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Geology and Tunneling Economics in Montreal

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The economic construction of transportation projects depends in part on the availability of all relevant geological and geotechnical data. In Montreal, Canada, all of the 120 km (75 miles) of subways, major sewers, and aqueducts constructed during the last 18 years have been affected by local geological factors. Contracted costs for subway tunnels in shale were about 20 percent higher than for those in limestone. Locally,

the presence of weathered zones in limestones and shales, where they have been faulted or intruded, increased actual costs to six times the normal unit price in good limestone. The contracted cost was 12.5 times the normal for a transition from an open cut into a tunnel in soil or rock. Variations of costs for contractors were estimated from rates of advance, amounts of concrete required to backfill overbreaks, and numbers of

steel arch ribs used for roof supports. Tunnel-boring machines were more sensitive to geological surprises than were normal construction methods. Comparisons were made between data from preconstruction investigations and both construction records and site mapping. It was confirmed that, although preconstruction data usually give general warning of problems, precise notice is often lacking. Even the use of techniques such as the measurement of rock-core lengths gives only a partial indication of actual tunneling conditions, which emphasizes the need for continuous detailed mapping during construction.

The costs of constructing facilities for road, rail, sea, and air transportation systems include the factors of availability of contractors for an acceptable construction schedule, costs of rights-of-way or land, the surface topography and geometry of geological units, and the geological conditions.

This paper reviews some of the major geological features of Montreal that have been significant in transportation tunneling engineering. Examples are given from the subsurface Montreal Metro system, now about 40 km (25 miles) long, as well as from the deep tunnels of the sewer and aqueduct systems, which have similar problems within their 75-km (46-mile) length. Attempts are made to relate costs to geological features, even though it is very difficult to separate the effects of geological and nongeological factors.

TYPES OF DATA

Three different classes of geological and geotechnical data are available:

1. Original field and laboratory notes and records in which data are related precisely to their source locations on past and current projects,
2. Detailed compilations and analyses of the original records (these usually have limited circulation), and
3. Generalized compilations and interpretations with some detailed examples such as are often published by government agencies.

Newly acquired data for a current project are usually by far the most valuable; however, their cost is very high compared with that of retrieving existing data. The latter should always be examined, even though they usually provide only useful generalizations and so must be supplemented by new detailed investigations.

The major problem in the assessment of the value of existing and new geological and geotechnical data is the scarcity of precise accounting that is available and can be released by designers and contractors (particularly under the present system of tendering and contract administration). Nevertheless, there are specific unit costs for the construction of structures in standard conditions, and it should be possible to relate extra payments for work caused by abnormal, and usually unforeseen, conditions to the cost of detailed exploration that would reduce those extras.

The specific unit costs in tenders are estimated by contractors from various factors and past experience in the same area. The completion and cost of each component of past contracts in Montreal has been dependent on the proportion of bad and good geological conditions, as well as on other factors discussed below. Thus, even if they are not specifically identified and located for each new project, the ground conditions are taken into account statistically in the average unit cost per item of a contract. The profit or loss for a bidder usually comes from the lack or excess of adverse conditions. Unfortunately, these profits and losses are seldom released publicly.

In this paper, three costing parameters are used to

discuss the Metro, sewer, and aqueduct systems. First, abnormally high volumes of concrete used in lining tunnels can indicate local zones of excessive overbreak (1) (although this effect can be caused by poor technique as well as by poor rock conditions). Second, relative rates of advance by a given excavation method are possible indicators of costs and soil and rock quality when the effects of a number of nongeological factors (such as local experience of crew, size of crew, efficiency of equipment, and strikes and holidays) are taken into account. Third, details of the types and extent of supports generally indicate the stability of a cut or tunnel (although local occurrences of poor technique must be remedied by otherwise unnecessary support and some methods of support may be used as a minimum throughout some contracts as a practical compromise).

LOCAL DATA

There are several reports and maps of the physical characteristics of the Montreal region (2) and of the geology of the area (3-8) that summarize the observations from outcrops, temporary excavations, and drill holes. The locations of some data are more or less closely described, but most information has been correlated and generalized on maps having scales of 1 cm to 180 m (1 in to 1500 ft) (1:18 000) to 1 cm to 633.6 m (1 in to 1 mile) (1:63 360). Some sections are also available. Most of the early geotechnical records are qualitative and describe troublesome problems such as marine clays and quicksands (3). Clark (5) has deduced and plotted an extensive fault pattern chiefly from stratigraphic studies, as there are few positive indications of faults on the surface except in quarries.

A major construction period started in about 1960, and there was a great increase in the amount of exploratory drilling. Much has been summarized in the latest reports and maps and, in 1972, data from some 25 000 holes were coded in computer format. Unfortunately, there was insufficient funding for the implementation of a computer system having ready availability of selective printouts. An earlier pilot system did produce tabular and graphic output (9), but that too could not be kept operational.

Thus, at present, although there are the above-cited published reports and others on particular areas (1, 10-15), searches of the files of individual organizations must be made for specific projects. For government projects, consulting engineers may be given authorization for full access to previous government data held by other consultants. The cost of such searches is often relatively small and there is the possibility of obtaining personal comments not in reports, yet there are definite chances that knowledge of isolated but significant geologic anomalies may remain hidden in the files of some small organization.

GEOLOGY

The geological succession to today can be summarized briefly by the sequence of geological happenings shown in Figure 1. The generalized succession of geological units is fill; peat; sands and gravels; lake clays and silts; marine clays and silts; tills; and limestones, dolomites, and shales or sandstones, all having weakened zones associated with local faulting and igneous intrusions.

The so-called normal geological factors significant in engineering are those that can usually be extrapolated from preexisting data and can be handled on a routine basis during construction; the special factors are frequently both difficult to locate and expensive to treat (15).

Figure 1. Geological history of Montreal: sections showing principal events and features.

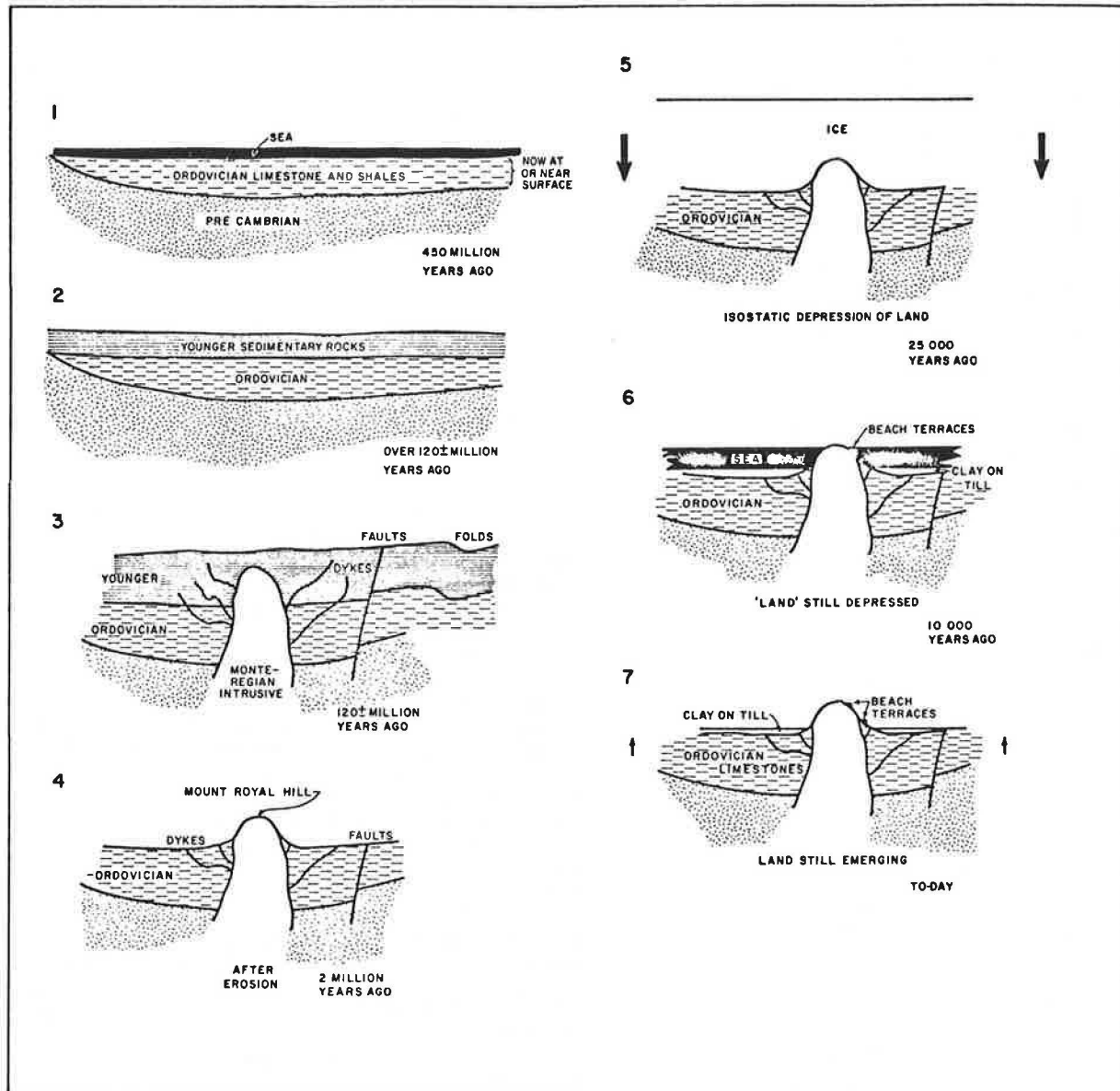


Figure 2. Montreal Metro: Intersection of subway tunnels and the White Horse Rapids Fault.

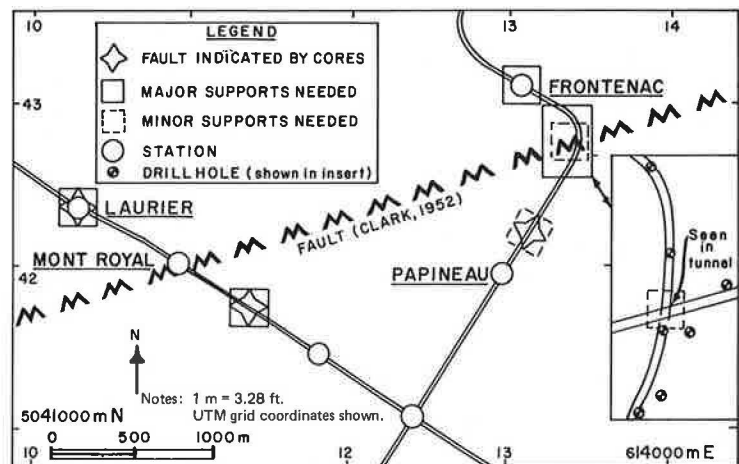


Figure 3. Montreal Metro: effect on construction of a disturbed zone in Utica shale—(a) profile showing locations of exploration drill holes, core recoveries, and tunnel supports; (b) average core recoveries; (c) relative monthly advances; and (d) estimated relative costs.

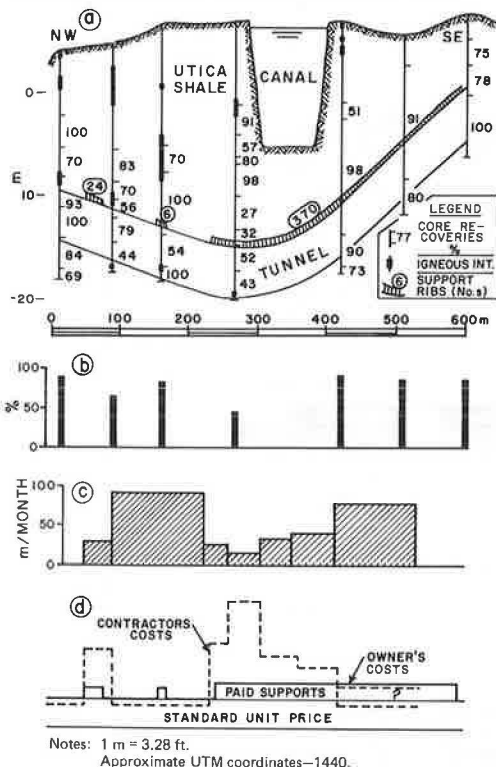


Figure 4. Montreal Metro: effect on the construction of a small fault zone in shaley Trenton limestone—(a) profile showing locations of fault and exploration drill holes, (b) RQD values, (c) average daily advances, and (d) actual and theoretical volumes of concrete lining.

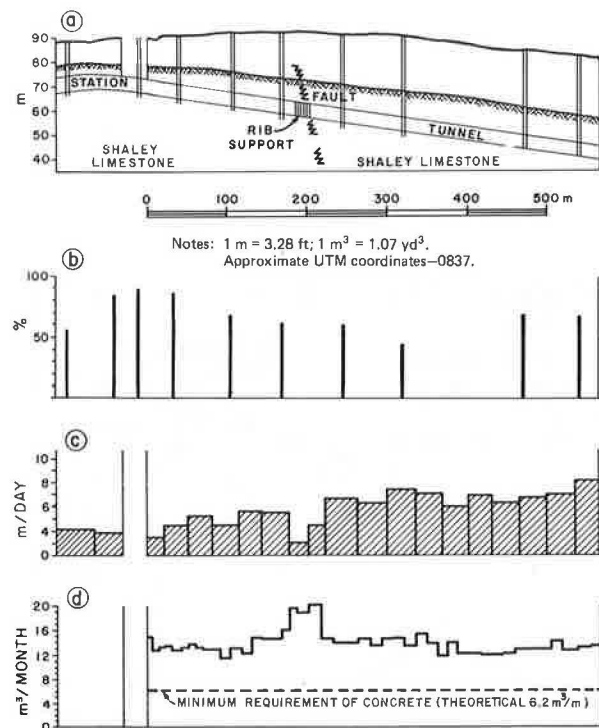


Table 1. Relative unit costs for excavation and construction of Metro lines.

Cost Item	Relative Cost
Contracted	
Open cut in normal soil and rock and tunnels in rock	1*
Tunnel in rock at times of high economic activity	2*
Open cut in unstable soil	3
22-m-long open cut in soil and close to buildings	10
400-m-long open cut that has a slurry trench in 25-m deep soil and transition to rock	12.5
Extra accepted by client in addition to those above 560-m-long open cut in Bentonite near river	0.03
Tunnel in shale	
3000 m long, few intrusions	0.12
2200 m long, adjacent to moderate-sized intrusion	0.17
1200 m long, few intrusions, thin rock roof	0.20
640 m long, adjacent to moderate-sized intrusion	0.25
Total actual to contractor	
18-m wide tunnel in limestone with altered intrusive zone	6
Cost of standard exploration drilling at 90-m centers	0.005

Note: 1 m = 3.28 ft.

*Standard unit price.

^bTwice standard unit price.

Nevertheless, if the occurrence of special factors in an area has been well documented, even if they are not encountered by chance, close drilling, or geophysical methods, during exploration, continuous careful observation can be made to minimize their effects.

METRO SYSTEM

Preliminary work on the Montreal Metro subway system began about 1960 at a time when Clark's report (5) was about eight years old and Prest and Hode-Keyser's report (7) was about to be published. Thus, the planners were fortunate in having two recent government interpretations on hand. Nevertheless, a standard pattern of holes at 90-m (300-ft) spacing was drilled that proved to be necessary. Examination of the cores confirmed the existence of Clark's faults but, more important, many of the features were located precisely by direct intersections with follow-up drill holes. In addition, data on the order of irregularities of the bedrock surface were obtained. This information was essential as many of the tunnels were planned to be at minimum depths compatible with safe rock cover.

The major White Horse Rapids Fault (see Figure 2) had been indicated by Clark on his map. The fault intersections appeared to be close to the proposed Mount Royal Station and between the Papineau and Frontenac Stations. Preconstruction drilling indicated that the fault is a disturbed zone about 180 m (600 ft) wide and located across the next station, Laurier, nearly 700 m (2300 ft) from the Mount Royal Station.

When the tunnel was excavated, the situation was found to be even more complex. The Laurier fault zone was confirmed and required 101 steel ribs for support, although a fault interpreted from cores to be north of Papineau Station caused no problems. A fault in an unexpected location was found in Frontenac Station and required 77 ribs, although the rock cores from the drill holes in the area were of good quality.

As another example, a 240-m (670-ft) long section of the tunnel through the Sainte-Helene Island breccia was excavated in a month. This was very stable, as might have been expected from the excellence of the breccia as a building stone. However, soon after, a 200-m (650-ft) long stretch (see Figure 3) of Utica shale was encountered. Here, the drill holes had intersected intrusions and there were some low core recoveries near tunnel elevations. Forward progress decreased to an average of less than 40 m/month (130 ft/month) for five

Table 2. Tunnel excavation rates.

Excavation Method	Type of Rock	Type of Support Installed	Rate in Normal Rock (m/day)*	Faulted Zone		
				Rate (m/day)*	Length (m)	Decrease Factor
Conventional	Shale	Ribs-shotcrete	9.5	4.3	75	2.2
	Shale-limestone	Shotcrete	10.4	5.5	45	1.9
	Limestone	Ribs	6.1	2.4	185	2.5
	Limestone	Rock bolts	6.7	4.6	150	1.5
	Limestone	Ribs-shotcrete	6.7	2.0	165	3.3
	Limestone	Shotcrete-bolts	15.2	7.3	250	2.1
TBM	Limestone	Some ribs	27.8	13.7	180	2.0
	Limestone	Steel plates	31.4	1.4	30	22.4
	Limestone	Steel plates	30.5	7.5	230	4.1

Note: 1 m = 3.28 ft.

*Rates computed as mean values for normal operating days only.

months, and continuous support, including complete backfilling of the tunnel with concrete after the ribs were squeezed, was necessary. The possible order of contractor's losses is shown in Figure 3d.

This case history demonstrated that rates of monthly advance can be cut to a quarter of the normal in disturbed zones within a kilometer (half mile) of a breccia plug and suggested that more core drilling during the construction period would have been desirable. This in fact was done a few months later when the first signs of instability were encountered at another heading in the Utica shale and resulted in a decrease to about 30 percent of normal production for only one month.

A third example is at an intersection of the Metro with a fault trace in shaley limestone (see Figure 4). The relative importance of one of the features is shown by the need for 13 ribs and the reduction in the rate of advance from about 6 m/day (20 ft/day) to about 2 m/day (7 ft/day) for 7 days, followed by a period of zero advance for 11 days.

The excavation began at the station and progressed to the right, at an increasing daily average rate unrelated to the rock-quality designation (RQD) of the core (16). The above-average overbreak and a decrease in excavation performance that occurred in the small fault zone where the ribs had to be installed had not been predicted by the RQD data because no bore hole was in the fault itself. After excavation, mapping of the tunnel showed that the overbreak was associated mainly with the fracture pattern and the presence of small intrusions related to the fault.

Contract and extra costs are summarized in Table 1. The 7 km (4.5 miles) of tunnels in shale appear to be the least stable and cost, on the average, an additional 20 percent. Costs for open cuts are also included. Nevertheless, the unit cost for the more weathered locations (usually with faults and more intrusions) must have been appreciably greater for the contractors (Figure 3). The delays were chiefly at the contractors' expense, as far as salaries and equipment were concerned, although the owner paid directly for additional supports and, in a few cases, some redesign. Other owner costs have been for loss of revenue when openings of new sections of the system have had to be delayed.

SEWER AND AQUEDUCT DEEP-TUNNEL SYSTEMS

Although sewers and aqueducts cannot be considered as true transportation systems, the data from a major network of deep-tunnel aqueducts built in the last 10 years are relevant. About 75 km of tunnels of varying diameters [from 2 to 6 m (7 to 20 ft)] were built in rock, mainly at depths of 10-70 m (30-200 ft) by using construction methods quite similar to those used for the

Metro [with the exception of the use of tunnel boring machines (TBMs) for a fifth of the total length].

The recent introduction of TBMs in Montreal has demonstrated their excellent performance in normal conditions in sedimentary rocks. Excavation rates of up to 30 m/day, with a peak of 65 m/day, have been achieved; comparable lengths of tunnels excavated by conventional method required four or six headings with two or three working shafts to be completed in the same time. However, the encountering of fault zones affects the rate of advancement when TBMs are used more seriously than when conventional methods are used (see Table 2). There is usually only one heading for the less-adaptable TBM rather than the two or more for the conventional method, so that the occurrence of a fault zone has a more pronounced impact on contractors' costs. In three of the nine fault zones that were crossed by TBMs, the rate of advancement was slowed by factors of 2-22, although comparable situations in conventional excavations resulted in decrease factors of only 1.5-3.3. Thus, rock quality should be predicted more precisely for tunnels to be excavated by boring machines. The weekly reports on 6.2 km (10 miles) of one tunnel job summarized below show that progress in bad rock is about 25 percent of that in normal limestone.

Type of Excavation Problem	Tunnel Length (% of total)	Working Time (% of total)
None		
In shale	6.5	7.8
In limestone	64.9	43.0
Equipment (in limestone)	16.4	17.9
Bad rock conditions (in limestone)	11.3	29.6
Personnel (in limestone)	0.8	1.7

DISCUSSION OF COSTS

Costs are minimized if the most economical design is used along the most satisfactory route where, among other factors, all areas of geologically caused difficulties have been located before design is finished. If the costs of overcoming these difficulties can be assessed, then more economical alternatives can be investigated. Intensive surveys are required, because there are enough anomalous geological conditions in Montreal to make it likely that some problems will be encountered along the extended paths of most transportation projects.

Most of the likely geologically related problems (except a large earthquake) have been experienced in Montreal within the last 20 or so years. The most frequently encountered problems include the following.

1. Thin limestones can alternate with shale or other weak interbeds: Assessment of the core is difficult because RQD values are affected not only by fracture

density, but also by bedding thickness; thus, many abnormally low RQD values were observed in relation to the actual rock conditions encountered in Montreal tunnels.

2. Roof instability requiring heavy support can be caused by a thin [approximately 1-cm (0.39-in)] layer in altered sills or dykes, usually in the chilled zones. Core samples of these layers are frequently described as thin clay seams or disintegrate in the core boxes. They do not significantly affect the RQD value computed on a 3-m (10-ft) length but are very important if they are located near or intersect the crown elevation at a low angle.

3. Fault zones sometimes have thicknesses of a tenth or less of the standard spacing of boreholes: This does not mean that the spacing should be decreased to the dimension of the expected fault, but rather that RQD values are only rough indicators of support requirements. Detailed geologic analysis of the cores is more effective. Bore holes located near a fault, but in good rock that has a high RQD, showed other indications of a probable fault: core joints with slickensides, lack of stratigraphic correlation with adjacent holes, abnormally high values of the apparent dip, or even the occurrence of a high proportion of minor intrusions. When such an analysis points out the approximate location of a fault, additional drilling, preferably inclined, should be done to precisely evaluate the location and extension of the bad-condition zone.

This should lead to lower bid prices because contractors will be less likely to encounter the costly problems that require the self-insurance of higher bid prices. Certainly, this study provides qualitative justification of the need for more-detailed geological observations, including probing during the construction period. This activity carried out daily, and more intensively during the weekend shut-down periods, should alert contractors to the precise locations of localized difficulties that may have been missed by the predesign drilling.

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