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WEAK SEDIMENTARY ROCK IN CALGARY, ALBERTA AND ITS IMPLICATION ON SMALL DIAMETER TUNNELLING

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ABSTRACT
Recent construction of small diameter water and sewer tunnels in the City of Calgary has employed Tunnel Boring Machines (TBM). The characteristics of the rockmass are an important factor in the selection of the TBM cutterhead, which has been particularly challenging given the high variability of rock properties. This variability is explained based on the geological history and depositional environment of the local sandstones, siltstones and mudstones, which are part of the Paskapoo Formation. Geotechnical properties collected during the investigations for seven tunnels and construction performance data are also reviewed.

RÉSUMÉ
Des tunneliers ont été utilisés pendant la construction récente des tunnels d'eau et d'égouts à petits diamètres dans la ville de Calgary. Le choix de la tête de coupe du tunnelier dépend des caractéristiques du massif rocheux, ce qui présente un défi lorsque les propriétés du rocher sont hautement variables. Cette variabilité est attribuée à l'histoire géologique et à la nature sédimentaire du grès, de la siltite et du mudstone qui font parties de la Formation Paskapoo. Les propriétés géotechniques recueillies pendant les programmes de reconnaissances pour sept tunnels et les données obtenues pendant la construction sont revues dans cet article.

1 INTRODUCTION

With the significant expansion of the City of Calgary, Alberta, the city has been working to upgrade and expand water and sewage systems to ensure adequate service is provided throughout the city. Until recently, the majority of these piping systems have been installed using open-cut excavation methodologies. Open-cut excavations allow for designs to be readily altered in response to the varying conditions encountered. However, due to the presence of existing above ground infrastructure and environmental constraints, many of the recent projects within the city have had to move to partially trenchless designs. Beginning in 2005, several projects throughout the city have involved trenchless segments of their alignments, for which Tunnel Boring Machines (TBMs) were used as the primary excavation method.

The recent infrastructure projects have led to significant advances in the knowledge of the city's bedrock and its behaviour with respect to TBM excavations. This work reviews the geological setting of the region, and the known geotechnical properties of the bedrock with influence on TBM tunnelling applications. Five of the tunnelling projects undertaken in Calgary since 2005 are summarized (total of seven tunnels) and the overall lessons learnt to date are discussed.

1.1 Tunnel Boring Machine Excavations

Due to the lengths of these installations, availability of equipment, relatively small diameters (generally less than 3 m), and project logistics, TBM tunnels have been the preferred choice for these recent works. Tunnel boring machines are full face excavators which use an arrangement of cutters and/or scrapers to penetrate through rock and soil units. TBMs often include a trailing unit which allows for the installation of support systems as the tunnel is excavated. For small diameter tunnels, TBMs can be designed to be propelled by the main body of the machine, where temporary support systems can be installed behind the main cutter head, or designed to be propelled by exerting pressure upon the support systems or at the entry shaft (pipe-jacking).

The success of the TBM drive depends largely on the ability of the cutterhead to excavate material at the face of the tunnel. Disc cutters and/or scrapers are used to fracture and remove material from the face; however, their efficacy is highly dependent on the rockmass properties encountered at the face. TBM selection and performance are related to the geotechnical behaviour of the material through which the tunnel will be driven and the diameter of the tunnel. The lithology, strength and quality of the rockmass are large factors in TBM selection and performance, as are the overall ground water conditions and in situ stresses along the alignment (Girmscheid & Schexnayder, 2003). If a TBM encounters homogeneous materials for which the cutterhead was designed, the advance rates of the method can exceed 10 m/shift. In a case where a TBM encounters material properties for which it was not designed, the machine will be prone to delays from the inability to penetrate the material and/or maintenance issues. Heterogeneous ground presents unique challenges for TBM excavation, as the cutterhead must be designed for a wide range of soils and/or rock properties and must be capable of operating through uneven face conditions.

2 GEOLOGY OF THE CALGARY AREA

In order to understand the conditions expected in underground works, a good understanding of the geological setting is required for any tunnelling project. The focus of the review is primarily given to the upper rock units and recent geological history of the area.

2.1 Geological History

The City of Calgary is located atop a foreland basin to the east (approximately 90 km) of the front ranges of the Rocky Mountains in Canada as shown in Figure 1. The Canadian Rocky Mountains are the easternmost mountain range of the North American cordillera. The formation of this foreland basin is linked to the formation of the Canadian Cordillera, where a depression was formed to the east of the rise of the mountain belt (Price, 1994). Erosional detritus from the neighboring mountains accumulated in the depression throughout the Mesozoic and Cenozoic Era, overtopping marine sediments deposited in the Paleozoic Era. The basin deposits vary depending on the source location and the depositional environment. The uppermost units of the foreland basin were deposited at the tail end of the mountain building activity, indicating that these units underwent little to no tectonic disturbance since deposition (Price, 1994).

Widespread uplift of the region, combined with a near-full basin resulted in the removal of up to 3 km of material from the top of the basin. Consequently, the uppermost units of the basin were scarred by an extensive river channel network throughout the region. The Pleistocene glaciation subsequently buried and preserved the incised river channels by glacial infill. Unconsolidated glacial sediments cover the basin rocks from several meters of cover to up to 80 m in the Calgary area. (Osborn & Rajewicz, 1998)

2.2 Geological Setting

The primary unit of interest in infrastructure development in Calgary is the uppermost sedimentary unit: the Paskapoo Formation. In Southwestern Alberta, the Paskapoo and Porcupine Hills Formations represent the final units deposited during the Paleogene Period (Lower Tertiary) (Demchuk and Hills, 1991; Grasby et al., 2008). The distinction between the two units is primarily regional: Calgary sits at the transition zone between the units, with the Paskapoo Formation extending north to central Alberta and the Porcupine Hills Formation extending south towards the United States (Osborn & Rajewicz, 1998; Osborn, 2006). As the units are similar in depositional environment and geotechnical properties, for the purpose of this paper, characteristics of the Paskapoo Formation will be used to describe the Calgary bedrock.

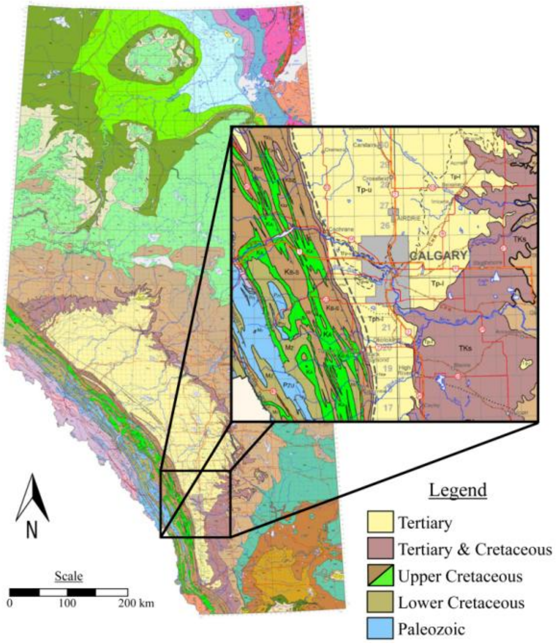

Figure 1: Geological Map of Alberta with enlargement of the region of study, Calgary (Hamilton et al., 1999)

The Paskapoo Formation was deposited in the foreland basin in a combination of channel and floodplain fluvial deposits. Fluvial deposits are characterized by highly variable vertical deposition sequences which are laterally non-uniform, as shown in Figure 2. Sediments deposited within a channel system are often fine to coarse grained sands which deposit at point bars or mid-channel medial bars as lateral accretion deposits (Boggs, 2004). Floodplain deposits occur on land adjacent to the river channel during overtopping or flooding events. The floodplain deposits consist of fine grained deposits (primarily silts and clays). As a result of the style and intermittency of deposition, the floodplain deposits are characterized by horizontally stratified fine sands and laminated mud. Rapidly breached river channel deposits are also common in the Paskapoo sequence, carrying both coarse and fine sediments onto the floodplain, creating crevasse splay deposits (Boggs, 2004).

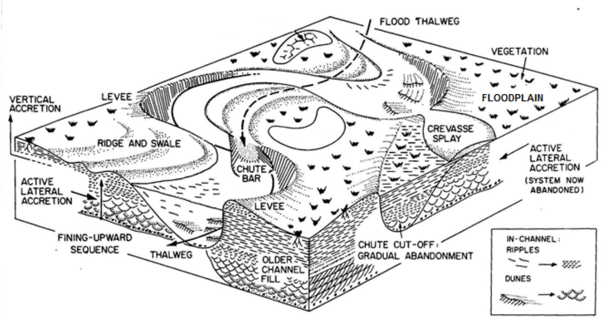

Figure 2: Block diagram depicting the morphological elements of a meandering river system (modified from Walker & Cant, 1984).

In fluvial systems, rivers often abandon channels or migrate flow paths over time, either relatively suddenly or gradually, resulting in highly heterogeneous distribution of deposits (Grasby et al., 2008).

The Paskapoo is commonly known as the “Paskapoo Sandstone”, however through an extensive data and literature study conducted by Hamblin (2004) it is important to note that the Paskapoo Formation has been found to be over 50% siltstone and mudstone deposits. The primary source of the discrepancy in general perception arises from the weathering bias of the rock types. In the Calgary region, the visible outcroppings of the Paskapoo Formation are the competent sandstone units, as the less competent siltstone and mudstone units often weather easily and become overgrown with plant-life, obstructing their visibility (Osborn & Rajewicz, 1998; Grasby et al., 2008).

Due to the variable nature of the depositional environment, the rock sequences found in the Paskapoo are significantly heterogeneous, both laterally and vertically and as a result, correlation between boreholes is often near impossible, and sections are often incomplete.

2.3 Geotechnical Properties

Regional data from numerous field investigations are used to characterize the rockmass properties and expected geomechanical behaviour of the units. The data consists of geological core logs, as well as the results of several geotechnical lab and field testing data presented for individual rock units. For the purpose of engineering classification, the Paskapoo formation is divided into three geotechnical units based on distinct geotechnical behaviors: sandstone, siltstone and mudstone. The units have been identified in borehole logs by field technicians.

As rock units are inter-fingered and laterally discontinuous, it is not always possible to draw direct correlation between each borehole, even within a specific project site. For infrastructure projects which pass through bedrock it is therefore often of more value to understand the expected behavior of the rockmass and the relative amounts of each rock type which could be expected at the project location and depth. It should be noted, however, that the project may encounter areas where one rock type can dominate the area, and therefore the tunnel face conditions will not always reflect the projected ratios.

A summary of lab and field properties determined for each rock unit which are presented in Table 1. Data distributions for layer thickness, UCS data and Point Load Indices are shown in Figure 3, 4 and 5, respectively.

The top surface of the Paskapoo unit is significantly altered due to its prolonged exposure and to glacial processes. As a result, a generally one to two metre weathered zone is present along the majority of the top horizon of the bedrock, as shown in Figure 6. This weathered zone consists of highly degraded rock, which is often reduced to soil-like properties when exposed.

As unit layers can often be smaller than 20 cm it is often not possible to constrain Rock Quality Designation (RQD) values to a rock type, meaning the rockmass must be assessed as a whole. An average rockmass RQD of 57% is recorded, with 33% of the all RQD values falling above 75%. An average sub-horizontal fracture frequency of 6 fractures/m has been recorded, with no significant records of sub-vertical fracture frequency due to sampling bias. Significantly lowered RQD values are often recorded in the upper 1-2 m horizon which correlates to the weathered zone. Occasional fractured zones have been observed at greater depths, but no trend has been identified with depth or location.

Table 1: Summary of geotechnical properties of Paskapoo Formation by rock type.

Property	Sandstone	Siltstone	Mudstone
Recorded Unit Abundance (%)	8.95	45.26	45.79
Common Layer Thickness (m)	0.3-0.4	0.2-0.3	0.1-0.2
Unconfined Compressive Strength* (MPa)	24.51	26.05	4.89
Axial Point Load Strength*, I_{50} (MPa)	1.08	1.12	0.56
Diametral Point Load Strength*, I_{50} (MPa)	0.92	0.94	0.48
Cerchar Abrasivity*	0.97	1.30	-
Swelling (% vertical strain, >3 day period)	-	-	18.5

*mean value reported for the seven project sites

There are buried channels on the surface of the Paskapoo Formation that can cause significant design challenges to underground works projects. The topography of Calgary gives certain indications of regions of larger risk of buried channels though glacial processes and recent drainage paths have hidden previous erosional patterns from view (Osborn & Rajewicz, 1998). As a result, it is extremely important to complete a full subsurface investigation along proposed tunnel alignments to reduce the likelihood of encountering an unexpected buried channel. Geophysical techniques such as seismic refraction and ground penetrating radar surveys were found to be useful in the identification of these channels.

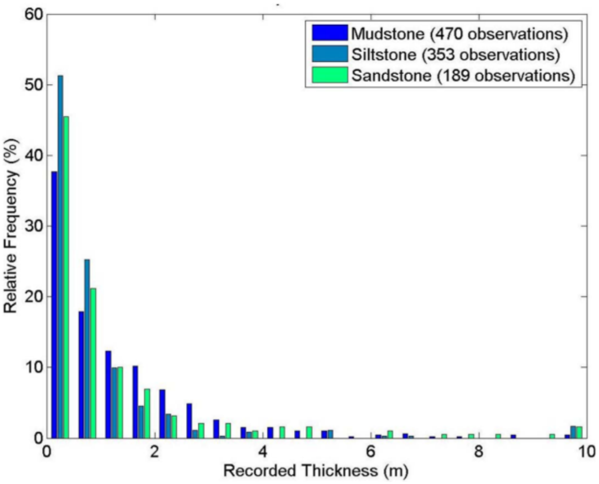

Figure 3: Distribution of rock type layer thickness observations in core logs.

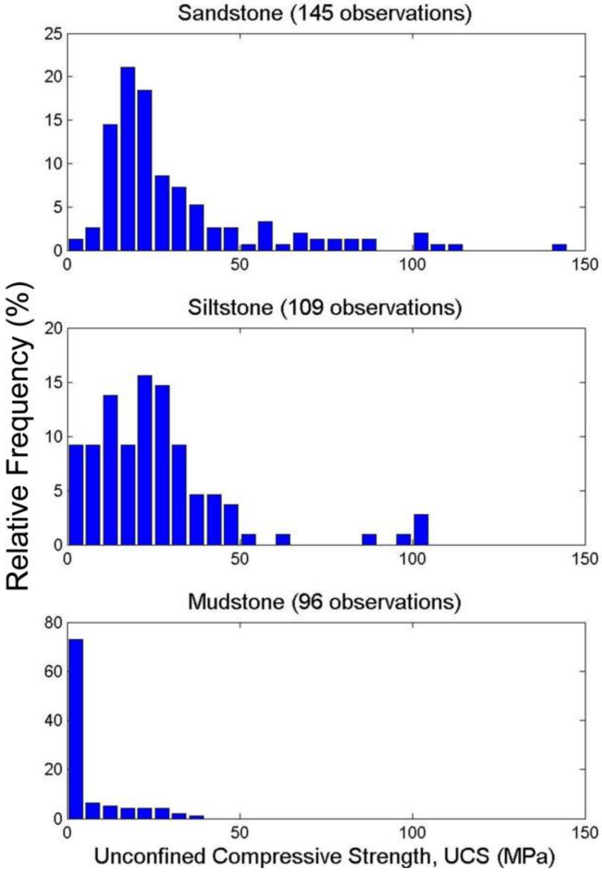

Figure 4: Distribution of Unconfined Compressive Strength (UCS) values for each rock type.

2.3.1 Rockmass Classification

In geotechnical design, it is common practice to use various classification systems in order to predict the rockmass behavior for a tunnelling project. Classification systems are empirical correlations between various quantifiable rockmass properties and the observed mechanical behavior during excavations. It is therefore critical that they are applied to projects for which the conditions are similar to those used to create the system. A classification system is of little value when they are used in situations for which they were not designed (Hoek, 2007).

The most commonly used classification systems include: Rock Mass Rating (RMR), Rock Tunnelling Quality Index (Q) and Geological Strength Index (GSI). It is important to consider the source of the empirical system when determining its applicability to a project; none of the aforementioned systems were created for small scale TBM tunnelling through heterogeneous rock (Hoek et al., 2005; Hoek, 2007; Bieniawski, 1989). The Q-system has previously been adapted from a drill and blast tunnelling tool for use in TBM tunnels, however the empirical data does not extend to untectonized heterogeneous ground, as described in the previous sections (Barton & Abrahao, 2003).

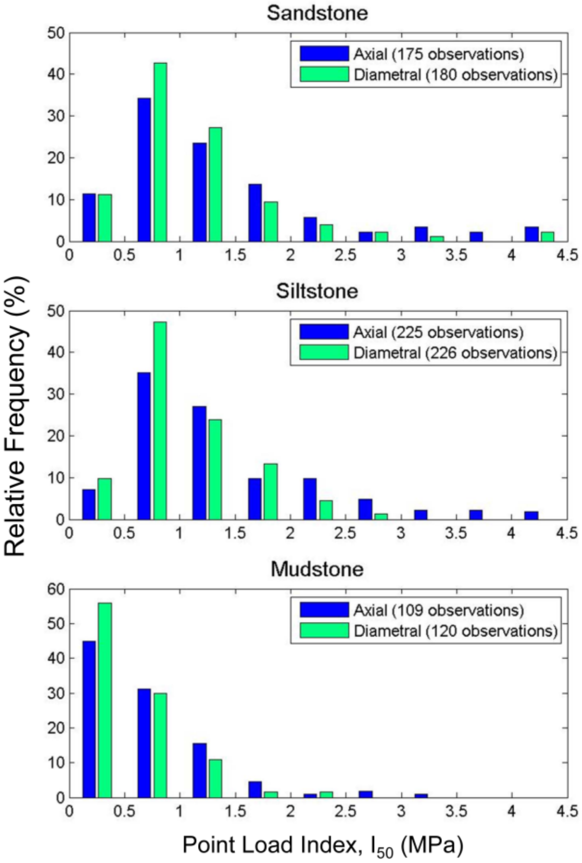

Figure 5: Distribution of Axial and Diametral Point Load Test results for each rock type.

Figure 6: An excavation site in Calgary SW in which the weathered zone atop the bedrock is clearly visible.

The major constraint with the application of these tools for predicting TBM performance through heterogeneous ground is that an averaging of the rockmass behavior will not capture the true behavior of the rock units. It is the extremes of the behavior which will dictate the advance rate through the medium. In the case of Calgary, the bedrock can be varied within the face of the excavation, as well as along the length. The expected rockmass properties range from competent sandstone and siltstone units which can be strong enough to cause wear to the main bearing, to weak mudstones which can degrade to soil-like behavior which can clog up the cutterhead. Both of these properties may be present in the face with the resulting behavior not equal to the homogenized behavior predicted by classification systems.

As current empirical systems are not ideal to adequately capture the conditions expected in Calgary, it is important to review previous tunnelling experience in the area to determine the expected performance of TBMs through the Paskapoo Formation, and optimize the TBM design for the conditions.

3 RECENT PROJECTS IN CALGARY

With the expansions and upgrades to the City of Calgary's Sewage and Waterworks System, many tunnelling projects have been undertaken in recent years. Seven TBM excavation tunnel segments from five projects are used to evaluate the competence of the excavation method through highly variable geotechnical conditions.

The projects used as case studies are the Glencoe Storm Sewer Upgrade, the 15th Street Siphon Upgrade (Upper and Lower Bow River crossings), the Valley Ridge Feedermain (Bow River and CP Rail crossings), the Beddington South Sanitary Upgrade (Nose Creek and CP Rail crossing) and the Nose Creek Sanitary Trunk Upgrade (16th Avenue crossing). The locations of each site are shown in Figure 7.

Figure 7: TBM project locations in Calgary AB; a) Glencoe Storm Sewer Upgrade, b) 15th Street Syphon Upgrade, c) Valley Ridge Feedermain, d) Beddington South Sanitary Upgrade, e) Nose Creek Sanitary Trunk Upgrade. (Google, 2012)

The construction details of each project are summarized in Table 2 and details are presented in the following sections, with emphasis placed on construction performance. Each tunnel project encountered unique geological conditions, with varying combination of the three primary geotechnical units. In most cases, "unexpected" geological behavior was blamed for the delays; however it may argued that TBM design and operation were also a factor.

3.1 Glencoe Storm Sewer Upgrade

The Glencoe Storm Sewer Upgrade tunnel was constructed through approximately 350 m of glacial till deposits on the east end, with the remainder of the alignment within bedrock. The water table was mostly above the tunnel crown, with a hydraulic head up to 4 m.

Actual advance rates were 8 m per 10 hour shift in the till, 4 m in the transition from soil to bedrock, and 5.3 m (average) in bedrock. The penetration rate was slowed through the bedrock as the TBM was designed for soft ground (Al-Battaineh and Tan, 2006). It was found that the alternating sequences, between 'hard' and soft' units, was a primary source of delay. The tunnel required one round of cutting tool replacements for the entire drive.

A slight delay was caused by relatively large volumes of water inflow, estimated at 21 l/min/m, categorized as "flowing", encountered within a short (~ 4 m long) section in bedrock. The problem was mitigated by means of supplementary pumping efforts, and required post-construction chemical sealing of the concrete segments in this section.

3.2 15th Street Siphon Tunnels

The 15th Street Siphon consisted of two stacked tunnels below the Bow River. Both tunnels were completed with the same TBM, which used a custom designed cutterhead for the project. Both tunnels are entirely in rock, with a minimum rock cover over the crown of the upper tunnel in the order of 9 m to 10 m or about four excavated tunnel diameters.

The upper tunnel was excavated first and then the lower tunnel. The upper tunnel was completed on schedule with no significant issues. In the lower tunnel slower penetration rates were reported from the beginning of the drive. The lower rates were initially thought to be linked to stronger geological units, however, upon later inspection it was found that the main bearing was damaged and the continued advance had cause significant wear to the gears and cutterhead. Due to the small diameter, it was necessary to remove the entire machine in order to repair the bearing, at which point the tunnel was left unsupported and unlined for over three months. Upon reinstalling the TBM, it was noted that minor overbreak had occurred in the crown of the unsupported segment.

A kink in the lower tunnel alignment is thought to be caused by either softer material in the walls causing the TBM to veer slightly off alignment, or as a consequence of the removal and reinstallation of the TBM for maintenance.

Table 2: Summary of project details for seven tunnel segments excavated by TBM in Calgary, AB

	Glencoe Storm Sewer Upgrade	15th Street Syphon Upgrade - Upper Bow River	15th Street Syphon Upgrade - Lower Bow River	Valley Ridge Feedermain - Bow River	Valley Ridge Feedermain - CP Rail	Beddington South Sanitary Upgrade - Nose Creek and CP Rail	Nose Creek Sanitary Trunk Upgrade - 16th Ave
Tunnel Details							
Depth (m)	16-42	22-26	24.5-28.5	24-33	11-13	> 6	1-16
Outer Diameter (m)	2.99	2.46	2.46	1.524	1.550	1.524	2-2.5
Inner Diameter (m)	2.92	1.5	1.5			0.75	1.8
Length (m)	935	290	290	280	170	100	250-300
Expected or Baseline Geology							
Rock Type	Clay Till (40%); Weak Mudstone with interbedded Medium Strong Sandstone layers (60%)	Mudstone (50%), Sandstone/Siltstone (50%)	Mudstone (50%), Sandstone/Siltstone (50%)	Mudstone (60%), Sandstone/Siltstone (40%)	Primarily Sandstone; likely some Mudstone and/or Siltstone	Primarily Mudstone; expect some Siltstone and/or Sandstone	Primarily Sandstone; likely some Mudstone and/or Siltstone
RQD (%)	12-52	66 (FI=10 frac/m)	66 (FI=10 frac/m)	75	0-70	0-60	18-75
Strength Range (MPa)	0.2-104	45-90	45-91	30-160	20-40	0.5-67	11-57
Excavation Method							
TBM Manufacturer	Lovat	American Augers	American Augers	American Augers	American Augers	Robbins	Lovat
TBM Type	M126 Soft Ground TBM	Open TBM	Open TBM	Open-faced rotary wheel TBM	Open faced rotary wheel TBM	Mix Ground SBU-M with water jets	M100 Soft Ground TBM
Cutterhead details	Carbide scrapers only	Custom built by TunnelTec; 12" (305 mm) disc cutters and scrapers, able to exchange cutters with rippers for soft ground	Custom built by TunnelTec; 12" (305 mm) disc cutters and scrapers, able to exchange cutters with rippers for soft ground	6" (152 mm) disc cutters only	Step-shank carbide scrapers only	Mixed ground single disc; 6.5" (165 mm) disc cutters and carbide scrapers	Carbide scrapers only
Support							
Temporary	-	Steel ribs and timber lagging (1.5 m spacing)	Steel ribs and timber lagging (1.5 m spacing)	Steel ribs and timber lagging (1.2 m spacing)	Steel ribs and timber lagging (1.2 m spacing)	-	Steel ribs and timber lagging (1.2 m spacing)
Final	One pass pre-cast segmental concrete lining	Grout backfilled Hobas Pipe	Grout backfilled Hobas Pipe	Grout backfilled steel casing	Grout backfilled steel casing	Steel casing	Grout backfilled Hobas Pipe
Logistics							
Start Date	September 1, 2005	July 14, 2008	November 22, 2008	October 1, 2009	July 13, 2009	October 30, 2009	June 22, 2011
End Date	March 22, 2006	September 12, 2008	November 13, 2009	March 3, 2010	May 2010	November 13, 2009	October 4, 2011
Length of shift (hr)	10	10	10	10	10	12	10
Av. Advance Rate (m/shift)	5.3	7.7	4.8	2.9	1.0	6.0	~ 4
Min AR (m/shift)	1.0	-	3.0	0.6	0.6	-	-
Max AR (m/shift)	12.0	13.7	9.1	5.8	7.0	7.2	-

Water inflows encountered during construction of the first upper tunnel were reported to be in the “wet’ to “dripping” category (< 12 l/min/m), in accordance with design predictions. Inflows in the lower tunnel were higher in some sections, possibly in the “flowing” category (> 12 l/min/m); however these did not have a significant impact in the rate of advance.

3.3 Valley Ridge Feedermain – Bow River Tunnel

The Valley Ridge Feedermain consists of two distinct tunnel segments, one below the Bow River and the other passing below Canadian Pacific (CP) Rail lines. The Bow River tunnel was predicted to pass through primarily softer units; however the launch shaft excavation showed a high concentration of strong units (Finney et al., 2010). It was therefore decided to use a TBM with a rock cutterhead with roller cutters and no water jet in the excavation chamber. The tunnel encountered primarily soft units which caused major delays. The mudstone slaked readily, and the cutters often became clogged due to the sticking clay, requiring constant removal. A foaming agent was used to reduce the clogging and was found to be ineffective (Finney et al., 2010). As no water jetting was fitted to the machine, the operator was required to apply water to the face through the excavation chamber to mitigate the clogging of the cutters. At 0+75 m, the TBM became trapped, and a complete replacement of the cutting tools was required in order to free the machine.

The alignment of the Bow River tunnel veered off course, over 1.2 m, for a portion of the alignment which is thought to be partially due to the soft material in one of the walls of the tunnel. The deviation from the alignment was so severe that it resulted in the need for additional excavation in order to install the final steel pipeline. Overbreak was noted in the crown of the tunnel, 10-20 cm, but was confined to two to three zones, and was not prevalent the full length of the tunnel.

Maximum steady-state inflows in the order of 4 l/min/m were estimated prior to construction, characterized as “dripping”. No significant groundwater inflow problems were reported during construction.

3.4 Valley Ridge Feedermain – CP Rail Tunnel

A soft ground cutter head was selected by the contractor for the tunnel excavation, with step shank carbide bits installed in an open face rotary wheel cutterhead. Initial advance rates ranged from 3 m to 7 m per shift, however progress slowed significantly whilst the face was under the CP Rail tracks, to about 0.6 m per shift in what was described as hard sandstone. The contractor began more frequently replacing the carbide bits on the cutterhead, and a series of machine malfunctions and delays ensued (Finney et al., 2010). Despite the low advance rates the contractor chose to continue just until the TBM had cleared the tracks and a retrieval shaft could be sunk to assess the condition of the machine. Upon accessing the cutterhead from the retrieval shaft, it was revealed that the bull bar had cracked and lodged behind the back side of the cutterhead, causing substantial wear and scoring to the cutterhead (Finney et al., 2010).

The contractor then elected to replace the damaged cutterhead with one containing both step shank bits and roller disc cutters, to handle both hard and soft rock. Mechanical issues continued to ensue, and after a delay of several months, the contractor chose to employ the TBM used for the Bow River crossing, which had become available. This second machine was used to excavate in from the exit shaft to complete the tunnel.

Maximum steady-state inflows in the order of 0.3 l/min/m (“damp”) were estimated prior to construction. Higher water inflows, estimated at about four times the expected, were reported during construction. These inflows are believed to have been confined to a short section of the alignment, in a zone of highly fractured sandstone.

3.5 Beddington South Sanitary

The Beddington South Sanitary upgrade included a tunnel segment passing below Nose Creek and CP Rail tracks. The tunnel was drilled on a downward gradient and significant water inflows were expected. The tunnel passed through primarily weak mudstone units and as a result the advance rate was slower than the contractor anticipated. Significant slaking of the mudstone and gumming of the cutting tools was reported, however the water jets installed at the face mitigated the issue substantially. The water inflow along the tunnel drive was less than expected and manageable with a pump, with an additional pump on stand-by in case of flooding. It is thought that the sub-zero winter temperatures were a leading factor in the lower groundwater inflow than originally predicted, as the creek may have frozen to its bed (Draper et al., 2010).

3.6 16th Avenue Tunnel

This tunnel is part of the Nose Creek sanitary line, which has been installed within the Nose Creek floodplain in NE Calgary. At the 16th Avenue crossing, the west valley wall encroaches onto the floodplain, and detouring the alignment was not practical due to the presence of railway tracks and the creek itself. The subsurface conditions in this 300 m stretch were characterized as predominantly sandstone bedrock with some interbedded siltstone and mudstone, with floodplain soils in the portal areas. Because excavations in nearby areas had encountered predominantly mudstone, it was anticipated it could also be encountered during tunnel construction.

The TBM cutterhead was equipped with carbide scrapers projected from the face, an arrangement previously used to excavate weak rocks in the Edmonton area. Boring of the tunnel was relatively straightforward, except for relatively minor delays related to one electrical issue with the TBM. Slower advance rates were encountered within an approximately 10 m long section at about 80 m from the portal. This was initially ascribed to harder rock; however subsequent testing of rock cores extracted from the walls of the tunnel in this area yielded unconfined compressive strengths which were much lower than the 90 MPa recommended in the geotechnical report for selection of the cutting tools.

Overall, average advance rates in excess of 4 m per shift were achieved, and excavation of the tunnel was completed within the proposed schedule. No water inflows were reported.

4 DISCUSSIONS AND CONCLUSIONS

The recent tunnelling projects within Calgary have led to a greater understanding of the geomechanical behavior of the Paskapoo Formation. Due to the depositional characteristics of the formation, the rock is prone to high variability. The variability is a leading cause in delays in recent TBM tunnelling projects; partially due to the use improper cutting tools at the excavation face, or the effect of uneven face or wall strength on the machine or the alignment. It may be argued that in some of the cases, the use of inexperienced operators also had an impact on the delays experienced. By reviewing the cases above, it is clear to see that many similar issues present themselves throughout the city, and that the major consistency between sites is the variability of rock conditions along the alignment.

Many of the challenges faced in the projects can be mitigated by designing or choosing a cutterhead that is suited to the variable geology. Though the data reported to date is too limited to establish a conclusive correlation, it does appear that the use of mixed ground cutterheads, featuring a combination of disc cutters and scrapers would be the preferred option. Provision for water jetting at the cutterhead to mitigate clogging of the cutterhead when mudstones are encountered is also thought to be beneficial.

Consideration should also be given, during TBM selection, to the extreme conditions presented in the geotechnical investigation at the site, as well as to those known to exist within the formation throughout the region.

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