Tunnel Database: An Information System Useful for Underground Construction in Montreal

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ABSTRACT
The City of Montreal constructed, in a period between 1960 and 1990, nearly a hundred major tunnel structures whose work data have been collected and archived in a paper format. This data is of growing interest as many major tunnel projects are being planned or completed in Montreal. In order to make this information accessible, the City of Montreal has created a database on production and geological data of tunnels. This data processing tool facilitates decision-making during project planning, refinement of geological interpretations during geotechnical studies, statistical processing prior to the preparation of geotechnical baseline reports (GBR) and work monitoring. Several elements of underground excavation monitoring data were statistically analyzed. Project progress encountered were thus correlated with the lithostratigraphic units, structural characteristics and excavation methods employed.

RÉSUMÉ
La Ville de Montréal a réalisé, au cours de la période s'étalant de 1960 à 1990, une centaine d'ouvrages majeurs en tunnel dont les données de suivi des travaux ont été colligées et archivées en format papier. Ces données soulèvent un intérêt grandissant alors que de nombreux projets majeurs de tunnels sont en planification ou en réalisation à Montréal. Afin de rendre accessible cette information, la Ville de Montréal a réalisé une base de données portant sur les données de production et de suivis géologiques de tunnels. Cet outil informatique permet une aide à la décision lors de la planification des projets, un raffinement des interprétations géologiques lors des études géotechniques, un traitement statistique préalable à la préparation de rapports géotechniques de référence (GBR) et une facilitation des suivis de travaux. L'analyse statistique de plusieurs éléments de suivi de travaux d'excavation souterraine a permis de faire ressortir les rendements en fonction des unités lithostratigraphiques, des caractéristiques structurales et des méthodes d'excavation employées.

1 INTRODUCTION

In recent years in Montreal, transportation needs, new environmental standards and increasing urbanization have led to the emergence of several tunnel projects serving the transportation of people, drinking water or wastewater. To prepare and construct these projects requires specialized engineering expertise and knowledge. With close to 30 years of work on some 100 tunnel projects since 1960, a solid experience has accumulated in Montreal, part of which has been lost. In order to exploit and make accessible the information drawn from past experiences, the City of Montreal has created a database on tunnel construction data and related geology. The growing interest in this data now justifies the challenge of integrating information that was previously collected and archived in paper format. The hundreds of kilometres of tunnel constructed in the past represent an opportunity to generate a preliminary portrait of the geological and geomechanical conditions of future tunnel routes in addition to allowing identification of potential problems.

2 ISSUES AND OBJECTIVES

The field of underground construction is often based on empirical science because of the impossibility of accurately predicting the geological conditions that will be encountered during excavation. Unforeseen problems may not only slow down the normal progress of work, but also lead to costly and difficult adjustment of methods of excavation, support measures, drainage, etc. This can lead to contractual and legal difficulties associated with the risk of cost overruns. Previous construction experiences are therefore very useful in predicting the conditions that will be encountered during construction. The more geological and geotechnical data available, the lower the risk to the project owner and the contractor, and the better the anticipation of project costs. Once analyzed, this data serves, among other things, to establish baseline values for the implementation of projects. The City of Montreal is moving increasingly to use the Geotechnical Baseline Report (GBR) for specifications in future tunnel work. This allows the contractor to better select its methods of excavation and support measures and for the City, to better manage the risk, contract administration and construction monitoring.

For the purpose of this article, attention is focused on interception projects, which are tunnel pipes used for the transport of sewage water with excavated diameters between 2.23 and 6.15 m that encircle the Island of Montreal. The interception projects carried out from 1974 to 1989 by the Montreal Urban Community (MUC) and its Service de l'assainissement des eaux (SAE) comprise 7 sections for the North Interceptor, 10 sections for the South Interceptor and 2 sections for the Outfall, totalling nearly 100 km of tunnels in rock excavated by drilling and blasting and tunnel boring machines (TBM) whose location is presented in Figure 1. For understanding purposes, the word interceptors is a direct translation from French which are sanitary sewer tunnels that collects all wastewater from secondary sewers in Montreal. These tunnel projects have been chosen primarily because they delimit the Island of Montreal, cutting through most of the geological formations in the region and because they possess monitoring data on a variety of works.

The purpose of the database which is the subject of this article, among other things, is to serve as a comparative basis when planning future tunnel projects, as a tool for geological interpretation during the preparation of geotechnical studies, as a statistical processing tool prior to the preparation of geotechnical baseline reports (GBR) and as a contract monitoring tool for future tunnel projects. It may be useful both for compiling data from future tunnel projects and for integrating data from other tunnel projects that have already been completed, such as the metro network, the aqueduct main system and certain wastewater collectors.

This article focuses on correlating project productivity data from interceptor projects with lithostratigraphic units. Several parameters of underground excavation monitoring data could also be statistically analyzed in the future in order to correlate typical geomechanical properties, project progress and tunnel supporting work encountered with the lithostratigraphic units, structural characteristics and excavation methods employed.

3 EXISTING DATABASES

In 1987, the ITA Working Groups on Maintenance and Repair of Underground Structures (1987) affirmed that good documentation of a structure can help reduce risks during maintenance and repair work, control project evolution, schedule preventive maintenance and reduce the cost of additional studies. The working group provided a list of pertinent data presented in various categories such as route information, detail plans, ground and groundwater conditions, sizing, construction of the structure and operations.

Since the development of technology to facilitate the integration, compilation and visualization of data via geographic information systems (GIS) and others, several organizations have created databases on their infrastructures. Withers et al. (2000) produced a database for the Jubilee Line Extension project collecting information on instrumentation monitoring, geotechnical investigations and construction. Marinos et al. (2013) developed a database called the Tunnel Information and Analysis System (TIAS) which they used to collect information from 62 tunnel projects. The data included in the TIAS includes a wide range of information including geological mapping, boreholes and test data, water tables, design parameters, construction and costs.

At the City of Montreal, a georeferenced database called Geotec® (Sobek Technologies) has been used for several decades to collect all information related to geotechnical investigations. This data, which includes more than 70,000 boreholes, is accessible via a GIS. However, this database does not yet include information concerning the construction of infrastructures such as tunnels.

4 GEOLOGY OF MONTREAL

Clark (1972) and Globensky (1987) described in detail the geology of the region of Montreal. Clark (1972) also published a map of the Montreal geology which an excerpt is presented in Figure 1. A summary of the geology and regional tectonics is presented below as context for the analyses presented thereafter.

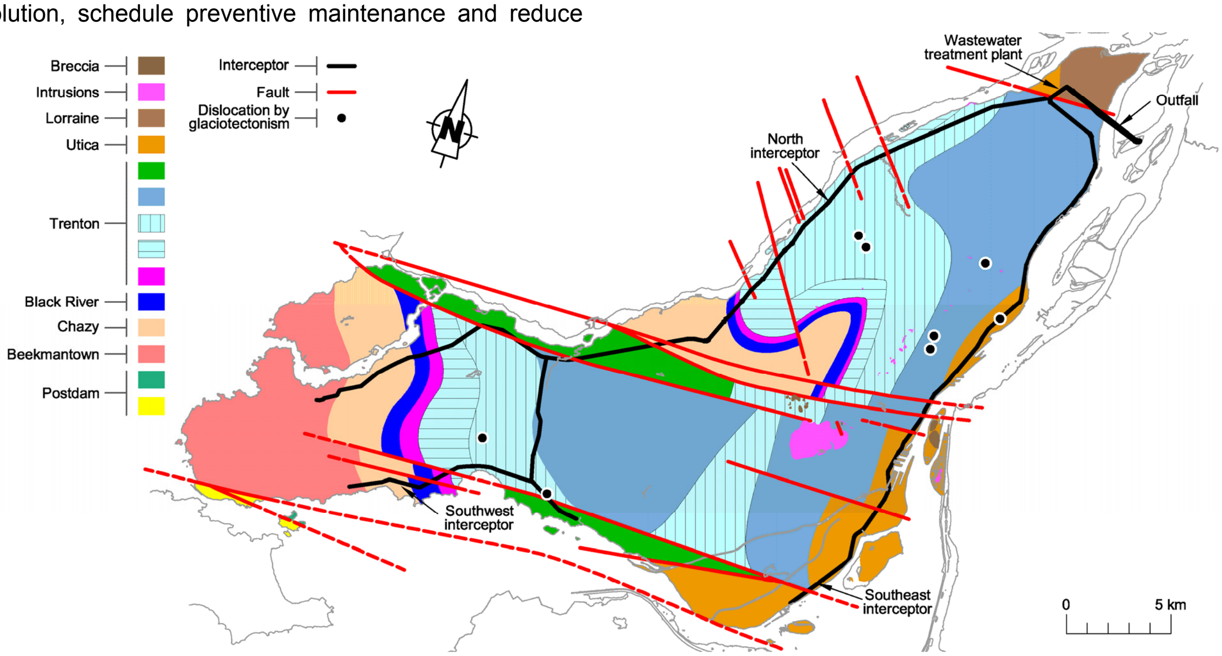

Figure 1. Master Plan of interceptors and geology map of the Island of Montreal adapted from Clark (1972) with locations of dislocations by glaciotectonism from Durand (1991)

4.1 Regional geology

In summary, the Montreal region is located in the middle of the St. Lawrence Lowlands, bordered on the northwest by the igneous and volcanic rocks of the Laurentian Plateau, and on the southeast by the metamorphosed quartzites, slates and granites of the Appalachian Mountains. The Lowland rocks are of sedimentary origin and were deposited during a complete cycle of Paleozoic marine transgression–regression. They lie unconformably on the Precambrian basement and form a Cambro-Ordovician sedimentary sequence with a thickness greater than 1000 m in the Montreal area. At the base are the conglomerates and sandstones of the Potsdam Group. They are followed by a thick succession of carbonates such as the dolomites of the Beekmantown Group, limestones and sandstones of the Chazy Group, dolomites and limestones of the Black River Group and limestones interbedded with shale of the Trenton Group. The Chazy group includes the formation of Laval (Saint-Martin and Sainte-Therese members) while the Trenton Group includes the formations of Deschambault, Montreal (Rosemont and Saint-Michel members) and Tétreauville to which we later refer in this paper. This last group is surmounted by the shales of the Utica Group and the siltstones and shales of the Lorraine Group. In the layer where the tunnel work is located on the Island of Montreal (less than 50 m deep), more than 70% of the rock is a limestone belonging to the Trenton Group formations.

The Chazy Group is mainly present in the north-central portion of the island, while the Beekmantown Group is found in the western end, and the Utica Group appears along the St. Lawrence River.

After the Ordovician, there were several cycles of deposition - erosion that left little clue as to the nature of the deposits, except for a few remains of the Devonian found in the breccia of St. Helen's Island. In the Cretaceous, an alkaline-type magmatic activity led to formation of the Monteregian hills, including Mount Royal. The rocks of Mount Royal are mainly composed of gabbro and nepheline syenites. Their hardness has made it easier to resist erosion and to form the hill that we know. The magmatic intrusion of about 4 km in area generated a metamorphic halo up to more than 200 m from the contact; the clay rocks are transformed into hornfels and the limestones are marmorized to varying degrees. The dikes and sills associated with the intrusion are very abundant in the immediate vicinity of Mount Royal, but they are also found several kilometres away. They are strong and very abrasive rocks although sometimes easily alterable under certain conditions. The rest of the geological time reflects a long period of Quaternary emergence and glaciations. In the Pleistocene, the erosion of much of the bedrock left glacial deposits. A brief Holocene marine invasion following the retreat of the glaciers overlaid marine clays, sand and peat deposits.

4.2 Regional tectonics

In the Montreal area, sedimentary formations were subjected to large curvature folds during the formation of the Appalachians by the Taconic orogenic collisions in the Ordovican and the Acadian in the Devonian. The Island of Montreal is located on the western flank of the Chambly-Fortierville syncline whose axis is halfway between the river and the Appalachians. This gives a regional dip of about 2 degrees eastward to all sedimentary strata. Minor folds such as the Villeray anticline and the Ahuntsic syncline affect the layers on the island but with dips rarely greater than 5 degrees. Only local folds, faults and intrusions upset the strata locally.

Since the opening of the Iapetus Ocean, the Lowlands have undergone many extension and compression events. Several complex fault systems have developed in the Montreal area which is located at the junction of the St. Lawrence and Ottawa-Bonnechère graben. The main system on the island (N090) is thought to be associated with Monteregian intrusions, which pierced the sedimentary layers of the Lowlands along an east-west axis. The system's faults take the form of horst in the northern part of the island, and graben in the southern part. Other systems have also been identified by Clark (1972) (N135) and by Rocher and Tremblay (2003) (N025). The faults are usually normal with subvertical dip. Areas of disturbed rock may extend several metres on either side of the fault plane depending on the formations they pass through and the magnitude of the displacements - displacements measured by stratigraphic correlations can reach more than 150 m. The fault zones can lead to problems with the stability of the excavation walls, a significant increase in the number of support elements to be installed, an influx of water and a slowdown in the work. The faults already listed by Clark (1972) and by Rocher and Tremblay (2003) are often accompanied by a network of secondary faults.

4.3 Glaciotectonism

Rock dislocation by glacier-induced thrusts is a particularity of the Montreal area. Strong interstitial pressures existed at the base of continental glaciers in the Ice Age. According to Durand and Ballivy (1974), these high pressures could then be transmitted to low-cohesion interbeds contained in some lithostratigraphic units up to about 12 m deep. This pressure, combined with the almost horizontal attitude of the clay interbeds sensitive to softening in the presence of water and the orientation of natural joints parallel to the horizontal thrust generated during the retreat of glaciers are factors favouring rock dislocation. Trenton limestone with shale interbeds are therefore good candidates for dislocation by glacier-induced thrusts. In addition, if there are pre-existing irregularities in the rock, they may constitute preferential paths for concentration of constraints and become triggers for offset by fault slipping. This phenomenon of glaciotectonism creates abrupt drops in the level of bedrock and can even contribute to the formation of caves. During tunnel excavations, a sudden unevenness of rock interbeds may not be detected by boreholes and may have serious repercussions if it results, among other things, in an excessive reduction in rock cover thickness. Location of known dislocations by glaciotectonism, compiled by Durand (1991), is shown in Figure 1.

Table 1. Description of the tables

Name of the table	Data category	Description
AXE	Location	3D localization of the tunnel and general contract information
TUN_TRONCON	Geometry	Tunnel geometry, section type and dimensions
TUN_ SOUTENEMENT	Retaining lining and support systems	Type of retaining lining and temporary or permanent support systems, characteristics and quantities
TUN_EXCAVATION	Excavation method	Excavation methods, equipment used, blasting and vibration monitoring data
TUN_HYDROGEOLOGIE	Hydrogeology	Conditions of water inflow encountered and flow rates
TUN_LITHOLOGIE	Geology	Stratigraphic units encountered, stratigraphic state and codes
TUN_GEOSTRUCTURE	Structural geology	Geological structures, discontinuities of the rock mass, directions and dips
TUN_PERFORMANCE	Performance	Productivity, rate of advance and penetration as well as elements that may affect the performance of the work
TUN_CLASSIFICATION	Rock classification	Geomechanical classification of rock, RMR and Q values

5 TUNNEL DATABASE

5.1 Database structure

The database created for the purpose of collecting construction information on tunnel work and geological monitoring information is implemented to be consistent with the structure of the City of Montreal's existing Geotec® database. As previously stated, this existing database includes geotechnical investigation data. For purposes of compatibility between investigation and tunnel data and to allow queries covering both, a table named AXE is used to associate a tunnel with its invert central axis positioned in 3 dimensions. All other added data is associated with the axis that represents the tunnel.

The new tunnel tables, with the TUN prefix, all have a similar structure. Each of them has a primary key linked to the distance. The properties these tables contain are associated with a section that has start and end distance. The selected data is based both on the data available in the City of Montreal's archives, the information required during monitoring of the work and the literature including Withers et al. (2000) and Marinos et al. (2013). The nomenclature used is in line with that already used for the investigations. The data is distributed in each of the tables containing broad categories of information described in Table 1.

5.2 Display output

After entering data into an Access or Oracle database, it is possible to progressively view the result of the data as profiles from a display module. Each tunnel table is displayed in a distinct editable profile paired with a plan and profile view of the tunnel illustrating drilling data with its geotechnical properties where applicable. You can also save profiles in DXF format. As shown in Figure 2, the profiles of the section, lithology, geostructure, hydrogeology, excavation, support measure and classification tables have the same template with the abscissa axis corresponding to the distance. The information is displayed with a set of patterns, colours, markers or text at its location on the profile. The profile of the performance table is displayed as a histogram. In this way, it is easy to visualize the progress of rates of advance in metres per day according to the distance. The user can change the display choices, attributes, and properties of each item based on their preferences.

This visualization tool makes it possible to gather all the information on the construction of a tunnel project on one drawing. The integration of all this information facilitates the interpretation of data according to cause-and-effect relationships. For example, it is possible to quickly visualize the impact of a fault zone on the other elements of the tunnelling work. According to the lithology present and the excavation method used at the location of the fracture zone, it is possible to see if the fault zone is responsible for significant water inflow in the excavation, if it has led to a significant increase of support elements to be installed and whether it has significantly problematic the rate of excavation progress. The visualization tool also helps to validate the integrity of the data collected in the field by displaying it on a regular basis.

5.3 Project monitoring

In tunnel construction projects, it is advantageous for both the contractor and the owner to compile a set of tunnelling data for productivity or contractual purposes. A monitoring registry or file that records all tunnel construction events and observations is typically used for tracking, but also to later investigate specific events. A database can therefore be used effectively as a monitoring tool during the course of work by integrating field data.

In this way, the tunnelling data can be viewed at any time in a single document. Monitoring data may include, for example:

- Position and progress of the tunnel
- Geological survey of the tunnel walls
- Groundwater seepage control operations with their location and flow rate
- Observations of ground losses or movements
- Reasons for interruption of tunnelling activities
- Type, number and position of the supports installed
- Classification of the rock according to the classes indicated in the GBR

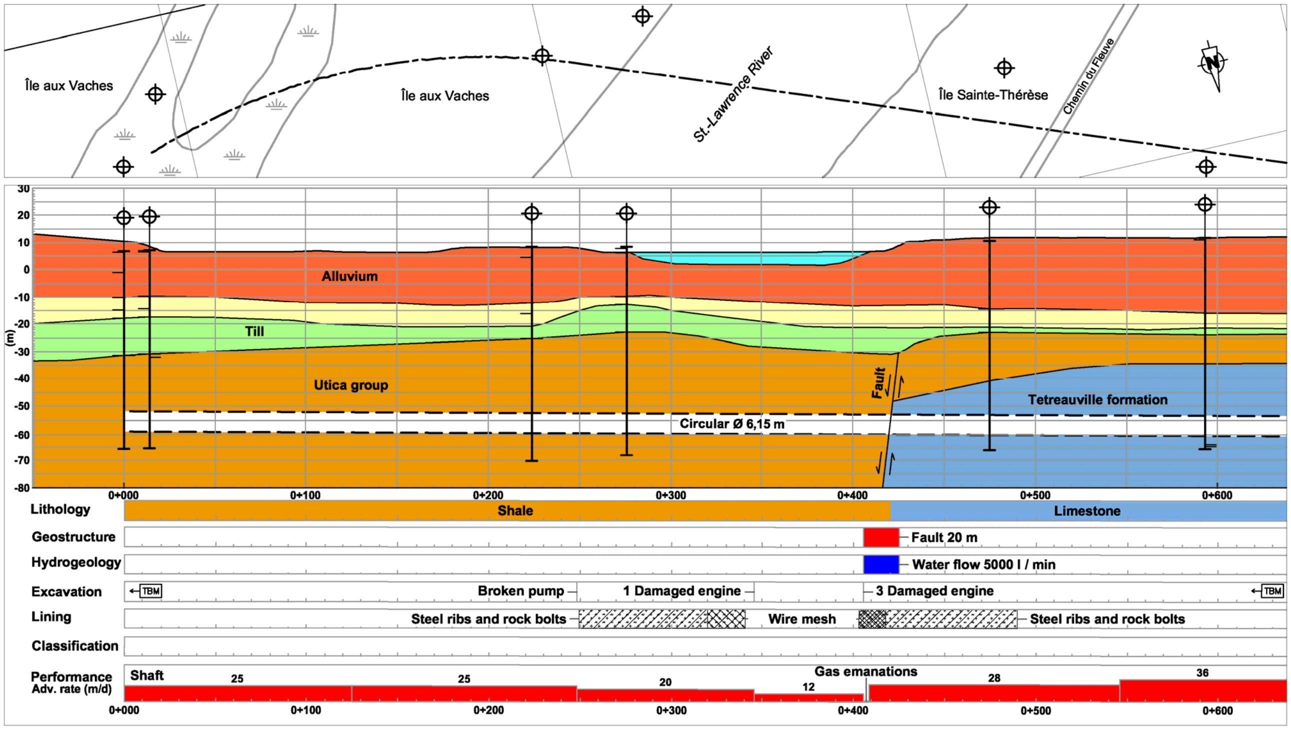

Figure 2. Schematic display output

6 STATISTICAL ANALYSIS

6.1 Summary of existing project data

The characteristics of the various lithologies as well as their overall behaviour are relatively well known in Montreal. All tunnel projects realised by the City of Montreal are also the subject of comprehensive geotechnical investigations highlighting the geomechanical properties of the rock to be tunnelled. However, the lack of geological and geotechnical documentation during excavation work makes it difficult to predict or even confirm with quantifiable data the effect of these geomechanical features on the work's rate of progress. Methods for predicting TBM rates of advance have been studied in Montreal; however the predictions obtained diverged too much to be used systematically without a good knowledge of the rock mass (Gill et. al. 1976). According to Durand (1978), the collection of geotechnical data should continue through all stages of a project in order to accurately assess the impact of the various problematic phenomena during tunnel excavation.

Grice and Durand (1979) provided a brief portrait of the effects of geology and excavation methods on the rate of advance and the costs associated with some of these structures. According to their observations, the average rate of advance could reach 30 m/day with peaks of up to 65 m/day for tunnelling excavations in sedimentary rocks with the tunnel boring machine method. They determined that approximately 4 to 6 excavation faces were required using conventional drilling and blasting methods to match these results. They also established that the impact of fault zones affects the rates of advance of tunnel boring more than drilling and blasting. This may be explained in part by the fact that when a fault zone is encountered in an excavation face using the conventional method, there is generally at least one other face that will advance normally.

The rate of advance is the linear length of excavation carried out in a working day. As described by Brierley et al. (1987), this rate is based on machine usage, shift length and penetration rate. The penetration rate being the linear length of excavation per hour of operation of the machinery, it would be more useful for the interpretation of excavation performance according to the type and quality of the rock. However, due to lack of data, the rate of advance is used in this article.

More recently, data on the rate of advance for the Rosemont Tunnel gave us insight into the effect that some geostructural elements may have. According to Gagné and Fuerst (2016), despite notable variations in the hardness of the rock, some significant water inflow and some fault zones, including one more difficult to cut through, the contractor managed to maintain an average rate of advance of 20 to 38 m/day in two nine-hour shifts using its Robbins double shield tunnel boring machine.

Most of the excavation was carried out in calcareous units of the Trenton Group's Montreal and Tétreauville formations interspersed with hard intrusives as described in detail by Boivin et al. (2013). Gagné and Fuerst (2016) note a nearly 80% drop in productivity in the Rachel fault zone. In addition to the fault zones, factors slowing the tunnel boring machine in its course of nearly 4 km included water inflow, heterogeneous rock zones, a limestone facies with more clay beds and passage under a filled former quarry. The large amount of information obtained in this project is useful for classifying rock formations according to their geomechanical characterizations. The data acquired upstream of the project will be profitable for future deep tunnel excavation projects in Montreal if they are well correlated with performance and monitoring data during project construction.

6.2 Historical data of wastewater interception tunnels

For the interceptor projects, Brierley et al. (1992) compared the construction of two tunnels of the outfall built side by side 11 years apart, with the same diameter using two different methods. They concluded that tunnel excavation using TBM was more economical and faster than drilling and blasting for relatively long tunnels with uniform sections.

The excavation performance of interceptor tunnels through rock has been recorded in the database by the authors. It is therefore possible to establish links between rates of advance and the type of rock encountered. Table 2 shows the average rates of advance obtained according to the excavation method and the type of rock. Intact rock, designated normal, is differentiated from rock affected by problematic geological phenomena such as fault zones, crushed or fractured zones, caves, water and gas inflows, weathered zones, intrusives and glaciotectonic phenomena. In order to be as representative as possible, the low rates of advance closer to shafts and near the junctions with other structures were not considered in this analysis. A reduction factor of the rate of advance between a normal and a problematic rock is presented in Tables 2 and 3.

It is important to put the data presented into perspective. Interceptor projects dating from 1974 to 1989 were not subject to the same requirements and standards as today's projects. Some average rates of advance presented are high compared to the averages of recent projects. The authors therefore recommend that these data be used with caution, avoiding direct transposition into current projects without weighting.

Regardless of the excavation method used, excavations in the Utica Group's intact shale show better average productivity than in the calcareous units of Montreal. Utica shale is generally homogeneous with a thin and even bedding and typically has lower uniaxial compressive strength than limestones, making it easier to excavate. However, as demonstrated by the performance reducing factors, the problematic shale areas cause many more problems during excavations than limestones and require the installation of more support elements.

Table 2. Average rates of advance per tunnel face according to the type of rock encountered (1974 - 1989)

Rock type	Normal rock		Problematic rock		Reduction factor
	length (m)	rate[2] (m/d[1])	length (m)	rate (m/d)	
TBM					
Shale	10219	29,9	467	8,7	3,5
Limestone	36380	25,6	4918	9,0	2,8
Conventional drilling and blasting					
Shale	456	9,1	419	3,2	2,8
Limestone	28097	8,0	2802	4,4	1,8

[1]A working day = 2 shifts of 8 hours + maintenance
[2]Rates computed as mean values

Table 3. Average rates of advance per tunnel face according to the geological unit encountered (1974 - 1989)

	Conventional drilling and blasting							TBM						
	Normal rock			Problematic rock				Normal rock			Problematic rock			
Geological unit	length (m)	rate[3] (m/d[1])	σ[4]	length (m)	rate (m/d)	σ	Reduction factor	length (m)	rate (m/d)	σ	length (m)	rate (m/d)	σ	Reduction factor
Utica[2]	456	9.1	6.9	419	3.2	1.2	2.8	10219	29.9	13.0	467	8.7	5.1	3.5
Tétreauville	3881	11.1	4.5	750	3.3	3.5	3.3	17008	31.3	8.5	1801	9.6	9.1	3.3
Rosemont	3415	6.4	3.4	294	2.9	1.8	2.2	7878	22.8	7.7	1653	7.3	7.1	3.1
Saint-Michel	6175	9.9	2.7	135	3.2	2.3	3.1	913	20.7	4.7	138	13.8	10.2	1.5
Deschambault	5488	7.2	2.2	188	5.2	1.8	1.4	3271	23.2	5.9	431	12.3	10.9	1.9
Black River	634	8.7	4.7	57	11.4	-	-	1191	21.7	6.2	340	10.0	9.6	2.2
Laval	5823	7.4	3.0	657	6.4	2.2	1.1	1033	26.5	6.9	-	-	-	-
Saint-Martin	1264	7.9	3.9	115	7.7	1.8	1.0	771	23.4	3.7	126	12.6	5.6	1.8
Beekmantown	1299	6.5	2.9	519	5.8	2.7	1.1	-	-	-	-	-	-	-

[1]A working day = 2 shifts of 8 hours + maintenance
[2]Only shale unit among the calcareous units
[3]Rates computed as mean values
[4]Standard deviation

In the case of limestones, problematic areas generally have a greater effect on TBM performance than on drilling and blasting which confirms conclusions of Grice and Durand (1979). The calculated performance reduction factor for limestone goes from 1.8 for the conventional method to 2.8 for tunnel boring machines.

The tunnel boring machines used in interceptor projects were rotary rock drillers with power ranging from 49.3 to 72.3 HP per square meter of face and a face pressure of 293 to 582 kPa. The rates of advance shown in Table 2 show that approximately 2 to 4 simultaneous excavation faces are required by the drilling and blasting method to achieve a performance equivalent to tunnel boring.

Limestones in the Montreal area can be separated into different geological units. Each unit has different composition and deposition structures. Table 3 shows the importance of identifying these units well before and during excavation since the average rates of advance recorded can vary considerably from one unit to another. Compared to other geological units, the Tétreauville formation shows excellent performance for both the drilling and blasting method and the TBMs under normal rock conditions as shown in table 3.

In general, more shaly geological units with more even and thin bedding with lower uniaxial compressive strength achieve higher excavation productivity. On the other hand, the more homogeneous calcareous or dolomitic units with thicker beds had lower average rates of advance with lower reduction factors.

Although they are useful for the understanding, it is important to note that the additional support needs and the comparison of the gathered data with the different methods of prediction of the advance rates according to the lithological unit have not been analyzed in this paper.

7 CONCLUSION

The integration of major tunnel projects construction data in the database carried out on the Island of Montreal's territory facilitates decision-making during project planning, refinement of geological interpretations during the preparation of geotechnical studies, statistical processing prior to the preparation of geotechnical baseline reports (GBR) and work monitoring. Indeed, the use of the database can make it possible to obtain a preliminary portrait of the geological and geomechanical conditions along future tunnel routes in addition to identifying potential problems and to finding possible solutions. The information contained in this data processing tool necessarily makes the City of Montreal, as an owner of underground infrastructure, more informed and effective for its future tunnel work.

The professionals responsible for carrying out tunnel geological surveys can take advantage of a standardized tool enabling them to progressively enter and analyze their data. This tool also makes available new data to assist them for benchmarking during GBR preparation.

The data already included in the database obtained from the interceptor projects allows us to conclude that:

- Intact shale excavations generally show better productivity than the calcareous units of Montreal's region, but are more sensitive to problematic rock conditions.
- Approximately 2 to 4 simultaneous excavation faces per drilling and blasting method were required to achieve rates of advance equivalent to the TBM method.
- Problematic limestone areas generally have a greater effect on TBM performance than on the performance of the drilling and blasting method.

This data analysis highlights the benefits of integrating more data into the tunnel database to further our understanding of tunnel construction in urban areas. Additional correlations may be established between geotechnical testing and the performance of excavation methods in different types of rock.

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