always been a critical factor in transit systems permanent structures design. As mentioned earlier, the requirement for this specific project was of 125 years life span. Hence, all materials used as part of the permanent structure and lining had to be selected or designed accordingly.

As shown in the previous section, the structural elements used for Edouard-Montpetit Station include rock bolts, steel fiber reinforced shotcrete for both initial and final lining and spray on waterproofing membrane.

3.5.1 Rock bolts

Durability of the rock bolt is ensured by the use of CombiCoat® protected CT-bolts, as manufactured by Vik Ørsta. The main degradation mechanism for rock bolts is corrosion, against which the protective properties of the CombiCoat® coating system are:

- Hot dip galvanizing,
- Phosphating,
- Epoxy powder coating.

In addition of having these various protective layers, the rock bolts will be fully grouted which means they are not expected to be exposed to oxygen. In terms of durability, these fully grouted CombiCoat® CT-bolts are designed to last at least 150 years as estimated by the research group SINTEF in 2016.

3.5.2 Steel Fiber Reinforced Shotcrete

The steel fiber reinforced shotcrete main degradation mechanisms include:

- Corrosion of the steel fiber, mainly by the effect of carbonation and the ingress of chlorides,
- Sulfides attack,
- Acids attack,
- Granular alkali reaction,
- Freeze and thaw cycles.

The durability requirement of 125 years specific to this project is higher than the normative ACI or Eurocode standards. As such, the design was developed based on an exposure class type of approach.

The mix designs for this project were developed using laboratory based formulations designed to resist the different degradation mechanisms identified above.

The formulations were based on various tests as specified by Fib 34, including ASTM C1202, NT Build 492-91, ASTM C457 and AASHTO TP-95-14.

3.5.3 Spray on Waterproofing Membrane

The MASTERSEAL® 345 as manufactured by BASF was selected for this project since it has been used on numerous tunnelling projects with design service life in excess of 100 years including:

- Giswil Tunnel, Switzerland,
- MTRC Disney Tunnels, Hong Kong,
- Ash Vale, Aldershot, UK,
- Extension of Prague Metro, Czech Republic.

In addition to its inherent durable chemical composition, the key component of this membrane in terms of durability resides in the fact that it is sandwiched between two layers of steel fiber reinforced shotcrete, limiting its exposure to temperature changes or UV rays, which would be the two main degrading mechanism for this polymeric membrane.

4. CONSTRUCTION

As in all other major construction sites, safety has been always the priority in planning and executing all construction activities. From the construction point of view, the major challenges of building the Edouard-Montpetit Station were consisted of:

- Proximity of major existing facilities and structures including a subway station with the same name and on another existing and shallower subway line and a main university building housing a state-of-the-art acoustic laboratory highly sensitive to the noise and vibration resulted from various construction activities,
- Very deep Station with a platform depth of 70 m excavated by the controlled drill and blast tunnelling method,
- Very limited area available at the ground surface to locate the required equipment and facilities,
- Highly restricted levels of allowable environmental impact parameters such as noise, vibration, and dust in this very congested urban area.

4.1 Main Construction Activities

The main activities from the civil engineering point of view included: First the excavation of the rock mass by drill and blast method, followed by the spraying of a first 5 cm thick layer of steel fiber reinforced initial shotcrete liner to prevent small pieces of loose rock from falling during excavation, then the installation of permanent grouted CT-bolts of 4 m long in a 3 x 3 m pattern, then the application of a thin layer of the MASTERSEAL® 345 spray on waterproofing membrane, and finally the installation of a second 5 cm thick layer of steel fiber reinforced final shotcrete liner.

4.2 Site Location Challenges

Being situated in Outremont, one of Montreal upscale neighbourhoods, the Edouard-Montpetit Station is facing multiple challenges because of its location. The main entrance building shaft excavation is located less than 5 meters from a 100 year old utility pipe, less than 10 meters from one of the University of Montreal main buildings, less than 15 meters from the existing STM metro tunnel, and within 100 meters from an elementary school, a preschool day-care and various residential buildings. Public hearings have been taken place before the start of each major work phase to inform the citizens living in the affected area and different third parties. A high degree of transparency including the organization of a site visit for all the parties attending these hearings have allowed the construction team to limit tensions to an absolute minimum level and to ensure that the work can continue and is not interrupted by the local residents protests.

4.3 Configuration of the Site

The configuration of the site should allow for the installation of the required equipment and at the same time should provide an area for stockpiling of the muck produced during the excavation process. In this particular case, the zone for stockpiling the muck was the starting point in defining the final configuration of the site facilities. Figure 5 shows the details of the site configuration used for the construction of the Edouard-Montpetit Station.

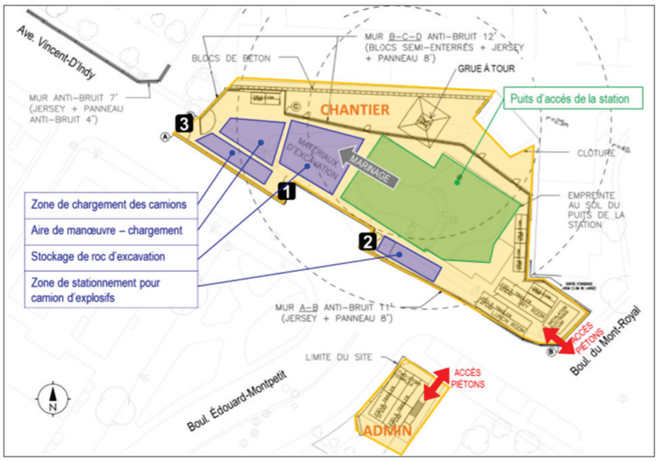

Figure 5 Construction site configuration

4.4 Preliminary Works

To minimize the vibration impact during the excavation of the Edouard-Montpetit Station main entrance shaft, it was decided to apply a controlled blasting approach using line drilling method. The vertical hole drillings of 14 cm diameter was performed at 11 cm clear distance along the entire perimeter of the main entrance shaft. This resulted in a significant reduction of the blast induced vibration and helped comply with the very strict peak particle velocity criteria specified for this particular site.

4.5 Sequence of Construction

The fact of dealing with a very deep station in combination with a very small available site area at the surface resulted in a situation where the definition of the sequence of construction was becoming one of the most important factors in achieving the planned performance.

The sequence of works for the excavation of the first 15 m of the Edouard-Monpetit Station entrance shaft after the perimeter line drilling included: drilling the blast holes, charging of explosives, installation of blast mattress, blasting, removal of blast mattress, stockpiling of muck in a place to be removed by long boom excavator, removal of muck from the bottom of excavation with a long boom excavator, loading of muck in the trucks, transportation of muck to the disposal area.

The sequence of works after arriving at the 15 m depth was changed to: drilling the blast holes, removal of equipment to the bench located at 20 m depth, charging of explosives, installation of blast mattress, blasting, removal of blast mattress, charge of muck on a skip box, removal of skip box using tower crane, loading of muck in the trucks, transportation of muck to disposal area.

The difference between these two sequences of works is because of the depth of the excavation (by long boom excavator to 15 m depth vs by tower crane from 15 m to the bottom of excavation).

Because of the importance and complexity of the works to be executed in this site, the general contractor decided to self-perform all the tasks by recruiting specialists in all required fields. Therefore, no subcontractor was used to implement these activities.

In order to maximize productivity, work was performed on the basis of 2 shifts, 24 hours a day, 5 days a week. Because of the noise and vibration control, no work between 11 PM and 6 AM was authorized. Therefore, the authorized 2 shifts were performed from 6 AM to 11 PM in order to maximize workable hours. Figure 6 shows the excavated main entrance shaft and the application of the spray on waterproofing membrane.

Figure 6 Excavation of Entrance Shaft

4.6 Winter Impact

As shown in Figure 4, the design included the application of a first layer of shotcrete prior to the installation of the permanent rock bolts. However, spraying a good quality shotcrete during the Montreal cold winter is practically not possible. To address this issue, the construction team changed the sequence of works as follows in order to be able to continue the excavation during the winter time:

From November to April: Excavation by blasting, installation of grouted permanent rock bolts, installation of a steel mesh to prevent falling of small rock pieces during excavation.

After April: At this time the weather is becoming warn enough to allow the application of shotcrete. Subsequently, after the steel mesh was removed, a large equipment was installed to spray the 3 layers of shotcrete and waterproofing as shown on Figure 4 for the excavation performed since November. Therefore, after April, the sequence of works was exactly the same as the one specified in the design.

4.7 Production Rate

As explained above, major constraints on blasting operation were imposed by the Owner through defining specific time slots to perform the blasting. This resulted in a significant loss of productivity, since the initial plan allowed to perform blasting when the site was ready and without considering any blasting time constraints. If a blasting time slot was not achieved, then the site team needed to reschedule it to the next time slot (in certain cases up to 12 hours later).

The removal of the excavated material using the tower crane was one of the critical activities, especially when the excavation was becoming deeper. This task was a controlling factor for all of the activities. If the excavated material was not removed on time, all the cycle activities including drilling, blasting, etc… was going to be delayed. Despite all these constraints, the overall planned production rate of 110 m3/day was achieved.

4.8 Key Numbers

After about 10 months of construction work at the Edouard-Montpetit Station, some of the key numbers are listed below:

- 26,000 m3 of rock excavated
- 750 rock bolts installed
- 800 m3 of shotcrete installed
- 75,000 manhours worked without accident

5. CONCLUSION

This paper discusses a case of a very deep transit station located in a dense urban area and excavated in hard rock on top of an existing 100 year old tunnel. The details of design and construction as well as their specific challenges are explained and the solutions selected to overcome these difficulties are described. Two thin layers of shotcrete combined with permanent rock bolts and a layer of spray on waterproofing membrane are used for both initial and final liner of the station shafts, tunnels, and caverns resulting in an optimized design and construction process.

4. REFERENCES

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