TBM selection and performance prediction for shallow tunnels in interbedded sandstones and siltstones

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ABSTRACT

In urban settings it has become fairly commonplace for infrastructure projects to use Tunnel Boring Machines for tunnel construction through both soil and rock. The selection and performance of a tunnel boring machine depends on geomechanical conditions within the proposed tunnel alignment. In interbedded sedimentary rocks, such as sandstones interbedded with clay and siltstones, the conditions at the face and within the walls of the tunnel behind can be highly variable, both along the tunnel and within the same tunnel cross section. Case studies in Calgary, AB are used to highlight the challenges faced and potential for improvements in the methodology.

RÉSUMÉ

Dans les centres urbain, il est devenu assez courant pour les projets d'infrastructure à utiliser le tunneliers mécanique (TBM) pour la construction de tunnels à travers le sol et la roche. La sélection et la performance d'un tunnelier dépend des conditions géomécaniques dans l'alignement du tunnel proposé. En roches sédimentaires interstratifiés, comme les grès interstratifiés avec de l'argile et de siltstones, les conditions au façade et dans les murs du tunnel peut être très variable, tant le long du tunnel et dans la section du tunnel de la section transversale. Des études de cas à Calgary, AB sont utilisés pour mettre en évidence les défis à relever et les possibilités d'améliorations dans la méthodologie.

1 INTRODUCTION

Initially when tunnel boring machines (TBM) were introduced to the construction industry, their dominant drawback was their inefficiency at advancing through difficult or variable geology. TBMs are well known for their superior advance rates through strong competent rock, resulting in tunnels with limited over break which were completed on or before schedule. However, if the alignment passes through varying lithologies of differing strength or structure, the advance rate of the TBM reduces dramatically. (Morimoto & Hori, 1986)

As geology is rarely uniform, the design of cutterheads and machine mechanics have been further improved and modified in order to accommodate the varying geology encountered. Soft ground TBMs, hard rock TBMs and mixed ground TBMs are all tailored to the predicted geologies along the project alignments.

Sedimentary rocks present an added challenge for TBM tunnels when the sedimentary layers vary in geotechnical properties and the layers are of significant width. If, for example, thin claystone layers are present within thick massive sandstones, the claystone layers act structurally similar to a joint surface and do not significantly affect the unit. However, if the weaker layers are of significant scale relative to the tunnel diameter, differential conditions can be experienced at the face, where the TBM must penetrate through both harder competent layers and softer layers. This can cause delays both with penetration rates and maintenance of the machine itself.

Small diameter tunnels are highly susceptible to the influence of sedimentary layering in the face due to the relative scales of the layers to the cutterhead size.

2 TUNNEL BORING MACHINES

Tunnel boring machines are full faced mechanized machines which use an arrangement of cutters and/or scrapers to break and excavate through rock and soil units. The choice to use TBMs during a tunnelling project is often linked to the length of the tunnel drive and the re-usability of the TBM upon completion. (Barla & Pelizza, 2000)

Large diameter projects often require a specially designed TBM for the project which typically limits the re-usability of the machine. However, for small diameter tunnels, contractors can often use refurbished machines as long as the cutterhead is either new or the correct arrangement for the materials. (Girmscheid & Schexnayder, 2003)

2.1 Types of Machines

Several types of machines exist in order to accommodate TBM excavation methods in varying geological settings. TBMs are subdivided by the International Tunnelling Association (ITA) by both the support typology that the machine is able to supply and the type of ground that it is able to operate in. (Guglielmetti et al., 2008)

The most common rock tunnelling machines are: unshielded (open), single shield, and double shield. Unshielded TBMs are used in “good” to “very good” ground conditions with primary support systems using rock bolts, shotcrete, steel sets, etc. Single shield TBMs are suited to “soil” or “weak rock”, where support is necessary almost immediately after excavation. Double shield TBMs are used in homogeneous ground ranging from “poor” to “very good” rock. The double shield can support immediately behind the machine similarly to the single shield TBM, but also allows for continual work cycles without immediate support in good ground conditions. (Guglielmetti et al., 2008)

The most common soft-ground tunnelling machines are slurry shield and earth pressure balance machines (EPBM). Both soft-ground TBMs exert a positive pressure on the face in order to support the face. The pressure exerted by the machine is greater than the earth pressure from the surrounding ground. Slurry shield machines are typically used in sandy and gravelly soils, often with significant groundwater pressures. EPBMs on the other hand are mostly used in clay and silty ground and are also able to excavate in saturated ground. (Guglielmetti et al., 2008) (Babendererde et al., 2004)

2.2 Machine Selection

Tunnel boring machine selection is based predominantly on 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, as are the overall ground water conditions and in situ stresses along the alignment. (Girmscheid & Schexnayder, 2003)

In homogeneous soils or rock, it is fairly simple to select the appropriate TBM type as long as the material properties have been adequately established. When non-uniform rock masses are within the scope of the project, classification systems are often used to represent the heterogeneous material with one representative grouping.

2.2.1 Rock mass classifications

Within industry, three common classification systems are used, both to initially classify the rock mass and, in some cases, also to determine the required support systems. Rock Mass Rating (RMR) and the Norwegian Q-system are used to both classify and assign required structural support, whereas Geological Strength Index (GSI) is used primarily to classify but can be associated to various case specific support systems.

The specific application of each classification system is not discussed at length in this paper but further details are provided by Hoek (2007) and Marinos et al. (2005).

When the classification method can adequately classify the varying rock mass with narrow range in the quality of the rock, the classification can often be directly used to select the appropriate TBM for the geological conditions using straightforward selection charts or tables. However, if too much range exists within the rock mass, the resulting wide range in classification does not easily translate to a TBM selection.

Direct correlations between classification systems and TBM selections and TBM performance predictions have been attempted, but have not proven universally applicable to date. (Sapigni et al., 2002) (Taheri & Borujeni, 2008)

3 IMPACTS OF VARRYING LITHOLOGIES IN SEDIMENTARY ROCKS ON EXCAVATION BY TBM

As previously mentioned TBMs are sensitive to varying geology, this section focuses primarily on tectonically undisturbed but lithologically varied sedimentary rocks. Figure 1 shows a schematic of potential conditions which can be expected within interbedded sedimentary rocks.

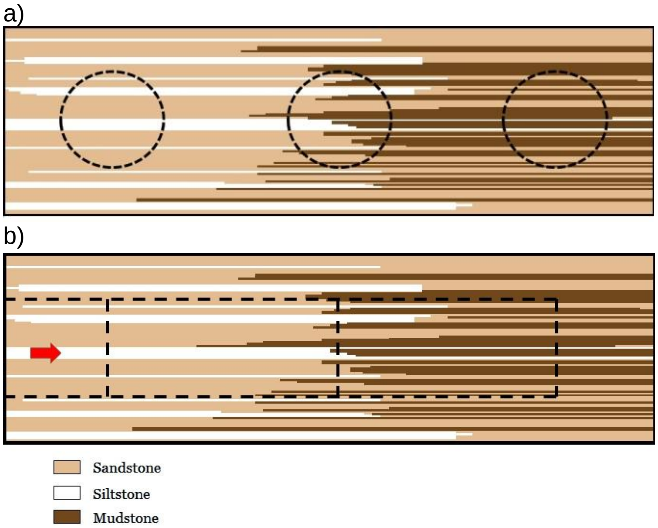

Figure 1: Potential cross-sections through varied sedimentary rock; a) lithological variation within the cross section of the face, b) lithological variation along the alignment.

3.1 Stability

Horizontally bedded sedimentary rocks often have similar structural properties in the roof of a tunnel as horizontal beams. When left intact, the layers can often be extremely competent and structurally sound; however, if the layers are cut by the excavation in roof weak point is established and the layer becomes significantly more prone to failure.

Overbreak in the roof of the excavation is the most common instability linked to circular tunnels through sedimentary rocks. As the rocks are not influenced by tectonics, stresses on the opening are limited to overburden. In shallow tunnels, stresses are not expected to present a significant design challenge.

3.2 Excavation

Excavation of lithologically varied sedimentary rocks is where the majority of the penetration and advance rate delays can be associated with respect to TBM excavation of tunnels.

3.2.1 Cutters & Scrapers

Boundaries between the weak units and stronger layers can result in increased cutter wear. The weaker layers tends to undercut the stronger layer which creates a step in the face when the cutter reaches the more competent rock. The step can cause chipping and intense wear to the cutters depending on the strength of the rock units and the abrasivity. Cutters could be dragged across the face if broken and not immediately replaced, causing them to wear down several inches.

Cutterhead arrangements can be modified to accommodate both cutters and scrapers on the head to allow for removal of a variety of geo-materials. If a softer unit is encountered, the cutters press into the unit slightly and the partly recessed scrapers are able to excavate the face. However, if the material is not efficiently removed from the face, the muck has a large chance of sticking to the cutters and therefore reducing the efficiency upon return to the stronger rock without significant maintenance.

3.2.2 Uneven strength in the face and walls

In order to optimize penetration of the tunnel boring machine, an even pressure is ideally applied to the face of the tunnel. When the strength of the rock at the face varies significantly a differential pressure can develop on the cutterhead. This differential pressure applies significant wear on the machine and is the main cause of bearing failures. Bearing failures cause significant delays in a project, especially in small diameter tunnels, where the machine must be completely removed in order to replace the bearing.

Uneven strength of the walls can cause significant issues with controlling the alignment of the tunnel. If one portion of the tunnel wall is weaker than the remaining rock, the TBM will tend to veer (sink) towards the weaker unit. Figure 1a illustrates differential strength conditions in the tunnel walls in the central schematic, where the TBM would be tend to veer towards the weaker mudstone layers to the right. In extreme cases, the entire machine can twist within the alignment, causing operational delays more than penetration.

3.2.3 Groundwater

Water significantly affects sedimentary rocks as they can range highly porous sandstones to swelling claystones. In the case of highly porous sandstones, an open face TBM is not recommended if the ground water table will be above the tunnel alignment during the tunnel drive. A slurry shield machine would be better suited to the conditions. However, in many cases water inflow can adequately be controlled by using a pump near the face to remove excess water from the tunnel.

In the case of swelling clays, or claystones susceptible to slaking, it is common for the clay rich muck to clump up and stick to the equipment. This process not only limits the amount of material able to be removed from the face, delaying the advance, but also causes significant maintenance issues throughout the machine, from the cutter head to conveyor system to waste removal. Soil conditioning can improve the conditions at the face, where conditioning agents are added to the muck to prevent conglomeration of the clay particles. However, additional infrastructure is required to mix the conditioning agent and to dispose of the conditioned muck.

4 CASE STUDY: THE CALGARY TUNNELS

Calgary, AB, is a city with a history of periods rapid population expansion, followed by periods of ‘catch-up’ for the city`s infrastructure. Currently the city is in the process of upgrading and expanding the city`s water and sewer systems to meet the increasing pressures from the growing population. As much of the work is below main roadways and watercourses, trenchless excavation methods have become a competitive design option for the more common ‘cut and cover’ techniques previously used in the city.

Due to the small diameter project scales, and project logistics, TBM tunnels have been the common design solution for the recent works in the city. However, due to the highly variable and unique geology, advance rates of the recent works have suffered. By reviewing the issues faced by excavating in Calgary, future construction project designs may be further tailored to optimize the excavation through the unique rock.

4.1 Geological Setting

Calgary is located about 90 km east of the Front Ranges of the Rocky Mountains. The city is underlain by up to 80 m of unconsolidated glacial sediment, from the Pleistocene glaciation. (Osborn, 1998) Below the surficial sediments Calgary sits at the transition point between two bedrock formations of southern Alberta; the Paskapoo and Porcupine Hills Formations. The boundary between the formations is often debated within the geological community, being tied to a depth or surface location. (Osborn, 1998) The case studies reviewed in this paper all fall within the Paskapoo Formation.

The Paskapoo Formation is Paleocene in age and consists of interbedded sandstone, siltstone and mudstone units. The Paskapoo was formed in a non-marine environment at the tail end of the compressive tectonics from the Cordielleran mountain building event. The deposits were formed in a very low energy meandering stream environment with point bar, overbank clays and flood plane deposits. The Paskapoo is the final Formation deposited in the Rocky Mountain Trough, the sedimentary basin that formed along the eastern edge of the Rockies. (Osborn, 2006) As the deposit occur after the Cordielleran mountain building event, the formation has been virtually tectonically undisturbed, with the primary lithification source being vertical compression.

Widespread uplift led to the erosion of the upper 2-4 km of the Paskapoo bedrock during the Eocene to Miocene, which resulted in a network of burried river channels along the top of the majority of the formation. (Dawson, F. M. et al., Unknown)

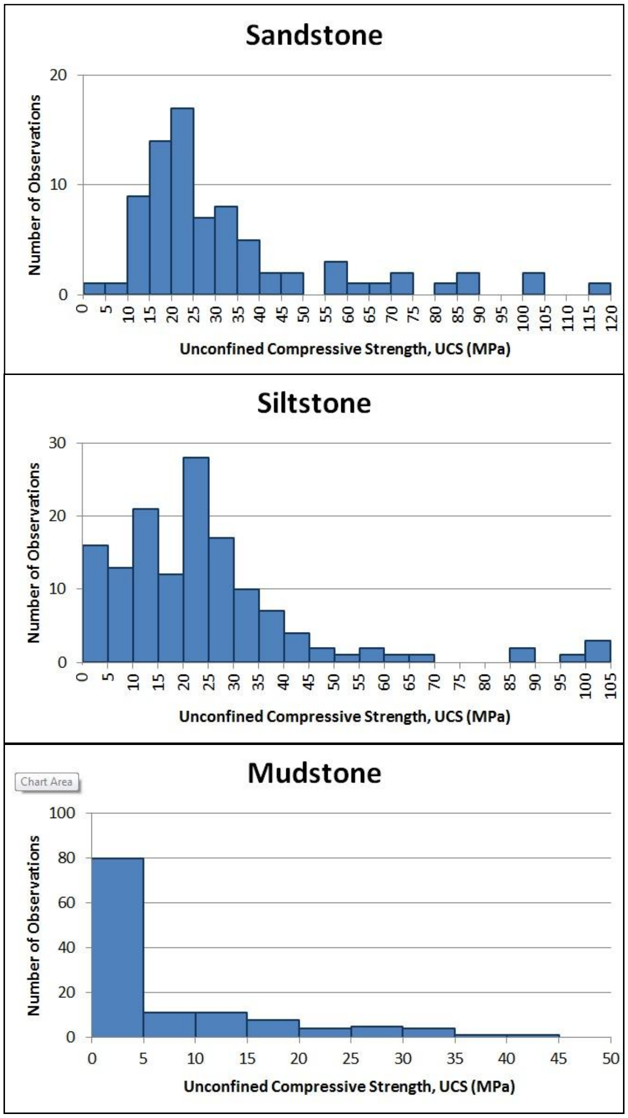

Figure 2. Distribution of UCS results from various projects around Calgary as collected by Thurber Engineering Ltd.

4.1.1 Geotechnical Properties

Due to the interbedded structure of the Paskapoo Formation, the geomechanical properties of the rock can vary significantly both horizontally and vertically.

Sandstone

The major rock type of the Paskapoo is the sandstone, which ranges from very fine grained to medium grained with a silica cement. The unit is an important aquifer for the region which leads the rocks to have localised areas of high porosity and lower cementation. The sandstone has also been previously mined for use as building stone throughout the city's development which demonstrates that in various regions the sandstone has a greater cementation to enable good structural integrity. (Osborn, 1998)

The primary depositional environment for the sandstone is a point bar deposit, and therefore it is common to have exposed units fining upwards with observable structures such as cross bedding. The units vary in strength both between deposition layers and horizontally within the layers themselves. The units have a measured UCS ranging from 3.6 to 116.6 MPa with an average measured UCS of 32.9 MPa and a standard deviation of 23.8 MPa. The large range of uniaxial compressive strength illustrates the range in quality of the sandstone and the degree of cementation. See Figure 2.

The sandstone is significantly interbedded with large siltstone deposits and numerous smaller mudstone deposits.

Siltstone

The siltstone layers have been a tested UCS ranging from 0.1 to 104.4 MPa, with an average measured UCS of 24.3 MPa and a standard deviation of 20.5 MPa. See Figure 2. The siltstone unit is often found to be more competent after prolonged exposure at surface than the sandstone unit.

Siltstone layers can range in thickness from less than a meter to a few meters in thickness.

Mudstone

The Paskapoo mudstone unit is the most problematic layer within the sequence for tunnel excavation. The unit ranges in description between the terms mudstone, claystone and locally within Alberta as clayshales. The unit ranges in strength from 0.08 to 40.2 MPa with an average strength of 7.2 MPa and a standard deviation of 9.3 MPa. See Figure 2. Accurate UCS results are difficult to obtain as core is rarely competent and in adequate condition for testing when retrieved. Point Load testing also presents challenges due to the softness of the rock and tendency for the points of contact to penetrate the sample prior to failure, which reduces the validity of the results.

The mudstones are prone to slaking when exposed to water or air, losing the majority of the structural integrity of the unit. When exposed to water the unit often degrades to soil like properties.

Mudstone layers range from a millimeter to more than a meter but are often less than 0.5 m.

The units within the Paskapoo are interbedded and often vary significantly even to the outcrop scale, which means that correlation between boreholes is difficult and often time unreliable.

4.2 Recent Projects in the City

Within the past 6 years, at least five projects have been undertaken which involve tunnel boring machines in various locations throughout Calgary. The five projects reviewed in this paper include: the Glencoe storm water tunnel, 15th Street siphon, Beddington Trail trunk sewer upgrade, Confederation trunk sewer and the Valley Ridge feedermain. Locations are shown on Figure 3.

The projects completed or currently under construction in Calgary are small scale tunnels which range from 0.75 m to 2.92 m in diameter. The TBMs used for the tunnels range from a shielded soft face TBM to small rock head boring machines.

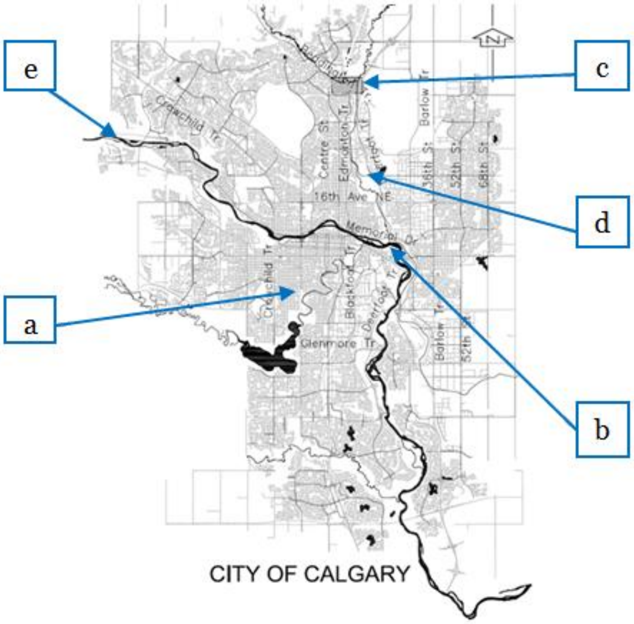

Figure 3. TBM project locations in Calgary AB; a. Glencoe storm water tunnel, b. 15th Street siphon, c. Beddington Trail trunk sewer upgrade, d. Confederation trunk sewer, e. Valley Ridge feedermain.

4.3 Successes and Struggles

Each project experienced a few setbacks during construction, often caused by the geology. A large contributor to delays was the mudstone layers, whether or or not the material was expected.

The mudstone often presented significant maintenance delays, with nearly every tunnel reporting troubles with clay sticking to the cutterhead and the surrounding machine. The issue was addressed by the application of foam at one site, with no significant improvement. Most sites used water on the face to loosen the clay from the machine, which also could have led to increasing volumes of sticking muck.

A significant challenge in the Calgary bedrock was the differential wall strengths causing the TBM to veer off course. Over one half of the case studies experienced at least one instance of the tunnel straying from the alignment, resulting in kinks and bends. This not only delayed the project due to the necessity to return to the intended alignment, but caused various complications later with infrastructure installation which required a straight path. For certain tunnels, the tolerance of the original infrastructure design did not allow for excessive deviation from the alignment and correcting excavations were required.

In one project, penetration rate decreased significantly in the second bore, to the point that the material was heavily tested to ensure that it was not too strong for the machine. The decrease in penetration rate was ultimately attributed to failure of the main bearing. The primary cause for failed bearings, as mentioned previously, would be differential strengths of material in the face. The predicted conditions of the face could be represented by the middle advance of Figure 1b. In order to replace the bearing, complete removal of the TBM and temporary support was required, leaving the tunnel unsupported and water filled for up to three months. Upon re-entry overbreak was observed within the tunnel roof, but did not present significant stability concerns. Penetration rates increased significantly with the new bearing.

Although groundwater was predicted to be a significant concern for many sites, many of them experienced less water than predicted. However, in projects where significant ground water was predicted but not observed, often the mudstone was more susceptible to slaking and sticking to the machine, which indicates the water may have been present within the unit and less flowing than originally predicted.

Where a soft-face TBM was used to excavate through both soil and rock units throughout the drive, significant challenges were faced with the rock units as they were too strong for the scraper only cutterhead arrangement. The penetration rates between the soil units and rock units decreased significantly and the project was delayed as a result. The use of a mixed face TBM may have provided the necessary cutting power for a faster penetration rate.

In a project where the ground conditions were more competent than expected, the TBM became stuck at two separate instances as the cutterhead was not optimized for the units. With a soft rock cutterhead arrangement, predominantly scrapers, excavation of hard sandstone and siltstones was difficult and where torque was inadequate the TBM was unable to continue. In one case, a rescue shaft was required to access the cutterhead and modify the arrangement, whereas upon the second jamming of the machine, a second machine was then used to complete the tunnel from the retrieval shaft to meet the first TBM.

When an alternate project encountered softer than predicted ground conditions, where the TBM was not optimized for the soft ground, the entire TBM twisted along its axis and became temporarily stuck. Figure 1a depicts the scenario in the right cross section, when less mudstone was expected from the preliminary investigations.

The projects in Calgary experienced greater than expected stability in many of the projects. Although temporary support was designed and implemented for the tunnels, anecdotal evidence suggests that the support was not heavily stressed by the rock masses and was more of a safety requirement than stability. A few tunnels did experience minor overbreak above the TBM and support systems, which results in increased grouting for the final support system, but few other concerns.

5 DISCUSSIONS AND CONCLUSIONS

Calgary presents a unique challenge for the use of tunnel boring machines. Although the soft units seem ideal for full faced mechanical excavation, the vertical and horizontal heterogeneity of the sedimentary rock units provide numerous challenges. The most significant challenge remains the inability to predict the conditions accurately for the alignment as the units are highly variable within small regions.

The use of mixed face TBMs could allow for further flexibility with unpredicted conditions, especially with the recent advances in mixed face technology and in optimization of cutterhead arrangements for mixed ground.

As the depositional environments for the Paskapoo Formation was a meandering stream sequence, flood planes and over bank clays are common and tend to be deposited near the coarser grained, higher energy deposits. Figure 1 depicts potential tunnel alignments through the horizontally varied units. Each case presents significant challenges in design.

The case studies indicate that in order to improve TBM utility in the Calgary bedrock, a solution to the sticking clay-rich muck is required. Various soil conditioning agents are available for TBM application which may reduce the conglomeration of the clay particles. However, certain conditioning agents require additional infrastructure at the project site which can limit the applicability.

Although challenges were face with soft ground TBMs previously in Calgary, recent successes in heterogeneous ground using EPBMs with additional slurry injection provide an alternative to previous methods. In this case, conditioning agents should be easy to apply to the rock mass, and penetration rates should be steady. However, additional costs may be associated to the muck disposal and slurry, as is the concern with the addition of conditioning agents. (Babendererde et al., 2004)

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REFERENCES

Babendererde, S., Hoek, E., Marinos, P. and Cardoso, A. 2004. Geological risk in the use of TBMs in heterogeneous rock masses – The case of “Metro do Porto” and measures adopted. *Conference in Aveiro, Portugal,* Course on Geotechnical Risks in Rock Tunnels.

Barla, G., & Pelizza, S. (2000). TBM tunnelling in difficult ground conditions. *Geoeng, Melbourne, Australia,* , 1-20.

Dawson, F. M., Evans, C.G., Marsh, R. and Richardson, W.A.D. Unknown. Chapter 24: Uppermost Cretaceous and Tertiary Strata of the Western Canada Sedimentary Basin. *Western Canada Sedimentary Basin Atlas,* Alberta Geological Survey.

Girmscheid, G. and Schexnayder, C. 2003. Tunnel Boring Machines. In *Practice Periodical on Structural Design and Construction*, American Society of Civil Engineers: 150 - 163.

Guglielmetti, V. Grasso, P. Mahtab, A. and Xu, S., ed. 2008. Appendix I: Types and characteristics of TBMs. In *Mechanized tunnelling in urban areas: design methodology and construction control*, Taylor & Francis Group, London, UK: 363 - 372.

Heinz, H., Cullum-Kenyon, S., Gorling, D. and Crockford, A. 2010. Recent experience with tunnels in weak rock in Calgary. *Geo2010 Conference*, Canadian Geotechnical Society.

Hoek, E. 2007. Rock mass classification. In *Practical Rock Engineering*, http://www.rocscience.com/education/hoeks_corner

Hoek, E., Marinos, P. and Marinos, V. 2005. Characterization and engineering properties of tectonically undisturbed but lithologically varied sedimentary rock masses. *International Journal of Rock Mechanics & Mining Sciences*, 42: 277 - 285.

Hydrogeological Consultants Ltd. 2002. Municipal District of Rocky View No. 44. *Regional Groundwater Assessment*: 21 - 22.

Marinos, V., Marinos, P. and Hoek, E. 2005. The geological strength index: applications and limitations. *Bulletin of Engineering Geology and the Environment*, 64: 55 - 65.

Morimoto, T. and Hori, M. 1986. Performance Characteristics of a Tunnel Boring Machine from the Geomechanical Viewpoint. *International Journal of Rock Mechanics, Mining Science & Geomechanics*, 23(1): 55 - 66.

Osborn, G. 2006. Calgary. In *Alberta Beneath our Feet*, (B. Hitchon, ed.) Geoscience Publishing, Sherwood Park, AB, Canada: 198 - 203.

Osborn, G. and Rajewicz, R. 1998. Urban Geology of Calgary. In *Urban Geology of Canadian Cities*, (P. F. Karrow and O.L. White, ed.) Geological Association of Canada Special Paper 42: 93 - 115.

Sapigni, M., Berti, M., Bethaz, E. Busillo, A. and Cardone, G. 2002. TBM performance estimation using rock mass classification. *International Journal of Rock Mechanics and Mining Sciences*, 39(6): 771 - 788.

Taheri, A. and Borujeni, H. A. M. 2008. Tunnelling Machine Selection for Tunnel Excavation in Rock, Using AHP Method: CASE STUDY: Line 1 of the Esfahan Metro Project. *International Conference and Exhibition on Tunnelling,* International Tunnelling and Underground Space Association.