Recent experience with tunnels in weak rock in Calgary

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ABSTRACT
There is a paucity of data related to construction of tunnels in weak rock in Calgary. The primary objective of the paper is to document data collected during the geotechnical investigations at two recent tunnel crossings of the Bow River, focusing on mechanical and hydraulic properties relevant to tunnel design and construction, as presented in a GBR format. Semi-empirical techniques used for estimating groundwater inflows during construction are described. A brief description is provided of issues encountered during construction of the tunnels, which was carried out using open face tunnel boring machines and a two-pass lining system.

RÉSUMÉ
Les données sur la construction des tunnels dans le rocher faible à Calgary ne sont pas couramment disponibles. Un des objectifs primaires de cet article est de fournir les données recueillies pendant des programmes de reconnaissance réalisés récemment pour deux tunnels qui traversent la rivière Bow, tout en mettant l'emphase sur les propriétés mécaniques et hydrauliques pertinentes à la conception et la réalisation des tunnels, tel que présenté dans le rapport géotechnique d'avant projet. Les méthodes semi empiriques utilisées pour estimer le débit d'écoulement d'eau souterraine dans les tunnels, ainsi que les problèmes rencontrés pendant la construction des tunnels réalisés par tunneliers à front ouvert et par un système de revêtement à deux passes sont présentés dans cet article.

1 INTRODUCTION

Except for a few historic tunnels, there is virtually no published experience with design and construction of tunnels in Calgary. Recent growth in the City has led to the requirement for design and construction of municipal tunnels for water and sewage, with associated geotechnical investigations.

Two of these projects, the Valley Ridge tunnel and the 15th Street Siphon tunnels involved crossings of the Bow River and are discussed herein. Note that the Valley Ridge project includes a second tunnel, under a railway yard, which is still under construction and is not discussed in this paper.

After a description of the subsurface conditions, a brief overview of previously documented experience with tunnels in weak rock in Calgary is presented. The geotechnical investigation approach is then described, followed by the general characteristics of the two projects from a geotechnical perspective. The discussion and lessons learned focus on the rock mechanical properties in the case of the Valley Ridge tunnel, and the hydraulic conductivity in the case of the 15th Street Siphon tunnels.

2 SUBSURFACE CONDITIONS

The location of both projects is shown on Figure 1. In both cases, the entry and exit shafts were within floodplain and/or terrace deposits of the Bow River and characterized by a relatively flat topography.

The gravel deposits are underlain by bedrock of Paleocene age, belonging to the non-marine Paskapoo Formation (Hamilton et al., 1999). The bedrock consists of flat lying to gently dipping sandstones, siltstones, and mudstones (locally called claystones and/or clay shales). All three rock types are typically calcareous. No major faulting or folding has been reported, however the bedrock is known, from previous construction experience in the Calgary area, to contain jointed, more permeable zones. As well, there is often a weathered horizon near the bedrock surface.

3 PREVIOUS TUNNELLING EXPERIENCE

For each project, a Geotechnical Data Report (GDR) and a Geotechnical Baseline Report (GBR) were prepared. The purpose of this approach was to describe, in a concise manner, the subsurface conditions anticipated along the proposed alignments, and to set baselines for the geotechnical aspects of the design and construction of the tunnels and associated shafts.

A review of previous local tunnelling experience, however limited, was considered to be an integral part of the GBR.

3.1 Historic Tunnels

During the initial investigations for these two projects, the authors reviewed three historic small tunnel crossings of the Bow River, located at 15th Street SE (immediately upstream of the new tunnels), 21st Street SW, and 14th Street SW. Information from the 15th Street SE tunnel is reviewed below.

Few construction details are available for the 15th Street SE tunnel, built in 1911 and located about 350 m upstream of the new tunnels. This old tunnel contains a 750 mm sanitary sewer and a 500 mm water main which were still in operation at the time of writing. This tunnel has a rectangular section (Width: 4.4 m & Height: 2.6 m), and is lined with reinforced concrete.

The tunnel is in bedrock, as determined from historic drawings, with a bedrock cover ranging from 5 to 7 m, estimated from an old longitudinal section which contained information from borings. The tunnel length is in the order of 300 m. Construction details are not available, however it is known that excavation of mine tunnels was well established in Alberta at the time.

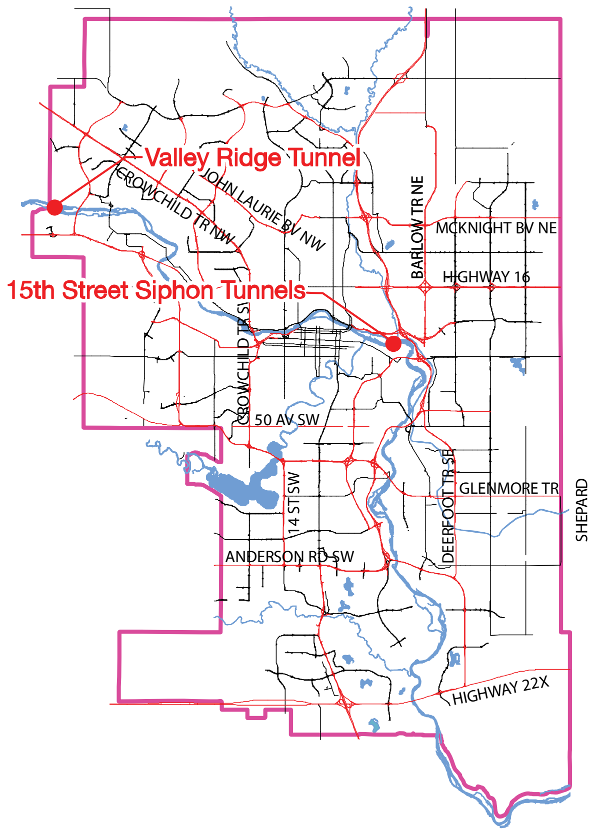

Figure 1. Location of the two projects in Calgary

3.2 Glencoe Tunnel

This stormwater storage tunnel was constructed in southwest Calgary between April of 2005 and March of 2006 (Al-Batteineh, 2007, Thurber, 2005). The tunnel is 935 m in length, 2.9 m in diameter, and has a cover ranging from 16 m to 42 m. The tunnel is lined with a single pass pre-cast concrete segmented liner.

The tunnel was constructed through approximately 350 m of a medium plastic, very stiff to hard clay till on the east end, with the remainder of the alignment within claystone, siltstone and sandstone bedrock, similar to that encountered at the Valley Ridge and 15th Street Siphon projects. Tests yielded highly variable unconfined compressive strengths, ranging from 0.2 MPa to 104 MPa, Rock Quality Designations (RQD's) typically in the range 20% to 50%, and hydraulic conductivities in the range 1 x 10^{-2} cm/s to 9 x 10^{-4} cm/s. The water table was mostly above the tunnel crown, with a head of up to 4 m.

Tunnel boring was conducted with a Lovat M126 soft ground TBM, owned and operated by the City of Edmonton. According to City of Edmonton staff, tunnel excavation productivity was hindered by the occurrence of alternating 'soft' and 'hard' bedrock layers, which required a one-time replacement of the cutting teeth. Actual TBM production rates were 8 m per 10 hour shift in the clay till, 4 m per shift in the transition from soil to bedrock, and 5 m per shift in the bedrock.

Relatively large volumes of water inflow, estimated at 21 l/min/m, were encountered within a short section in the bedrock, requiring post-construction chemical sealing of the concrete segments in this area.

4 GEOTECHNICAL INVESTIGATIONS

The geotechnical assessments for the Valley Ridge and 15th Street Siphon projects were completed using a similar, phased approach. Initially, a desk study consisting of a review of available geological and geotechnical information was conducted, to provide input into the selection and fine-tuning of the crossing method. Field investigations were subsequently performed, initially involving relatively limited drilling and geophysical methods (combination of seismic refraction and ground penetrating radar - GPR), followed by additional drilling and coring of the bedrock.

Test holes were typically drilled using a Becker Hammer or ODEX downhole hammer rig through the upper gravels, with casing set into the top of bedrock. This was followed by continuous coring with HQ (nominal 61 mm diameter) triple tube wireline equipment and water flush. Both on-land and in-stream test holes were drilled to depths of one to two tunnel diameters below the proposed tunnel invert. All holes were drilled with an offset of 5 m to 10 m from the future tunnel walls, and were grouted to the top of the bedrock upon completion.

Preliminary logging of the core was completed in the field, and the core was returned to Thurber's laboratory in Calgary for detailed logging, photography, and testing. Coring was typically conducted in 1.5 m (5 ft) runs, with total core recovery (TCR), solid core recovery (SCR), and rock quality designation (RQD) measured in the field. Typical tests included moisture contents, Atterberg limits, grain size and swelling tests (in claystone samples), point load and unconfined compressive strength (UCS) tests, and a limited number of CERCHAR abrasiveness index tests (Plinninger et al., 2004).

Standpipe piezometers and nested vibrating wire piezometers were installed within the proposed tunnel depths, on both banks, to establish the piezometric conditions. Pump tests, rising head tests and constant head packer tests were conducted in selected test holes and at selected depths using a double packer system, in general accordance with the method outlined by CANMET (1976).

Some of the relevant data collected at both sites is discussed in the following sections, in conjunction with the presentation of the two projects. Emphasis is placed on the mechanical properties in the case of the Valley Ridge tunnel, and the rock hydraulic conductivity in the case of the 15th Street Siphon tunnels.

5 VALLEY RIDGE TUNNEL

5.1 Project Overview

The project is located in northwest Calgary, approximately 1 km west of the Stoney Trail bridge, north of the TransCanada Highway (Figure 1). It is part of the City of Calgary's Valley Ridge Feedermain project, which will consist of a 900 mm feedermain connecting the Tuscany Phase 1 feedermain on the north side of the river, and the South Big Hill feedermain on the south side of the river.

A key component of the project is a crossing of the Bow River and part of a golf course on the south side, which included an approximately 280 m long, approximately 1.5 m diameter tunnel and associated (temporary) launching and receiving shafts. The tunnel was entirely in rock, with a minimum rock cover between the crown of the tunnel and the river thalweg, as established using GPR, of 10.6 m or approximately 7 tunnel diameters (Thurber, 2008).

5.2 Geotechnical Assessment

A GDR and a GBR were included with the design drawings and specifications. The following descriptions are based primarily on statements given in the GBR.

The surficial gravel deposits are underlain by flat lying to gently dipping sandstones, siltstones, and claystones. Bedding was near horizontal, with unit thicknesses ranging from a few centimetres to several meters. The siltstones and sandstones are typically much stronger than the claystones, which can have the consistency of a stiff to hard clay and are often high plastic. These lithologic units typically grade gradually from one rock type to another, with few clear unit boundaries. The units are interfingered and laterally discontinuous, precluding the establishment of correlations between borehole locations.

The GBR stated that variable conditions would be encountered during excavation of the tunnels and shafts, with interbedded strong and weak layers. It was noted that either claystones or siltstones/sandstones, which are much stronger, could comprise up to 100% of a tunnel or shaft excavation face at any given location. It was not considered practical to estimate the relative percentages of rock types along any of the excavations in an accurate manner. For baseline purposes it was stated that claystones would comprise 50% of the total volume of material excavated along the tunnels and shafts, with the remainder being stronger siltstones/sandstones.

Unconfined compressive strengths (UCS) were determined from laboratory tests performed on intact bedrock cores, generally on fresh (non-weathered) samples and ranged from 0.1 to 154MPa. Based on the histograms presented on Figure 2, and bedrock strengths measured at the 15th Street Siphon and the Glencoe tunnels, the stated baseline UCS was 90MPa for selection of cutting tools, and 2.5MPa for design of the initial rock support for tunnels and shafts. Average RQD of the material more than 3m below the top of rock was 67%, increasing to 71% for material more than 5m below the top of rock. For baseline purposes the RQD was defined as 70% with a fracture frequency of 10 fractures/m (sub-horizontal fractures).

Based on the results of index testing, the claystone bedrock was classified as moderately to highly plastic with a moderate to high swell potential according to criteria presented by Taylor and Smith (1986). The results of two one dimensional free swell tests performed with distilled

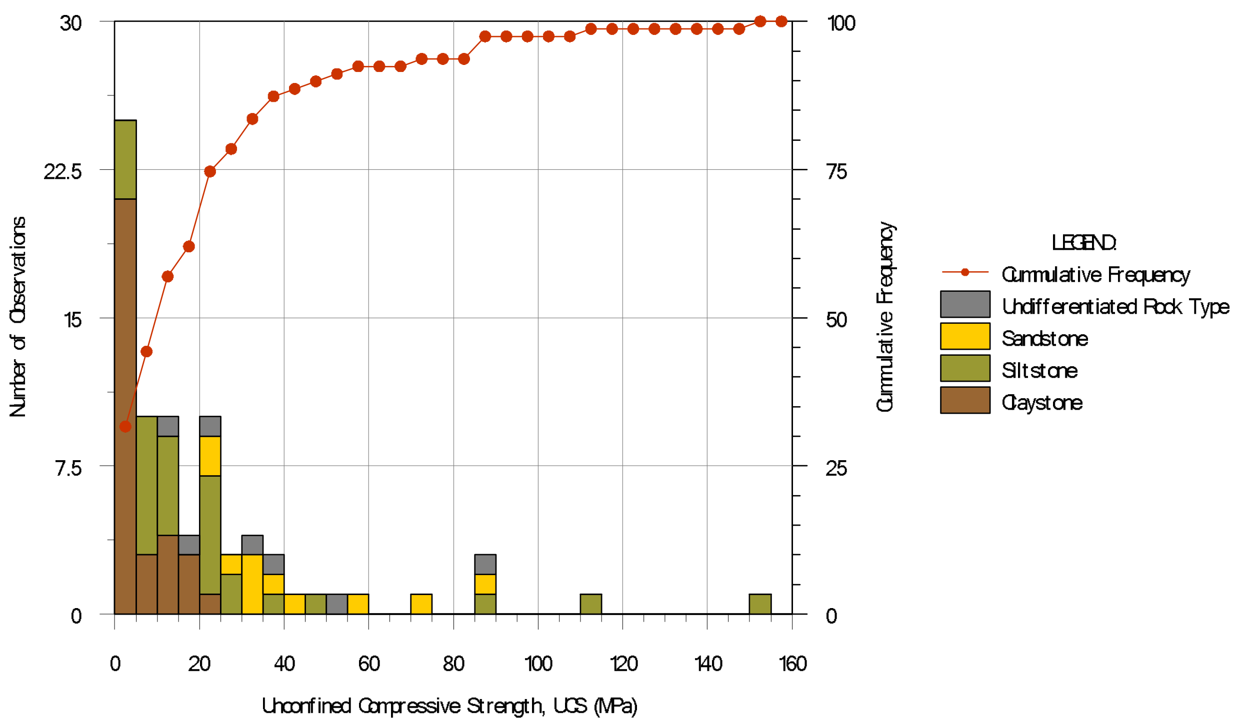

Figure 2. Histogram of Unconfined Compressive Strength Test Results for the Valley Ridge Site

water indicated a very high initial rate of swelling (up to 14% uniaxial strain for the 10-100 minute log cycle). During the investigation, some of the claystone bedrock was found to slake i.e. lose strength and disintegrate on contact with water. The possibility that TBM cutters appropriate for the stronger siltstones and sandstones would "gum-up" in the softer claystone was also highlighted.

5.3 Construction

Construction aspects and performance were published by Finney et al. (2010) and are summarized below.

The contractor elected to bore the tunnel with a 1.524 m (60 in) tunnel boring machine (TBM), with a radial overcut of 12 mm (0.5 in). Primary support was provided by timber lagging and steel ribs spaced at 1.2 m. The contractor employed an open face rotary wheel TBM with 0.15 m (6 in) roller disc cutters (and no scrapers). According to Finney et al., it was anticipated that higher strength bedrock encountered at the bottom of the entry shaft would be present throughout the drive and would be more effectively mined with a rock cutterhead rather than a soft ground one.

After launching the TBM in November of 2009, the advance rate was about 0.6 m per 10 hour shift, only increasing to about 2.7 m per shift after a change in operators. The contractor repeatedly had to clean out the disc cutters, which became clogged with the claystone, which slaked and turned to very sticky clay in the presence of seeping groundwater and air.

The TBM had no provisions for water jetting, and to facilitate tunnelling, the contractor applied water to the excavation chamber from a port within the chamber. In addition the contractor tried adding a foaming agent to the excavation chamber to facilitate the breakdown of the clay materials. The foaming agent was found to be ineffective and was discontinued.

Following a relatively long holiday break, construction resumed at a much higher rate of advance of about 5.8 m per shift, with an experienced operator at the controls. The tunnel was completed in March of 2010.

6 15TH STREET SIPHON TUNNELS

6.1 Project Overview

The project is located east of Calgary's downtown area, near the Calgary Zoo and at the confluence between the Bow River and Nose Creek (Figure 1).

The siphon was needed to increase capacity of the existing sewage transmission across the river, which presently consists of a 750 mm main installed in the aforementioned historic tunnel, and 900 mm and 1200 mm mains installed by open cut in 1961 and 1974, respectively (Strayer, 2008).

The siphon consists of two separate CCFRPM pipelines of 1.65 m diameter, over an approximately 290 m long crossing length in two stacked 2.5 m diameter tunnels (note that this arrangement was not known at the time of the investigation). The 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.

6.2 Geotechnical Assessment

As in the case of the Valley Ridge tunnel, a GDR and a GBR were included with the contract documents. Because this was the first tunnel crossing of the Bow River in recent times, the paucity of published data on hydraulic conductivity of the bedrock, and because the three aforementioned historic tunnels are presently flooded, the potential ingress of groundwater during construction had to be investigated in detail, and reported in clear baselines of anticipated subsurface conditions upon which bidders could rely.

As in the case of the Valley Ridge tunnel, the bedrock consisted of nearly horizontally bedded sandstones, siltstones and claystones. A particular feature of this location was the presence of a deep buried channel, incised into bedrock during geologic time and approximately parallel to the alignment of the tunnels. Geotechnical drilling performed in the initial phases of the project showed that the top of the bedrock within this channel was at least 10 m deeper than that at the existing historic tunnel, located approximately 350 m upstream. There was also qualitative indication from geophysical surveys that the top of bedrock was uneven, with the presence of sub-channels within the main buried channel to an elevation well below the river bed.

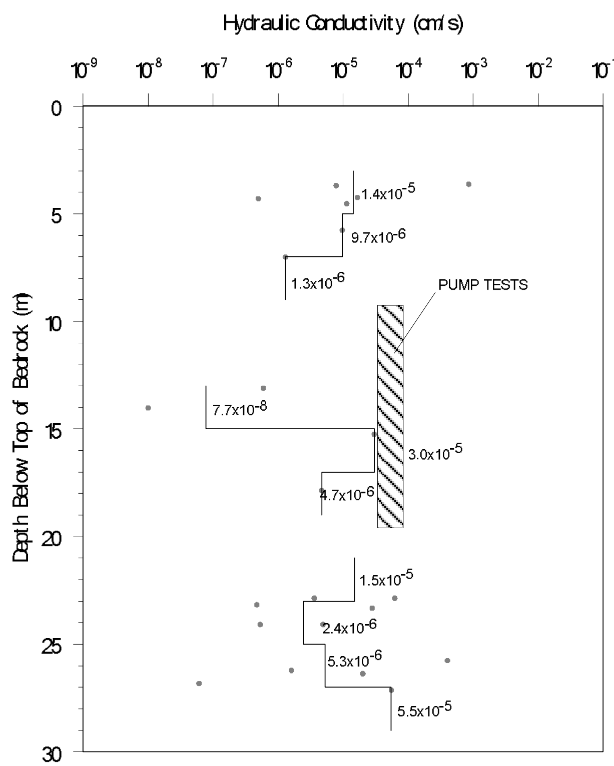

Figure 3. Bedrock Hydraulic Conductivity with Depth

To investigate the occurrence of jointed, more permeable zones and the potential connectivity with the river, pump tests and rising head tests and/or constant head packer tests were conducted at selected locations and depths, both on land and in-stream. Hydraulic conductivities derived from these tests ranged from about 10^{-8} cm/s to 10^{-3} cm/s, with no apparent trend with depth, as illustrated in Figure 3. As well, no meaningful correlation with RQD or fracture density was found. A histogram of hydraulic conductivities measured in 22 in-situ tests is shown on Figure 4.

The geometric mean was 6.6×10^{-5} cm/s for the pump tests and 5×10^{-6} cm/s for the rising head and packer tests. The maximum and minimum hydraulic conductivities measured in these tests were 8.6×10^{-4} cm/s and 1×10^{-8} cm/s, respectively.

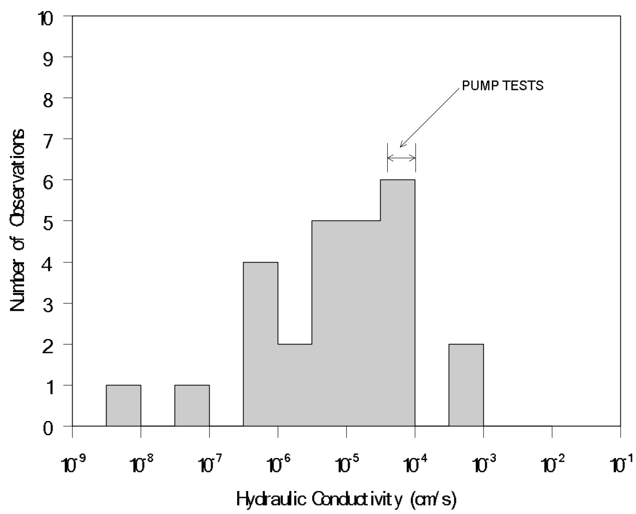

Figure 4. Distribution of Hydraulic Conductivities.

Note that these hydraulic conductivities were assumed to represent a homogeneous isotropic porous medium, which is a significant simplification, but necessary for the analyses and interpretation of inflows. Note also that the hydraulic conductivities were not considered to be baselines – instead, baseline estimates of groundwater inflows were obtained using the semi-empirical procedure outlined by Heuer (1995, 2005). This procedure provides an estimate of percentages of tunnel length which will experience different intensities of long term steady state inflow (q_s), and provides an estimate of possible initial heading inflow (q_i). Initial inflows are usually higher than steady state inflows due to factors such as the three-dimensional nature of the flow near the excavation face, and storage depletion.

Inflows were estimated and presented in the GBR for 1.5 m and 5 m diameter tunnels, as at the time the actual construction scheme had not been established. The analyses indicated that about 90% of the tunnel, irrespective of the diameter, would have inflows in the "damp" to "dripping" category (less than 2.4 l/min/m). However, about 10% of the tunnel would have more significant heading and/or steady state inflows, in the "flowing" range (more than 12 l/min/m). Note that the initial inflows in the Heuer method are determined using semi-empirical correction factors, and it is not possible to establish the time required for the initial inflows to decrease to the steady state values. To determine pumping equipment requirements, the GBR stated that the estimated values should be multiplied by the length of exposed bedrock within the tunnel, dependent on the construction methodology.

6.3 Construction

Planning and construction aspects for this project have been published by Strayer (2008),Tunnels & Tunnelling (2008), and Lukez (2008). Construction details have not yet been published.

The first (upper) bore was initiated in mid July, 2008 and completed in mid September, 2008, with normal and peak advance rates of 10.7 m and 13.7 m per 10 hour shift, respectively. The second (lower) bore started in November of 2008 and was only completed in November of 2009, due to mechanical problems experienced with the TBM. This ultimately led to removal of the TBM from the site for repairs, for several months.

The contractor elected to bore two stacked tunnels about 2.5 m in diameter using an American Augers TBM. According to Lukez (2008), the machine was equipped with a specially designed cutterhead, capable of handling the conditions outlined in the GBR, and with two arrangements – one consisting of disk cutters for hard rock applications, and one cutterhead arrangement of ripper teeth for soft rock conditions. Lukez further states that the TBM was going to be launched in "disk cutter" mode based on the conditions reported in the GBR, but to be modified "based on the in-situ conditions of the excavated rock encountered" during the shaft excavation.

The primary support consisted of timber lagging and steel ribs spaced 1.5 m, with the annulus between the carrier pipes and the primary support backfilled with a light weight cellular concrete.

Detailed records of groundwater inflows during construction are not yet available. Based on information provided by the contractor during site meetings, inflows into the first upper tunnel were in the wet to dripping category, in agreement with the baselines. Inflows in the second, lower tunnel were apparently higher in some sections of the tunnel, possibly in the "flowing" category but still in agreement with the GBR.

7 CONCLUDING REMARKS

Planning, design and construction of the recently completed Valley Ridge and 15th Street Siphon crossings of the Bow River in Calgary required comprehensive geotechnical investigations, conducted in several phases, with the results for each of the projects incorporated into a Geotechnical Data Report (GDR) and a Geotechnical Baseline Report (GBR). The phased investigations included an initial desk study using existing subsurface information available for each project area, followed by two additional site-specific field programs. This phased approach was beneficial in the selection and final design of the crossing methods.

Incorporating a GBR into the tendering process and contract documents is beneficial from a risk management perspective in that it streamlines the process of resolving claims where conditions encountered during construction fall outside of prescribed baseline limits. However, considerable effort and communication between the owner and consultant(s) is recommended to establish what the baseline statements should be. Tunnelling contractors also need experience in how to properly interpret the information provided in the GBR, which may require the assistance of a geotechnical engineer with experience in tunnel construction.

From the perspective of a rock mass characterization for selection of TBM cutting tools, based on this recent experience, bedrock in the Calgary area should be considered extremely variable. The siltstones and sandstones are typically much stronger than the claystones, and the units typically interbedded in such a manner that there is little or no lateral continuity between them. Attempting to correlate individual bedrock units between test holes is virtually impossible, and not recommended. Based on experience gathered during the investigation and construction phases of both tunnels, any of these units can be encountered in a tunnel or shaft excavation face at any given location.

8 ACKNOWLEDGEMENTS

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