Multi Attributed Selection of Excavation Methods in Tunneling Construction

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Abstract

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Tunneling construction operations are considered dynamic and complex processes. The success of tunneling construction projects is affected by essential factors. Various methods have been developed in the past, such as simulation models that facilitate and improve the tunneling construction processes and consequently mitigate potential time and cost overruns. Proper selection of excavation method is among the most important factors in tunneling project success. Current practices in selecting the best possible technique for excavation are based on the highest productivity rate as well as the availability of resources. Many of these techniques neglect the interdependencies and concurrency of influencing factors in selecting the best possible excavation method.

In this research, a new method for selecting the most efficient excavation method for tunnels is developed. The method considers a series of significant factors in tunneling construction - namely length, cross-sectional area, geotechnical characteristics depth of the tunnel, and level of water table - and a variety of excavation methods, such as different types of TBMs, Road-header, and drilling and blasting. The factors used in the developed method were constructed based on knowledge extracted from literature and gained from interviews with experts and an online survey. The survey gathered data on the relative importance of the set of selection factors for different soil and project conditions. The collected information was used as input to a developed MCA model (AHP, TOPSIS) that ranked the methods based on their respective suitability for the project at hand to select the most appropriate equipment. The developed method is applied to real case studies to demonstrate its use and highlight its essential features. Also a sensitivity analysis was carried out on each of the case studies, to identify and analyze the most sensitive tunneling variables affecting equipment selection. Based on sensitivity analysis geotechnical condition is the most sensitive factors among all effective variables in both case studies. In the Montreal-Laval Metro Extension, the selected method was Road Header, and in the Spadina Subway project EPB Mixed Shield was selected as the most favorable method of excavation. These results confirm the actually selected excavation methods on the two projects, and indicate that the developed method is reliable.

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First and foremost, I am very grateful to God for keeping me blessed and granting me the ability to follow through and achieve my goal.

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Last but not least, I would like to thank my parents, Naser and Parirokh, and my brothers, for their unconditional love, support, and for always being there for me. I would like to express my deepest gratitude to my family for teaching me how to live.

Finally, I would like to dedicate this thesis to my parents.

TABLE OF CONTENTS

List of Figures

List of Tables

Chapter 1 – Introduction

1.1 Introduction

Tunneling technology is used all over the world for metros, railways, road construction, and underground pipes, all with the maximum degree of safety and minimum impact on the surface (Hitachizoosen., 2008a). The decision to utilize the tunneling method may be divided by overall hydrological and geological conditions, tunnel cross-section, length of continuous tunnel, local experience,time/cost considerations (what is the value of time in the project), limits of surface disturbance, and many others factors.

Tunnel construction methods, both past and present, have been practiced and modified using different methods, such as Classical methods, primarily common in Belgian, English, German, Austrian, Italian, and American systems (Yagiz, 2006a). These methods had much in common with the primary mining/tunneling methods used until the last half of the 19th century. Today, however, improved technology have introduced new techniques, such as mechanical drilling/cutting, cut-and-cover, drills, blasts, shields, and tunnel boring machines (TBMs). To select and plan any of the current practice methods tunnel structures preferably should result in optimum solutions. Choosing the best tunneling approach, in terms of design and structure solution, is not very straightforward, due to the high degree of complexity establishing such solutions (Y. Wang, H. W. Huang, 2007). Tunneling design includes considering countless parameters, each of which may result in a number of diverse effects within the fields of financial costs, environmental impacts, hazard-related effects, and traffic effects (Rostam & Høj, 2004).

When it comes to making decisions regarding the tunneling method, various elements should be taken into account. One should consider all available facts with the goal of reaching the optimal solution is seen in a life-cycle perspective (Rostam & Høj, 2004). With the term "utility" describing the overall benefit of an individual activity, the optimal decision is formulated.

Regarding the process of creating and operating tunnels as a chain of decisions, which can all be modeled in terms of decision trees as depicted in Figure 1, an important notion for modeling is the uncertainty of the information available to you. This involves not only the physical and statistical uncertainty in the classical sense but also the uncertainty in terms of the degree of belief (Rostam & Høj, 2004).

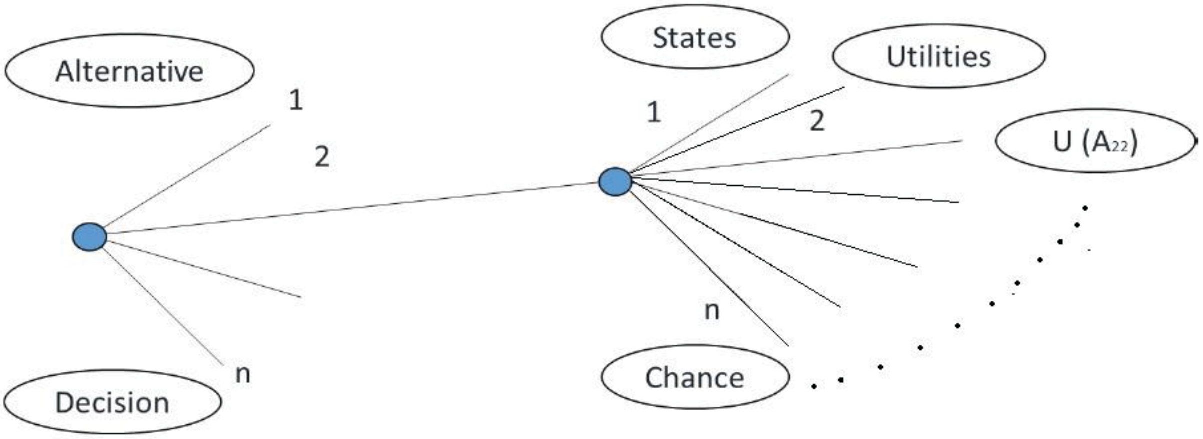

Figure 1. Prior decision tree (Rostam & Høj, 2004)

1.2 Brief Historical Background of Tunneling

The first human beings confronted the challenge of breaking rocks found in nature in order to build or create safe places to live, such as caves. Later in the Bronze Age, with the creation of metallic tools, and then continuing into the Iron Age era, breaking rocks was still a boundless challenge. For a very long time, nails and hammers were used for this chore. Heating the surface of the rock to be broken was an advancement at that time. The surface of the rock was heated by placing it in a big fire and then cooled very quickly with water, which weakened the rock and made it is easier to break with primary tools. This procedure was used in many applications - such sculpturing, mining, and tunneling - for a very long time (Stack, 1982).

Tunneling applications developed rapidly with the creation of Quanaates by ancient Persians (Bybordi, 1974). Since then, tunneling has had many purposes, such as hydropower generation, mining, ventilation, traffic, and transportation. The various needs for tunneling and the development of technology led to today's method of tunneling. Various techniques of rock breakage in tunneling applications are now available, including drill and blast methods, which use explosives, and mechanical methods that use mechanical excavators, such as tunnel boring machines (TBM) or road headers (Stack, 1982).

1.3 Research Motivation

Selecting the most suitable alternative based on multi-attributed criteria has always been an issue for tunneling construction. Particularly in underground excavation, there is no “best method” since, different methods are suitable for various project conditions and owners’ construction needs. Proper selection of excavation methods is among the most important factors in tunneling project success.

In this research, varieties of tunneling projects and methods of excavation worldwide are explored.

Literature and current practices in the selection of tunneling methods have been reviewed. In previous studies, various methods had been developed such as simulation models, which facilitated and improved the tunneling construction processes and consequently mitigated potential time and cost overruns. Current practices in selecting the best possible technique for excavation is based on the highest productivity rate as well as the availability of resources. This method is time-consuming and costly and requires experience and extensive knowledge. If the decision maker lacks such knowledge and experience, some viable alternatives may not receive proper attention and be left out. A gap of an integrated model which, would gather a variety of effective factors and alternatives in one model was found. Such an integrated model would accelerate the decision process and prioritize alternatives in order of suitability, based on major project parameters. This thesis introduces a pathway improving the selection of tunnel excavation methods by providing an integrated multi-attributed decision model.

1.4 Research Objectives

This research aims to propose a model for the selection of most suitable tunneling techniques for decision makers, by ranking the techniques in order of suitability, based on a set of project conditions. In other words, users can compare and examine the known excavation methods to select the best method for their tunneling projects. The selection assessment in this model will focus on the following aspects:

- ✓ Technical feasibility
- ✓ Productivities
- ✓ Time
- ✓ Cost effectiveness
- ✓ Contractual requirements

The main objective of this research is to propose an integrated model that provides users with an automated and comprehensive computational platform, which considers a broad range of aspects for evaluation and selection of near perfect alternatives that satisfy tunnel construction needs. A set of tools and factors are integrated with the proposed model to assess multiple alternatives to determine the best feasible technique.

To achieve the abovementioned objectives, several sub-objectives are acknowledged as follows:

- ❖ Study and understand the tunneling construction's different phases
- ❖ Identify, study the factors affecting tunneling equipment selection
- ❖ Develop a meticulous understanding of the current situation in tunneling construction and the suitability of existing techniques.
- ❖ Propose a model to collect essential data regarding the equipment selection process (Technical feasible study)
- ❖ Develop a multi-criteria analysis model to weight, rank, and select the tunneling equipment
- ❖ Apply and analyze different scenarios to optimize equipment utilization

Research objectives are summarized in Figure 2.

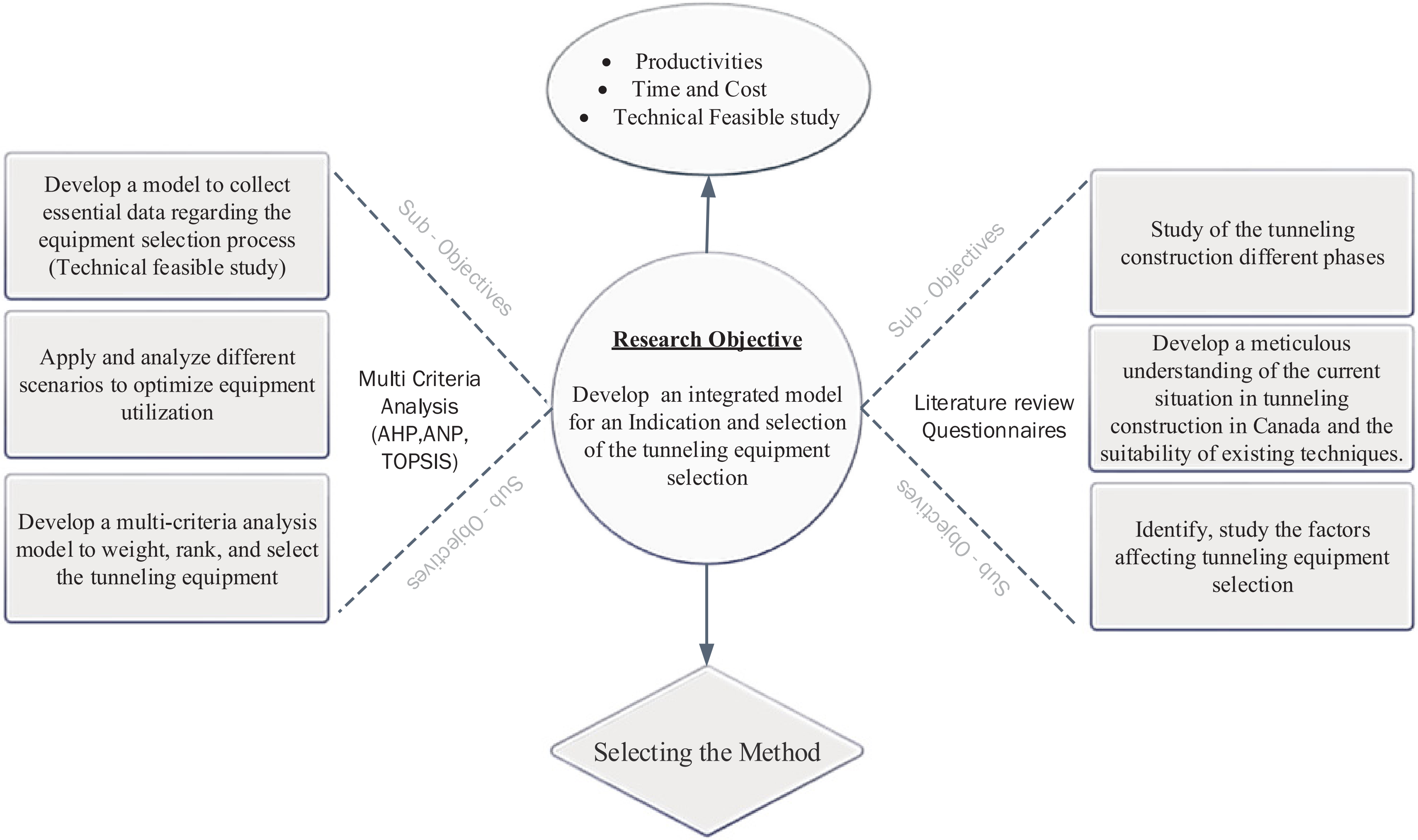

Figure 2. Research Objectives

1.5 **Thesis Organization**

Chapter two presents a comprehensive review of the literature in tunneling construction, tunneling risk assessment, multi-attribute decision analysis, factors affecting methods of tunneling selection, as well as current practices. Chapter three is dedicated to the developed model and related data collection. It describes the conducted survey and the analysis of the questionnaires results. The research methodology is described as well as the preparation and design of the survey. Chapter four describes the application of the proposed method to two case studies: metro Laval extension and Spadina metro extension. The developed model is applied to both case studies, and the results are compared to actual project decisions. Chapter five represents the summary and concluding remarks of this research. Contributions and limitations of the developed method along with recommendations for future research work are briefly stated.

Chapter 2 Literature Review

2.1 Tunneling Construction Processes

To study the tunneling construction methods, it is important to define all the tunneling steps and requirements in the construction of a tunneling scheme (Girmscheid & Schexnayder, 2002). Judgments have to be made concerning the modality of excavation such as Road-header, drill & blast, TBM (Mix Shield, EPB Shield, Single Shield and Gripper TBM), the material handling process, and the tunnel support systems. In this chapter, various activities related to the tunneling construction process will be explored. The purpose of this literature study is to get a general overview of the different construction processes involved in tunneling, and of the interaction of various processes involved in the context of tunneling construction. First, the main excavation methods - namely drill and blast, tunnel boring machine (TBM), and road-header - will be described. Because of the importance of the material-handling processes and tunnel support systems in tunneling construction, an extensive literature review specifically concerning these subjects will be provided subsequently. The chapter ends with a description of the influence factors affecting productivity, a risk assessment of tunneling construction, and multi-criteria analysis.

2.2 Tunneling Excavation

Tunneling excavation techniques are divided into three broad categories: excavation with road-headers, drill & blast, and TBM. At present, drilling and blasting and TBM tunneling are considered the two most common excavation methods in tunneling (Obeidat, Al-Barqawi, Zayed, & Amer, 2006a). When comparing these two methods, the performance (advance rate) for drill and blast is, in most cases, lower than that of TBM. Also, the total labor cost using drill and blast method is higher, whereas its investment cost is lower than that of TBM technology (relatively low capital cost for the equipment). Drill and blast technology is cost-efficient when the length of the tunnel to be excavated is less than three kilometers (Girmscheid & Schexnayder, 2002). Cost efficiency decreases as tunnel length increases. There are also other significant differences between these two methods. Tunnel excavation using TBM requires a predetermined tunnel diameter, and assuring such a shape can be excavated accurately. In using the drilling and blasting method, the cross section can be of any shape. Furthermore, the drill and blasting method will perform better than TBM as the geology of the soil becomes complicated and when there are zones of disturbance (Girmscheid & Schexnayder, 2002).

2.3 **Drilling and Blasting Method**

The drill and blast process is a cyclic operation. Each round consists of four successive operations: drill, blast, muck, and installation of primary support. The drilling process consists of drilling a series of small blast holes in the tunnel face by a so-called “drill jumbo.” The number of holes and their locations is dependent on the type and condition of the rock, the type of explosive, and the blasting technique used. After all the required holes are drilled, they are loaded with explosives, as shown in Figure 3 (Likhitruangsilp, 2003). Once the explosives are loaded into the blast holes, the tunnel face is cleared and the explosives are detonated. This operation leads to excavated soil, which must be removed. Also, pieces of loosened rock remaining on the tunnel roof and walls have to be removed before the mucking process begins. Once this is finished, mucking machines and materials-handling equipment are mobilized, and the muck is hauled out of the tunnel face. After the mucking operation, primary support systems are installed to stabilize the opening. Primary support systems are fixed at the same time as the excavation process to keep the opening stable during construction. For the drill and blast method, the main support is usually installed after the mucking operation is completed in each round, but before or during the drilling process for the next round (Likhitruangsilp, 2003). The supporting systems, such as electricity, ventilation, and tracks, are subsequently extended to the new tunnel face. The final lining is installed at some later stage, after the installation of primary support. In general, final lining occurs after the tunnel has been entirely excavated and supported. Common lining systems are monolithic concrete lining, steel segments, and pre-cast concrete segments.

Figure 3. Qualified professionals are carrying out drill and blast works (MTR, 2013)

Drill and blast methods offer the following advantages and Mitigations:

- Fast mobilization and demobilization
- Fastest advance in hard ground
- Lowest cost per m3 of excavation
- Suitable for all excavation shapes
- Flexibility in varying geometry and geology

- Site sensitization of emulsions dramatically reduces site explosives inventory
- Mobile bulk systems have reduced the time and labor required to charge a face
- Fume reduction to acceptable levels by emulsion explosives technology
- Damage decrease during the blasting by low energy perimeter products.
- Profile controlled by improved drilling accuracy and tailored energy products
- Performance enhanced by the technical capability of suppliers to manage outcomes
- Vibration is run by accurate programmable electronic detonators, smart blast designs and precise metering of bulk explosives into the blast hole (Spathis & Thomson, 2004a).

2.4 **Road-Header**

Road-header machines (Figures 4, 5) were initially developed for the coal mining industry but are being used more often in rock tunneling (Copur, Ozdemir, & Rostami, 1998). Road-Header also called a boom-type road header, is a form of excavating equipment with a boom-mounted cutting head, a loading device frequently involving a conveyor, and a crawler traveling track to move the whole machine into the rock surface (Schneider, 1989). The cutting head can be either an all-purpose rotating drum, mounted in-line or perpendicular to the boom, or a particular function head. This machine contains certain function heads: a jack-hammer similar to a spikes, compression fracture micro-wheel heads, and a slicer head, like a gigantic chainsaw, for chopping the rock (Likhitruangsilp, 2003).

The crawler frame contains a power system, a muck-gathering system, and a conveyor that transports the dust to the back of the machine. The muck is then loaded into the muck-handling system and hauled out of the tunnel. Road-headers can achieve a better advance rate than the drilling and blasting method, but significantly lower than the tunnel-boring machine can achieve.

The advantages of the road-header method are similar to those of TBM method; advantages include continuous operation, limited non-productive time, and improved quality of the tunnel opening. However, road-headers are more flexible than the tunnel-boring machine because they are functional to various types, shapes, and sizes of underground excavation (Likhitruangsilp, 2003). Tunneling construction using road-headers involves three main processes: excavation, dirt removal, and tunnel support (Obeidat, Al-Barqawi, Zayed, & Amer, 2006b). After a certain amount of excavation, the road header is pulled back in order to start the next process. The removal of dirt from the face of the tunnel can be by conveyor belts, trucks, or trains. This is followed by the installation of initial support. This operation involves installation of wire mesh or shot-Crete at specific locations. Road headers are normally transported within 1- 9 months and mobilization time is respectively similar. Similarly to the drill and blast method, there is a reasonable chance that a spare road header may be available sooner. The speed of excavation is similar to drill and blast at 40- 60 meters per week in soft rocks (Spathis & Thomson, 2004a).

Figure 4. Road-Header (RTM Equipment, 2008)

Figure 5. Continuous Miner (Joy Mining, 2015)

2.5 Tunnel Boring Machine (TBM)

TBM is a huge machine that can have a diameter of 14-15 meters and a length of 400 meters. TBMs were first used 150 years ago, concurrently in North America, the UK, and Europe. Tunnel Boring Machines were applied widely in the industry in the mid-1920s (Diponio & Dixon, 2013). Another major attempt with TBM was made in the United States during the early 1950s and continued into the 1960s, with some success in very soft rocks (Diponio & Dixon, 2013). Despite advances in technology and a desire to excavate harder and harder rock, success was not always realized. Nevertheless, the usage of Tunnel Boring Machines (TBMs) increased in the years of the 1960s and 1970s with technological advances that allowed successful tunnel-boring in harder as well as a less competent rock. With each advance in technology and success in the field, unsuccessful projects were not uncommon (Goel, 2008). The construction of a tunnel using TBM begins with the excavation and liner support of the vertical shaft (Ruwanpura, 2001). The tunnel constructions using TBM operations occurred as follows:

- Excavation and support of the undercut area

- Excavation of the tunnel and tail tunnel
- Disposal of dirt from the tunnel face
- Hoisting dirt to ground level
- Lining the tunnel
- Extending the services and rail tracks
- Excavation and support of the removal shaft.

Two types of tunnel-boring machines are mostly in use for different circumstances of the tunneling construction, namely the open-faced and closed-face shielded machines. The open-face boring machine is suitable for stable soils. For less stable soils, such as silt or sand, closed-face shielded machines are used. Important properties in the excavation processes using TBM are the excavation rate and stroke length. The excavation rate is dependent on soil conditions and TBM horsepower (Messinella, 2010). The stroke length determines how often the TBM will need to be reset. Dirt handling involves the transportation and disposal of spoil from the tunnel face to the shaft, from where it is transported to the surface. Different methods are used to haul the spoil from the tunnel face to the shaft, such as trains and belt conveyors. Using trains to haul spoil has many advantages. First, this method is compatible with most excavating and loading methods, and can be used for almost all sizes of tunnels. Second, laborers and support liners can also be transported by trains. Depending on the tunnel diameter, either a single or double-track system can be used. The spoil that is hauled to the shaft of the tunnel using trains and /or belt conveyors subsequently has to be lifted up to the surface. The methods of hoisting dirt are skip, clamshell bucket, crane, gantry, or derrick hoist. The working shaft is also used to transport construction material and personnel (Ruwanpura, 2001).

2.5.1 **Minimum Specifications for TBMs**

Precedent training in the tunneling industry has demonstrated that it is not practical to over-specify the requirements for TBMs. The risks associated with the selection of any type or make of TBM is a concern of the tunnel contractor (Brox, 2013). The minimum requirements for the application of TBMs on any tunnel project should be based on the following key issues:

- Rock types, strength, quality, and durability.
- Quantification of number and extent of major fault and shear zones.
- The presence of weak rock units and the potential for overstressing and squeezing conditions.
- Installation requirements for initial tunnel support.
- Final support and lining requirements.

One important factor in the selection of a TBM is the shape of cross-sections or construction conditions. There is a variety of specific shield TBM, like a multi-face shield tunneling machine, rectangular or horseshoe-shaped shield tunneling machine, and built-in parent-child shield tunneling machine, that changes its cross-section in the ground (Hitachizoosen, 2012).

2.5.2 **Statistics of Tunnel Boring Machine (TBM)**

Several successful and economically beneficial applications of TBMs tend to be implemented in the construction of tunnels for modern day projects. Table 1 presents some well-known projects where TBMs have been used for the construction of tunnels for access, conveyance, drainage, exploration, and water diversion purposes for new and existing mines (Brox, 2013).

Table 1. List of the project accomplished by TBM at mining projects (Brox, 2013)

Project	Location	Year	Length, (km)	Size, (m)
Step Rock Iron	Canada	1957	0.3	2.74
Nchanga	Zambia	1970	3.2	3.65
vghnghOak Grove	USA	1977	0.2	7.4
Blyvoor	South Africa	1977	0.3	1.84
Fosdalen	Norway	1977	670	3.15
Blumenthal	Germany	1979	10.6	6.5
Westfalen	Germany	1979	12.7	6.1
Donkin Morien	Canada	1984	3.6	7.6
Autlan	Mexico	1985	1.8	3.6
Kiena	Canada	1986	1.4	2.3
Stillwater EB	USA	1988-91	6.4	4
Fraser (CUB)	Canada	1989	1.5	2.1
Rio Blanco	Chile	1992	11	5.7
San Manuel	USA	1993	10.5	4.6
Cigar Lake	Canada	1997	> 20	4.5
Port Hedland	Australia	1998	1.3	5
Stillwater EB	USA	1998-01	11.2	4.6
Mineral Creek	USA	2001	4	6
Amplats	South Africa	2001	0.35	2.4
Monte Giglio	Italy	2003	8.5	4.9
Ok Tedi	PNG	2008	4.8	5.6
Los Broncos	Chile	2009	8	4.2
Stillwater Blitz	USA	2012-13	6.8 b	5.5
Grosvenor Coal	Australia	2013	1.0 b	8
Oz Minerals	Australia	2013	11.0 b	5.8
Northparkes	Australia	2013	2.0 b	5
El Teniente	Chile	2014	6.0 b	10

The first use of TBMs in a mine was for the exploration of tunnels and mine development: access tunnels remained a necessity for fast excavation to complete exploration and offer new access as part of mine expansions. The most important use of TBMs for mining has been for the Stillwater Mine in the USA, where a third movement of TBM excavation is presently underway (Brox, 2013).

2.5.3 **EPB Shield**

The earth pressure balance (EPB) shield tunneling machine (Figure 6) performed in a broad range of ground conditions including rocks, soft soils, and cohesive soils with high clay and silt contents and low water permeability, in which we can stabilize face by using excavated materials. For this approach, the machine turns the excavated materials into a soil paste, which is used as a plastic support medium to balance the pressure at the tunnel face and control the machine's navigation (Hitachizoosen., 2008b).

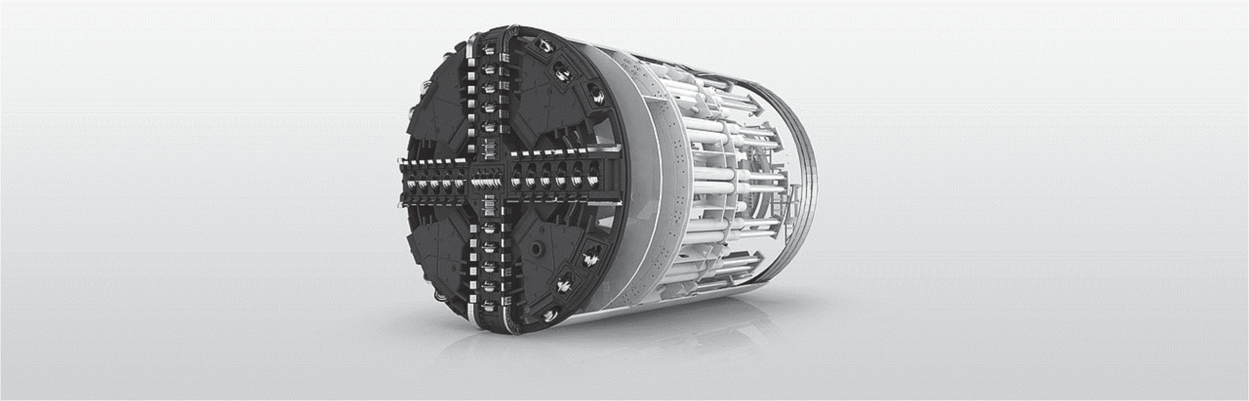

Figure 6. EPB Shield Tunneling Machine (Hitachizoosen., 2008b)

The Operation of is EPB by cutting wheel is pushed into the tunnel, and it excavates soft soil. The excavated materials enter the excavation chamber where they are combined with soil paste to achieve a required texture. When the pressure of the soil adhesive in the excavation chamber equals the pressure of the surrounding soil and groundwater, the required balance is achieved. This pressure can be adjusted and controlled by a screw conveyor that transports the excavated material from the base of the excavation chamber to the belt conveyor. The interface between the screw conveyor's and the TBM's advance rates ensure that the support pressure of the soil can be controlled accurately. This balance is continuously observed using earth pressure sensors. This way, the machine operator can control all tunneling parameters to achieve high productivity rates and reduce the risk of collapse, even under changing geological conditions (Hitachizoosen., 2008).

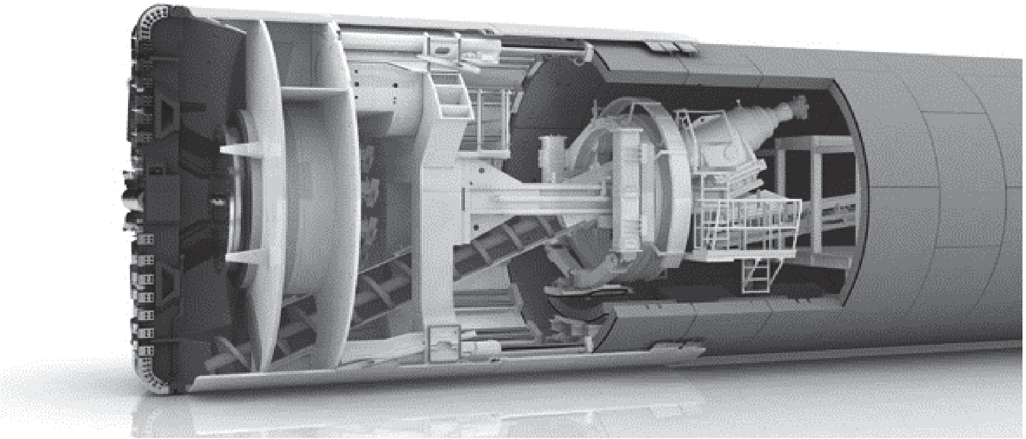

Figure 7. Illustration of a typical segmental lining machine diameter 6 m (Hitachizoosen., 2008b)

However, not all ground situations in their natural state are ideal for EPB tunneling. By soil conditioning, we can change the plasticity, texture, and water permeability of the soil by inserting deferent conditioning materials like water, concrete, or foam. This allows EPB shields to achieve good advance rates even in insecure geological conditions (WSDOT, 2012). The TBM advance rate and screw conveyor regulator for the pressure support at the tunnel face (figure 8 and 9) show the geology and diameters for which TBM is suitable.

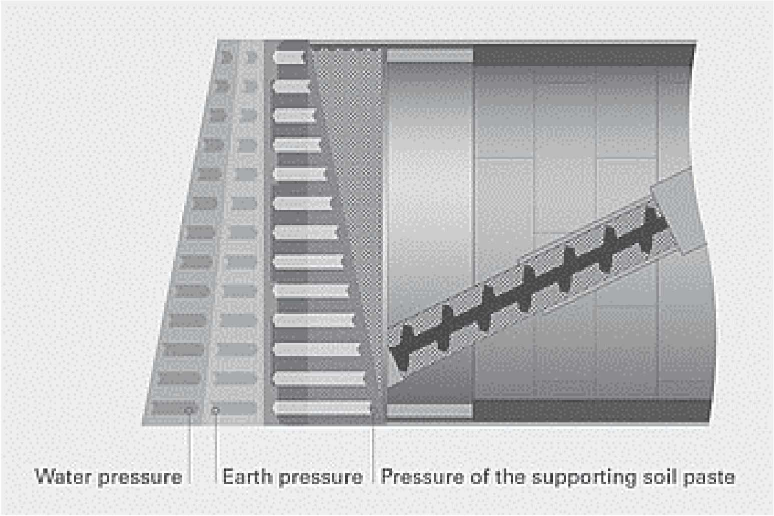

Figure 8. TBM Advance Rate and Screw (Hitachizoosen., 2008b)

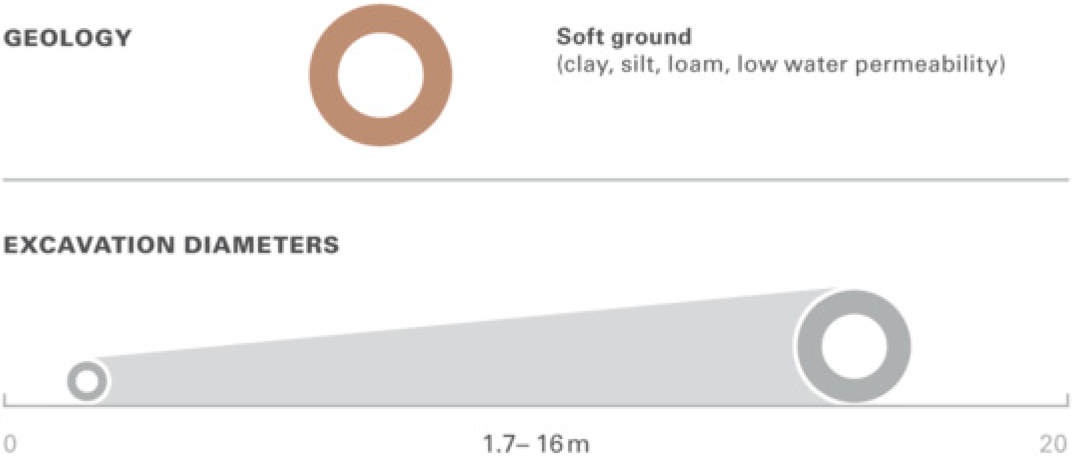

Figure 9. TBM Geology & Diameters (Hitachizoosen., 2008b)

2.5.3.1 *Summary of EPB Shield TBM Tunneling Process*

The following are the principal stages in the tunneling process using the EPB shield:

- <u>Excavation</u>: Cutting discs remove the soil.
- <u>Tunnel face support</u>: Plastic soil produces active support pressure for excavation.

- Removal: An attach conveyor transports the excavated material to the logistics systems at the back.
- Thrust: Hydraulic thrust cylinders in the shield or a jacking frame in the launch shaft push the machine forward.
- Tunnel lining: Segmental lining or pipe jacking.

The advantages of this method are the following:

- The geological variety of application can be enhanced by soil conditioning.
- No additional support medium obligated.
- A variety of superior solutions available for heterogeneous soil conditions.
- Very high and consistent advance rates are possible in cohesive soils with high clay or silt content.
- This machine is suitable for excavation for a wide range of diameters between 1.7–16 meters (Hitachizoosen., 2008b).

2.5.4 **Mix Shield TBM**

Mix Shield technology is an advance in conventional slurry technology. In the slurry type shield tunneling model, the machine excavates the ground preventing the tunnel face from collapsing by using the pressure of circulated muddy water in the cutter chamber. In the mix shield method, this support pressure is achieved by using an automatically controlled air cushion. In this model of excavation, an entirely automatic sensor always monitors the pressure. Since it is possible to respond by an air cushion, even small fluctuations in pressure or volume can be measured accurately and managed safely during an identical excavation in heterogeneous and high water pressure conditions (Hitachizoosen, 2012).

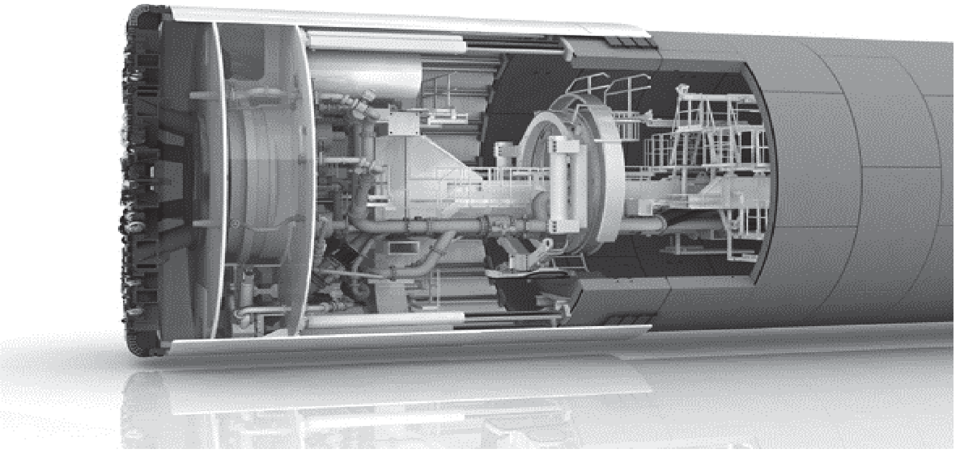

Figure 10. Illustration of a Typical Segmental Lining Machine, Diameter 10 m

(Hitachizoosen, 2012)

2.5.4.1 *Sealing Against High Water Pressures*

Mixed shield TBMs are equipped with multiple sealing systems and closed the hydraulic slurry circuit, this machine is sealed against high water pressures of more than 15 bars. In addition, this machine is equipped with a jaw crusher (Figure 11) which can crush large stones or blocks in heterogeneous soils to reach a conveyable size, therefore allowing the hydraulic removal to carry out the dust smoothly. This jaw is usually positioned in front of the intake screen (Hitachizoosen, 2012).

Figure 11. Jaw Crushers (left) and Drum Crushers with Agitators (right) Crush Boulders or Stones during Tunneling (Hitachizoosen, 2012)

2.5.4.2 *Measures against Clogging*

Clogging is the most significant threat during an excavation in heterogeneous soils. The following approaches have been developed to avoid clogging:

- Cutting wheels with a relatively open center segment, allowing the optimum drift of the excavated material.
- Increased flow rate of suspension in zones prone to clogging by optimizing the hydraulic feed and conveying scheme.
- Separate slurry systems with adjustable jets in the cutting wheel arms, the submerged wall, the submerged wall opening, the crusher, and the intake screen (Hitachizoosen, 2012).

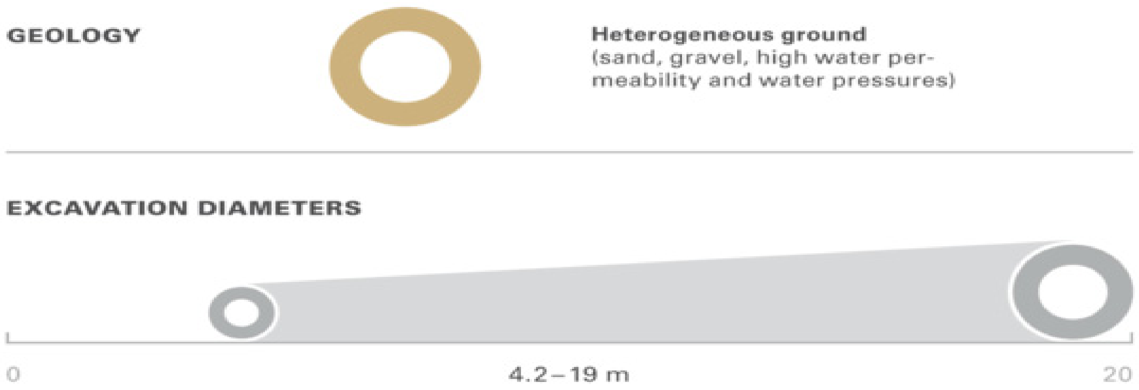

Figure 12. Mixed Shield TBM Geology & Diameters (Hitachizoosen, 2012)

2.5.4.3 *Summary of Mix Shield TBM Tunneling Process*

- Excavation: Cutting knives and soil disc cutters removal
- Tunnel face support: Hydraulic support using slurry suspension with a controlled pressurized air cushion
- Removal: Hydraulic conveyance of the excavated material through a closed slurry circuit
- Thrust: Hydraulic thrust cylinders in the shield push the machine forward
- Tunnel lining: Segmental lining

The advantages of mix shield are the following (Hitachizoosen, 2012):

- Usable in high water pressures of more than 15 bars
- Colossal diameters of up to 19 m are possible
- Maximum tunneling safety due to the precise support of the tunnel faces with an automatically controlled air cushion.
- A variety of particular ways out available for special project requirements.

2.5.5 **Single Shield TBM**

Single Shield TBMs are the perfect machine for fast tunneling exaction through rock and other stable, non-groundwater-bearing soils. In several cases, they are the best solution for tunneling with very high rock strengths. Both segmental lining and pipe jacking methods are used in the post-excavation process, and high tunneling performances can easily be achieved in a short time (Hitachizoosen., 2012).

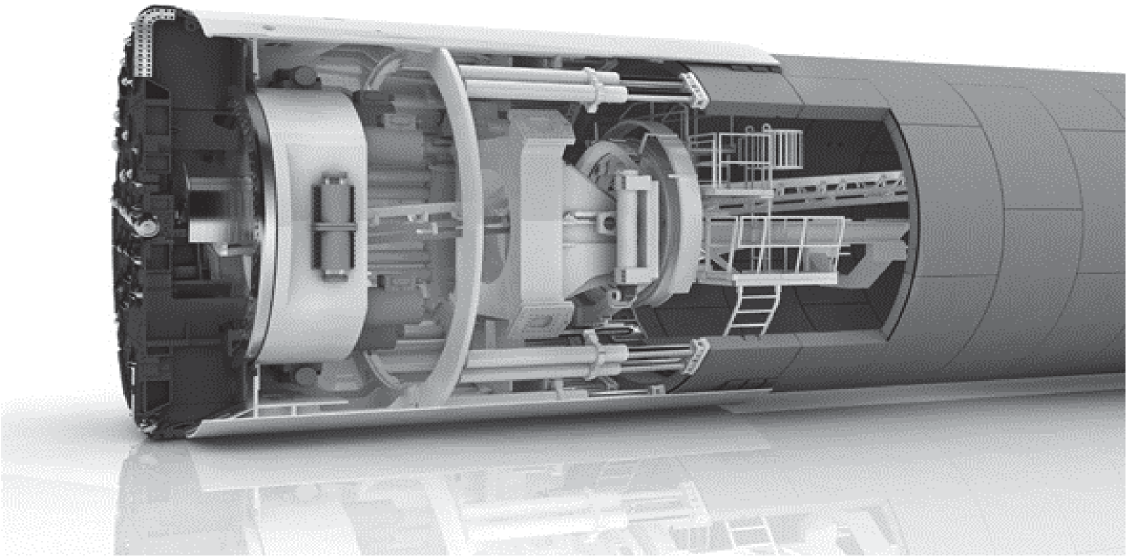

Figure 13.. Single Shield TBM (Hitachizoosen., 2012)

2.5.5.1 *Advancing with Power*

In Single Shield TBM, a rotating cutter head equipped with disc cutters is pushed against the front soil. Tunneling over a hard rock with strengths of up to 250 mph at some places requires enormous forces. The contact pressure must be coordinated exactly, taking into consideration the expected geology. The optimum arrangement of the disc cutters on the cutter head and drives with contact pressure are some of the most significant factors used to ensure high performance in tunneling (WSDOT, 2012). Because of the rolling movement and disc pressure, pieces of rock called chips will be broken and cut. Water jets usually cool down hot cutting discs and reduce dust formation. Excavated rock chips will be transferred out of the cutter head by built-in buckets passed on to belt conveyer to be removed from the tunnel. The older disc cutters worn out in the excavation process can be changed (Hitachizoosen, 2012).

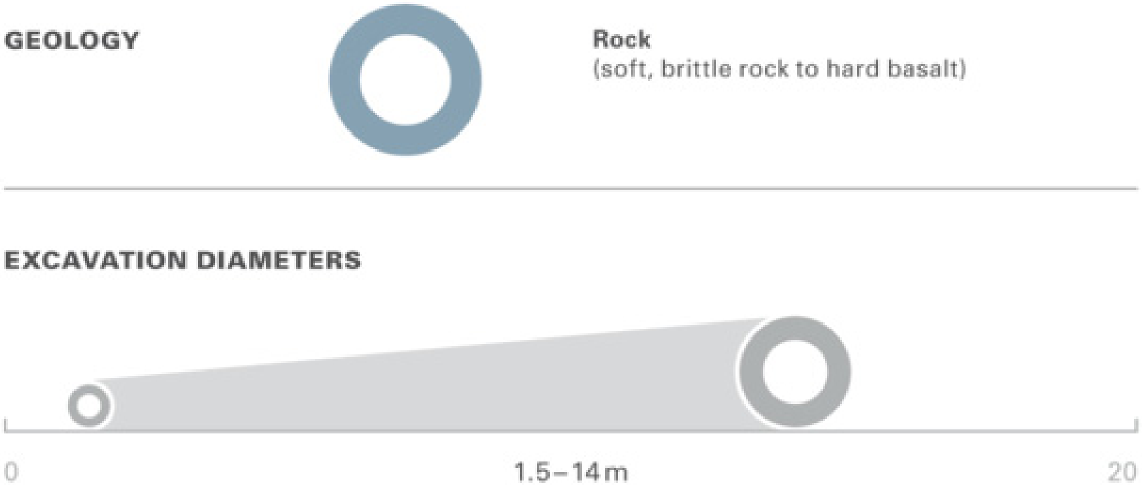

Figure 14. Geology & Diameters of Single Shield TBM (Hitachizoosen., 2012)

2.5.5.2 *Summary of Single Shield TBM Tunneling Process*

- <u>Excavation</u>: Disc cutters break chips from the tunnel face by applying high contact pressure.
- <u>Removal</u>: Buckets, muck chutes, and muck rings provide for an efficient removal of the excavated material onto a center belt conveyor.
- <u>Thrust</u>: Hydraulic thrust cylinders in the shield or a jacking frame in the launch shaft push the machine forward.
- <u>Tunnel lining</u>: Segmental lining or pipe jacking

The advantages of single shield TBM are:

- High advance rates in all varieties of rock.

- Optimal tunneling safety in brittle, non-stable rock formations.
- Also usable in groundwater-bearing geologies with prior soil conditioning.

2.5.6 **Gripper TBM**

Gripper TBMs (Figure 15) is an efficient solution for fast mechanized tunneling in hard rock. In excavation, this machine works exactly like single shield TBM in the front end, but with a different tunnel forming approach and movement. Gripper TBM is an open type machine, as it utilizes direct counterforce against the ground for forward progression. In this process, medium to high rock strengths are a requirement for high productivity. In more broken geological foundations, some fast rock support must be performed behind the cutter head.

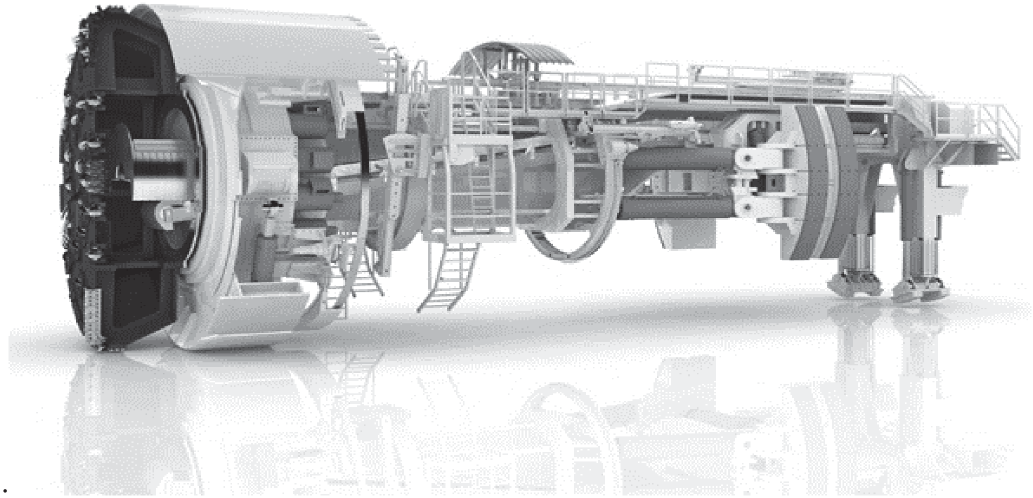

Figure 15. Gripper TBMs (Hitachizoosen., 2012)

2.5.6.1 ***Functionality***

To move forward, Gripper TBM is fixed against the previous segment of excavated tunnel by extendible hydraulic cylinders. Several telescopic fractional shields stabilize the machine against vibrations during the boring process. The insert shield similarly serves as a guide shoe for the TBM component. Lateral partial shields are pressed against the rock with a stabilizing effect. The roof shield, often equipped with a finger shield extending backward, offers protection against breaking the hard rocks. After completion of a stroke, tunneling is interrupted, and the gripping element will be transferred. The gripper component can control the machine by moving the main hydraulic cylinder vertically and horizontally to achieve precise control. Permanent monitoring is required in this process to control the machine (Hitachizoosen., 2012).

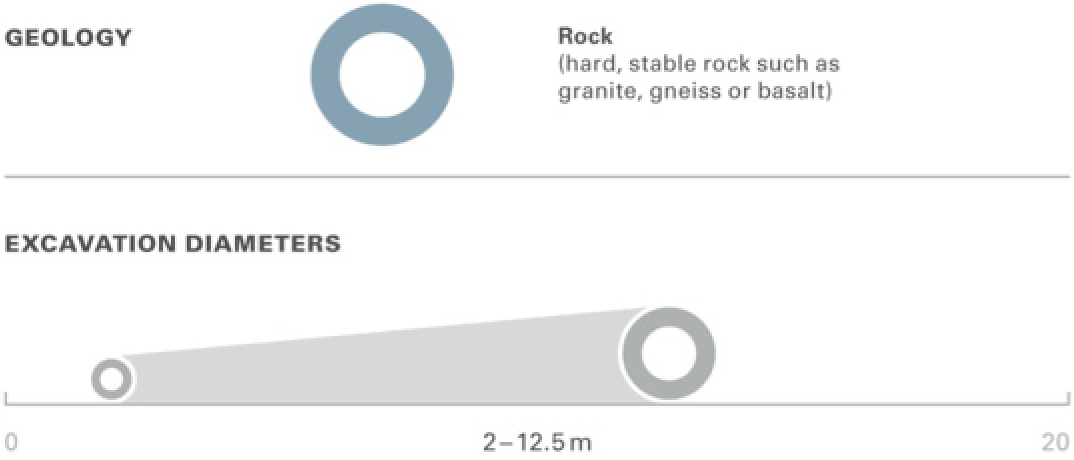

Figure 16. Geology & Diameters of Gripper TBMs (Herrenknecht AG, 2014)

2.5.6.2 *Summary of Gripper TBM Tunneling Process*

- <u>Excavation:</u> Disc cutters break chips from the tunnel face by applying high interaction pressure.
- <u>Removal:</u> Buckets, muck chutes, and muck rings provide for an efficient removal of the excavated material on top of a center belt conveyor.
- <u>Thrust:</u> Hydraulic thrust cylinders brace against the gripper shoes and push the cutter head forward.

- Tunnel lining: With rock anchors, steel mesh, steel arches, and shot-Crete, depending on the geology.

Advantages of Gripper TBM are as follows:

- High and constant tunneling performances and highly accurate excavation in stable rock formations.
- Measures to secure the rock increase safety for workers and machines in liability zones.
- Mobile partial shields permit the flexible reactions to convergences.

2.5.6.3 *Analysis of TBM Penetration Rate*

Parameters affecting the penetration rate can be classified into two categories (Torabi, Shirazi, Hajali, & Monjezi, 2013)*:*

1) Parameters related to rock:

These parameters divided into two groups:

a) Intact rock parameters including: strength (tensile strength), stiffness, hard rock drilling capability, brittleness index, abrasiveness index, Poisson ratio, Young’s modulus, friction angle and porosity, etc. (Resat Ulusay, 2001).

b) Rock mass parameters including discontinuity spacing, the orientation of discontinuities, rock mass rating, and others (in situ stress and groundwater conditions, etc)(Banaitienė, Banaitis, & Norkus, 2011).

2) Parameters related to TBM design and operation:

These parameters also are divided into two groups:

a) The operational factors of the machine are the force, cutter head torque, the rotational speed of cutter head, and power consumption (Yagiz, 2006b).

b) Design parameters of the machine including: amount of disc cutters installed on the cutter head, geometric profile of disc cutters (such as diameter, edge width, and edge angle), mechanical profile of disc cutters (Oyenuga, 2004).

Table 2 shows the comparison of the advance rate using three excavation methods.

Table 2. Compression of 3 Different Approaches Advanced Rate (Spathis & Thomson, 2004b).

Feature	Drill and Blast	Road Header	Tunnel Boring Machine
Rock Strength	Any - Not Clay	60 - 70 Mpa	200 Mpa (Fractured)
Gradient Down	Any	1:04	1:40
Gradient Up	Any	1:12	1:40
Radius of Curve	Any	>30m	>250m
Shape	Any	Flexible	Circular

2.5.7 Productivity of Tunnel Boring Machines

As all earthmoving equipment, tunnel-boring machines have many factors that affect the production rate. Some of these factors are similar to the ones mentioned above such as job and management conditions, versatility, type of rock, the diameter of the tunnel, tunnel accessibility, precision tolerance, and many others. Also, there are some factors that are machine–related, such as penetration rate, machine downtime, utilization time, and tool wear (tool changes per shift). Therefore, in order to improve the machine production rate, the penetration rate and utilization time have to be increased. On the other hand, the machine downtime and tool wear have to be decreased. Also, there are factors that affect the penetration rate such as the cutter geometry, the rock strength, and the rock mass (Lislerud, 1988).

2.5.7.1 *Summary of Tunnel Boring Machine Productivity Factors*

The factors affecting the productivity of tunneling with TBM are divided into six broad categories (Messinella, 2010):

- Shape and size of tunnel
- Soil characteristics (including type of soil, plasticity, water content)
- Operator's skill and experience
- TBM Type (if it is the right machine for the particular type of soil)
- Condition of machine
- Job and management condition

Moreover, there are many other specific factors that will influence productivity of this huge machine including:

- Type of head cutters
- Diameter of tunnel
- Length of tunnel
- Water content of soil
- Density of Soil
- Speed of rotation
- Distance and the way of soil disposal
- The technique for lining of tunnel after excavation
- Necessity of injection of materials to fill the void part of soil, in order to prevent depression in street pavements

It is obvious that many of these factors are associated with soil characteristics, so this factor entertains a significant role in the productivity of Tunnel Boring Machines.

2.5.7.2 *TBMs Advantages and Disadvantages*

The main benefits of TBMs for mining projects are as follows:

- Significantly higher and sustainable progress rates for generally good quality hard rock conditions.
- Less rock support required due to less damage caused to tunnel profile.
- Long single drives where no intermediate access audits are possible on vertical terrain.
- Lower ventilation requirements, allowing smaller tunnels to be constructed.
- Improved health conditions for laborers without exposure to blasting smoke/fumes.

There are also many another advantages in the operation stage of tunnel boring that are problematic, with considerable influence on the outcome of excavation amounts and costs. These are difficult to value in a tender (Efron & Read, 2012). These advantages cannot be fully appreciated except through firsthand tunnel boring excavation experience. Some of these are:

- structural stability and safety in the face and work area.
- continuous operation (non-cyclic).

Consistent, less-skilled, and easily trained operations (labor assigned to limited tasks that are repetitive, become routine, and may even produce competition amongst the laborers).

2.6 Materials Handling Processes

Bickel et al. (1996) stated that the materials handling is the key element in the tunneling construction process. To achieve the designed productivity for all tunneling activities depends upon the materials handling systems. Also, the facilities required to support the tunneling operations are mainly oriented toward keeping the material handling schemes operating efficiently and at their planned rates of production (Kuesel, King, & Bickel, 2012). Ouran and

Asai's (1987) studied the advance rate in the construction of a tunnel and the consequences of different variables on the tunnel advance rate. One of the conclusions of this study is that the main problem in long tunnels with a small diameter is the logistics. They found that the reduction of the tunnel advance rate was not due to the power and capacity of the TBM, but the complex interaction between the logistical processes inside the tunnel. Nestor (1974) stated that the reason material handling considerations are important in planning tunnel operations is that TMB capability is often greater (due to technological development) than that of the backup system. Any increase in TBM capability must be matched or exceeded by improvements in the material handling and other components of the backup system (Nestor, 1974).

2.6.1 **Logistical Processes**

Materials handling systems essentially deal with materials going into the tunnel face and materials leaving the face to go to the surface. The materials that enter the tunnel are essentially the materials and equipment for all tunnel systems and personnel. The materials that leave the tunnel are usually muck, drainage water, gasses, equipment for repair, and replacement of the staff. These activities occur at the surface of the tunnel and vertically, at the shaft of the tunnel. Beside the principal materials handling, the system also includes the handling of water, ventilation and high air, drainage, fuel, and power (Cooper, 1974).

The logistical processes distinguished (Touran & Asai, 1987) regarding tunneling construction are:

- Transfer of the excavated material from the tunnel faces to the shaft area.
- Vertical material handling at the shaft.
- Transfer of tunnel support system to the tunnel face.

- Installing the support system.
- Switching trains, moving forward and backward in the tunnel.

2.6.2 **Transportation Systems**

Selecting a transportation system for underground and shaft hauling, the following factors are essential to keep in mind: cost calculation, existing machines, traffic in the tunnel, traffic safety, possible hindrances at site, and ventilation requirements (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2013).

According to Nestor (1974), the material handling system chosen depends upon the following variables: type of formation, diameter of the tunnel, length of the tunnel, whether access to the tunnel is through a shaft or portal, location of and space available at the shaft or portal, and, from an economic standpoint, the material handling system already accessible to the contractor. The effective factors for muck haulage system complex according to (Faddick & Martin, 1977a) are: problems of confined space, wide variation of mucking rates, wear of equipment, and the noise and dust inside of the tunnel.

2.6.3 **Basic Transportation**

There are two basic types of transportation for moving personnel and materials inside the tunnel: railroad track and different types of cars. The latter type uses a roadbed for rubber-tired vehicles (Kuesel et al., 2012).

Rail

The most energy efficient handling of materials inside the tunnel is provided by rail haulage (Kuesel et al., 2012). Rail haulage consists of a train system using multiple trains on either a single track with passing tracks or double track with crossover for passing trains. The key advantages of this type of system are the simply maintained traffic way - compatible with most excavating and loading materials, it is adaptable to almost all sizes of tunnels, and it can transport personnel and material into the tunnel.

There are also a few disadvantages, including a constant requirement of extension at the heading, and the fact that, in the event of any accidents, the entire system needs to be shut down. Different kinds of track layouts are used in the train haulage for tunneling construction, namely the so-called 'Californian switch', the 'Jacobs sliding floor' (drill and blast), and the 'Navajo blanket'. They allow trains to move in opposite directions and pass each other at various points in the tunnel. The portable, or Californian switch, consists of a section of double track with turnouts and ramps at each end, all of which slides on the main path. The Jacobs sliding floor includes a steel floor occupying most of the invert width. It is built in three or more sections so that it can be moved along as the heading advances. The Navajo blanket provides for extending the track in the heading, in standard rail length increments (Kuesel et al., 2012). Kuesel et al. (1996) also describe the choices for the propulsion of the trains inside the tunnel, as well as the considerations concerning the track itself (e.g. the selection of the track gauges, the weight of the rail, the track accessories, and track ballast) and the construction of the roadbed.

Rubber-tired vehicles

In contrast to rail haulage, transportation with rubber-tired vehicles is more flexible because they do not need fixed facilities. The use of rubber-tired vehicles has some significant advantages. In a wide tunnel, passing locations can be selected at will. When accidents happen, the entire system does not have to be shut down. Also, the work on tunnel invert is usually simplified. The main disadvantages that come with this system are that the roadbed is hard to maintain, the system is not compatible with all excavating and loading equipment, and vehicles are often not usable in small tunnels. Rubber-tired vehicles are often used for driving in short tunnels in which installation of a track system would not be economic (Nestor, 1974). There are different kinds of rubber-tired vehicles defined in Kuesel et al. (1996), specifically the load-haul units (standard front-end loaders), dump trucks, and special vehicles (for explosives delivery or supply services).

2.6.4 Special Muck Transporting Systems

Besides the basic transportation systems, there are also other methodologies used in special cases to haul the muck. The two main systems are belt conveyors and pipeline.

Belt conveyors

The belt conveyor system is used in combination with the tunnel boring machine (TBM) excavation method, as it can transport an enormous amount of muck relatively fast. Most TBMs have a conveyor incorporated into their design for removal of the muck to an intermediate point on the machine, where it is transferred for removal. This method can also be used with any other excavation methods, as long as the operating requirements are met. Belt conveyors offer the simplest, most acceptable, and most economical way of continuous transportation. The main advantages of this method are:

- Capable of handling excavated material in any quantity.
- Suitable for almost all dimensions of tunnels, decent reliability, and low maintenance.

The disadvantages include the high capital cost, the breakdown of one part shuts down the entire system, and the level of complexity for an extension at the heading (Kuesel et al., 2012).

Pipeline

Pipeline systems can be used when bulk materials can be transported using either air or fluids as the medium of transportation. The pipeline systems have the ability to transport high volumes of muck relatively quickly using limited space. These systems are more useful as the tunnel diameter decreases, and hence the volume of the muck to be transported and space for installation of the muck removal system decreases. Amuck haulage pipeline is a system that consists of three elements: preparation, transportation, and separation. The excavated material needs to undergo a size reduction before it can be transported through the pipeline. The reduction of size and particle shape is done to optimize the pipeline performance.

Three types of systems are distinguished: the slurry system, the hydraulic system, and the pneumatic system (Kuesel et al., 2012). The slurry system, in particular, offers high transport capacity with very low space requirements. In tunnels with a small diameter, where trains cannot pass each other, a slurry system makes it probable to achieve high advance rates. Faddick and Martin (1977) describe the use of slurry pipelines for muck haulage in tunneling construction operations. A slurry pipeline for main muck haulage necessitates two pipelines: an outgoing pipeline to transport the muck slurry and an incoming pipeline to carry water supply (Faddick & Martin, 1977).

The advantages of using a pipeline system included high capacity, minimum space requirements in the tunnel, and guaranteed continuous operation. The main disadvantages are that maximum size of material to be handled is limited, it requires a complicated system for extension at the heading, and, in case of any breakdown, and the entire system needs to be shut down (Kuesel et al., 2012).

2.6.5 **Vertical Material Handling**

When the excavated material is brought to the shaft and dumped into a temporary storage facility, it has to be hoisted to the surface. This vertical material handling can be done using different systems, such as skips, cages, a muck car lift-up system, multi-bucket system, and vertical conveyors (Kuesel et al., 2012).

In the skip system, a skip is placed at the bottom of the shaft in which the muck is loaded, and subsequently hoisted through the shaft, and eventually emptied at the surface. When the depth of the tunnel is more than 30 m, a cage or skip is often used with a head frame for hoisting the muck. Cages are used to convey personnel, material, and equipment. Even loaded muck cars can be hoisted in a cage. In the muck car lift-up system, the muck cars themselves are hoisted to ground level, in a special guide cage that provides for the automatic dumping of the car. Vertical conveyors and bucket-type elevators (multi-bucket system) are available for lifting large volumes of tunnel muck, usually generated by TBM, from the tunnel to the surface. However, these systems are not able to supply construction material to the inside of the tunnel.

2.7 **Tunnel Support Systems**

Tunnel support systems are applied for stabilization (primary support) previously, during, or immediately after excavation, to provide initial support and to permit safe, rapid, and economical excavation. Final lining systems are installed either shortly or considerably after excavation to provide permanent support and durable, maintainable long-term finishes. The type of system chosen depends primarily on the ground conditions and the end use of the tunnel (Kuesel et al., 2012).

2.7.1 **Primary Support**

The purpose of the primary support is to stabilize the underground opening until final lining is installed. The main goal is to ensure the health and safety of the working crew during the construction of the tunnel. Furthermore, usability of the underground structure is an important object for placement of primary support as well as the protection of the environment (e.g. neighboring buildings, lines of communication in or above ground facilities, etc.). The most common elements for the primary support are:

- Rock bolts
- Shot-Crete
- Steel ribs and lattice girders
- Wire meshes
- Lagging

These elements can be applied individually or in combination with different types of support, depending on the ground conditions and the design of the tunnel. The elements of primary support are placed, in each round, up to the excavation face of the tunnel, according to structural analysis of the tunnel and the assessment of the ground conditions (ITA, 2009).

2.7.2 **Final Lining**

An underground structure excavated by drill and blast or road header often needs a final or secondary lining in addition to the primary lining according to the requirements of the project to (Messinella, 2010):

- Cater for all the final load cases
- Fulfill the final safety margin

- Include the necessary protection measures (e.g. water tightness)
- Guarantee the required service lifetime

In general, there are two options to construct the final lining: an independent secondary lining to withstand all the final load cases, or additional layers of Shot-Crete to strengthen the primary lining for all the final load cases. According to the requirements of the project, the secondary lining can consist of the placement of Shot-Crete or cast in situ concrete, which may or may not be reinforced with steel bars or fibers.

2.8 Comparison of Mining Methods for a Deep and Surface Excavation

To extend the life of a hypothetical mine, an access bore must be excavated to a depth of 750 m below the surface. Assuming a 15% grade, the bore will need to be approximately 5 km in length. Because this is an existing mine, there is minimal site prep, logistics, and permitting, and therefore excavation can begin in six months (Ryan Gratias. Craig Allan, a. D., 2014).

Table 3. Comparison of TBM and Drill and Blast Methods (Ryan Gratias. Craig Allan, a. D., 2014)

Factor	Drill and Blast	Tunnel Boring Machine
Site prep time	Requires less start up time	Requires 3 to 12 months
Equipment storage	Requires explosive storage permits	Requires slightly larger footprint
Length of the tunnel	Slower excavation rate (typically 3 to 9 meters per day averaging 180m/month with three shifts)	Significantly faster excavation rates from 15 meters to 50 meters per day, 450+/month)
Shape of the tunnel	Typically horseshoe-shaped but can be other shapes	Uniformly round

Length and depth of required tunnel	Difficult in low overburden settings Substantially slower in longer access tunnels (over 2 km)	Not comparable to drill and blast for short tunnels (less than 2 km)
		Minimum 30 m turn radius
		Faster for long, straight tunnels
		Can be used in low or high overburden
Ore body orientation/mining method used	Can be used with any or body orientation	Best for use with deep or long or bodies
Removal, disposal or reuse of spoils	Can be reused but spoil size and consistency is highly variable. Removal due to the variable size of rocks can be difficult.	Can be reused; uniformly sized muck chips. Uniform rock also makes for easier removal by continuous conveyor
Means for removing mined material	Continuous conveyor; muck cars	Continuous conveyor; muck cars
Ground vibration	High	Low
Existence of explosive and/or hazardous gasses	Mitigation possible	Mitigation Possible
Populated or unpopulated area	Typically unpopulated, or in populated areas with restrictions	Populated or unpopulated
Access to skilled labor	Requires unique skill sets and certification	Primarily mechanics

Surface mining for such a deep mineral frame, while possible, is unlikely. Removing hundreds of meters of overburden would probably not be financially viable, and would have undesirable environmental inferences. Gratias and Allan (2014) useed an hypothetical example for deep ore body. An access bore must be excavated to a depth of 750 m below the surface for extending the life of a mine (Figure 17). They assumed a 15% grade, the bore is approximately 5km in length.

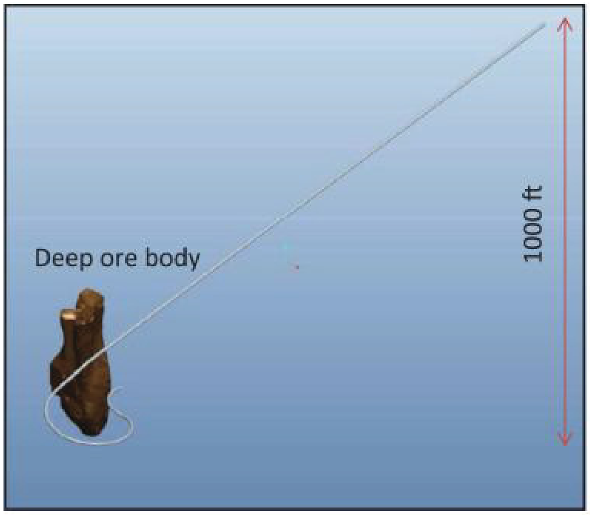

Figure 17. Deep Ore Body with Access Tunnel (Ryan Gratias. Craig Allan, a. D., 2014)

While Drilling and Blasting (D&B) is likely to be favorable for low depth excavation up to certain deepness, the method has advantages and disadvantages (Ryan Gratias. Craig Allan, 2014):

- D & B is suitable to excavate short radius turns in tunnels.
- The D&B method can be prepared considerably fast, and starting the excavation instantly after the site prep is complete.
- In a long length tunnel, particularly from 5 km or more, D & B methods, has a low advance rate.

In general projects, average excavation rate of a drill and blast operation varies around 6 m per day (Tarkoy & Byram, 1991).

5.1 Comparison of TBM and D&B Method

Through years of experience in tunnels all over the world, it has been observed that in tunnels over 3 km in length and more TBMs are the most efficient tunneling method compared to other techniques (Figure 18).

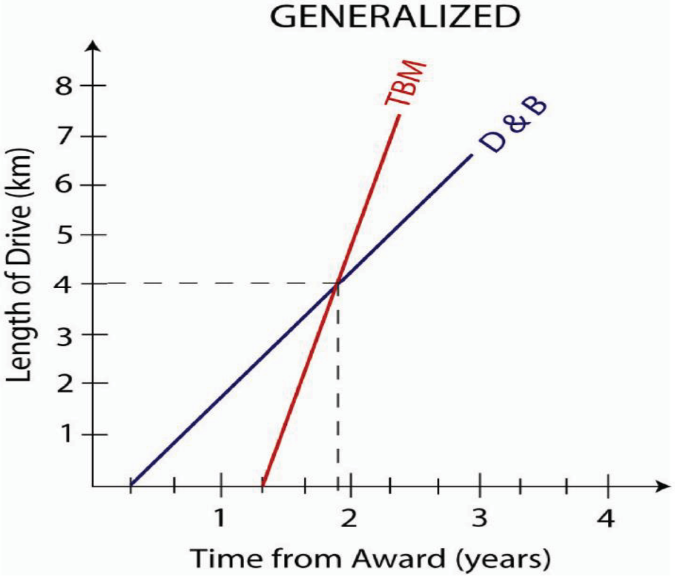

Figure 18**. Generalized Graph Comparing Advantages and Disadvantages of TBMs vs. D&B (Ryan Gratias. Craig Allan, a. D., 2014)**

In comparison with Drilling & Blasting methods and TBMs, tunnel boring machines are a more automated form of construction, requiring fewer workers. It requires less ground support compared to drilling and blasting, which is attributed to the smooth excavation profile (Ryan Gratias, 2014). The type of ground support is also extensively variable for TBMs. In McNally Support Systems, for example, wire meshes to ring beams, rock bolts, and steel slats are usually used. In terms of Installation for ground support between TBMs and Drill and Blast, method TBms are safer (Ryan Gratias. Craig Allan, a. D., 2014).

Time is an important aspect of construction projects, particularly in tunneling project, where TBM has both advantages and disadvantages. The advantage derives in the procedure of advance rate, the disadvantage due to delivery time and setting up the machine. According to the manufactory guidelines, the average speeds of TBMs is around 20 m per day. In other words, a TBM takes only 250 days to excavate the entrée tunnel with 5000m, as opposed to the 830 days needed for D&B. However, delivery and setup for a new, custom TBM is about one year. By counting the provision and preparation time, TBM will start approximately six months after the D&B operations would. Despite the six-month latency, using a TBM will still need less compared to the D&B method by finishing one year ahead.

Furthermore, a TBM can be used several times, so if a tunneling operation were to own one, then the startup time could be reduced from one year to a couple of months. Also, a continuous conveyor for waste removal can provide additional escalation to the tunnel boring machine's overall advance rates over long distances. Through a typical conveyor system, availability rates of 90% or higher are observed. Ventilation is also much better in TBM tunnels using conveyors, as there is a substantial reduction in the exhaust from locomotives. Continuous conveyors could be used with drill and blast operations, as well. (Ryan Gratias, 2014).

5.1.1 **Tunneling Minimum Cross size for TBM**

Tunnel cross sections size is a major issue considering the application of TBMs is required for the minimum acceptable tunnel diameter to meet the minimum internal clearance requirements (Dean Brox, 2013). Clearance is dictated by the purpose of the tunnel, as well as practical construction considerations for the effective installation of initial tunnel support and any final support and lining. Assessment of the least acceptable TBM diameter for a proposed mining tunnel should be carried out by identifying the minimum clearance and the maximum anticipated initial tunnel support requirement. Also, maximum anticipated deformation against weak rock conditions and maximum final support (lining) requirements must be calculated. In some cases, it is common to oversize the TBM diameter above the minimum size requirements to achieve higher productivity compared to the a smaller tunnel cross sections. A TBM diameter of about 4 m is considered to be a minimum practical size based on the criteria mentioned above (Dean Brox, 2013).

5.2 Geotechnical Specifications:

In general, major geotechnical change occurs at 2400 feet below the ground level, where the contractor come across an unstable material, which proves extremely difficult to support (Hoek, 1982). The excavation of a tunnel may cause many changes in the original structure of the soil and rock, such as modifying the existing stress status, to produce deformations. The response of soil /rock to the excavation subjected geotechnical characteristics of the soil and rocks as well as the excavation and support systems. A detailed knowledge of these characteristics must be obtained from geological, hydrogeological, and preliminary studies to select the appropriate tunneling type technique. This can determine the tunnel plan and help decrease the risks of tunnel instability and the modification of the surrounding environment (EFNARC, 2005).

According to the engineering perspective, the ground beneath a site can conveniently be distributed

into the categories presented in Table below, which are based upon generalizations of its expected behavior in underground construction.

Table 4.Categories of Ground Beneath a site (Clayton, Simons, & Matthews, 1982)

Material Type	Strength	Compressibility	Permeability
Rock	Very High	Very Low	Medium to

			High
Granular Soil	High	Low	High
Cohesive Soil	Low	High	Very Low
Organic Soil	Very Low	Very High	High
Made Ground	Medium to Very Low	Medium to Very High	Low to High

These extensive generalizations are, of course, limited in precision. However, they give a geotechnical specialist a decent understanding, at the beginning of the project, of both the likely construction problems and the methods of investigation that might be used. In practice, the ground varies continuously beneath a site, and it is hard to discover the changes from one kind of material to another. This calls for a more refined, systematic description and classification of soils and rocks. Soil Classification, established on Casagrande's Airfield Classification System, became standardized. As originally proposed, the system is based exclusively on particle scope distribution and plasticity tests, and soils are designated by letters alone, related to which categories they are a part of. At the same time, a soil description system has been developed, based on visual examination and simple land tests (Clayton et al., 1982).

5.2.1 **Soil And Rock Description**

A standard terminology is used to describe soil and rock subjective in the systematic component. The systematic investigation includes whether the material is in natural contact, experimental pit face, or models recovered from a borehole. Using these, a standardized system of description makes sure(Clayton et al., 1982):

- Entire factors are considered and inspected in logical sequence
- No essential information is omitted

- Assumed description is using all terms in an identical manner for all users
- The description conveys an accurate mental image to the readers
- All operators can quickly extract the relevant information

5.2.2 The Soil Classification

In the scheme of soil description, samples must be described in a routine method, with each component of the description having a secure position in the overall description(Clayton et al., 1982):

- Consistency or relative density
- Fabric or fissuring
- Color
- Minor constituents
- Angularity or grading of principal soil type
- Principal soil type
- More detailed comments on constituents or fabric
- Soil classification symbols

In soil description, the material being deliberated is first placed into one of the principal soil types in Table 5.

Table 5. Principal Soil Types (Clayton et al., 1982)

Soil Type	Description
Clay	Cohesive Soil
Boulders	Granular Soils
Cobbles	Granular Soils

Gravel	Granular Soils
Sand	Granular Soils
Silt	Granular Soils
Peat	Organic Soil
Made Ground	Man-Made Soils and Other Materials

Geotechnical soil classification schemes are also called textural classification. At the present, soil classification systems are mostly aimed at guiding the tenders.

5.2.3 **Geological Classification of rock**

Rocks are characterized into three groups based on the manner of formation. These groups includes the following (Clayton et al., 1982):

- Igneous rocks: These are formed by the solidification of the molten material.
- Sedimentary rocks: These are formed by the accumulation of fragmental rock material and an organic material or by chemical precipitation.
- Metamorphic rocks: Alteration of existing rocks forms these through the action of heat and pressure.

In many cases, a full petrographic analysis is required to classify a rock specimen in geological terms. Such classification systems are too elaborate for engineering application, and usually offer tiny or insufficient evidence for engineering significance. For engineering practice, the classification schemes have been simplified, and the number of rock names kept to a minimum.

The primary criteria used in classifying all types of rock material include:

1. mineral assemblage;
2. texture and fabric,
3. grain size.

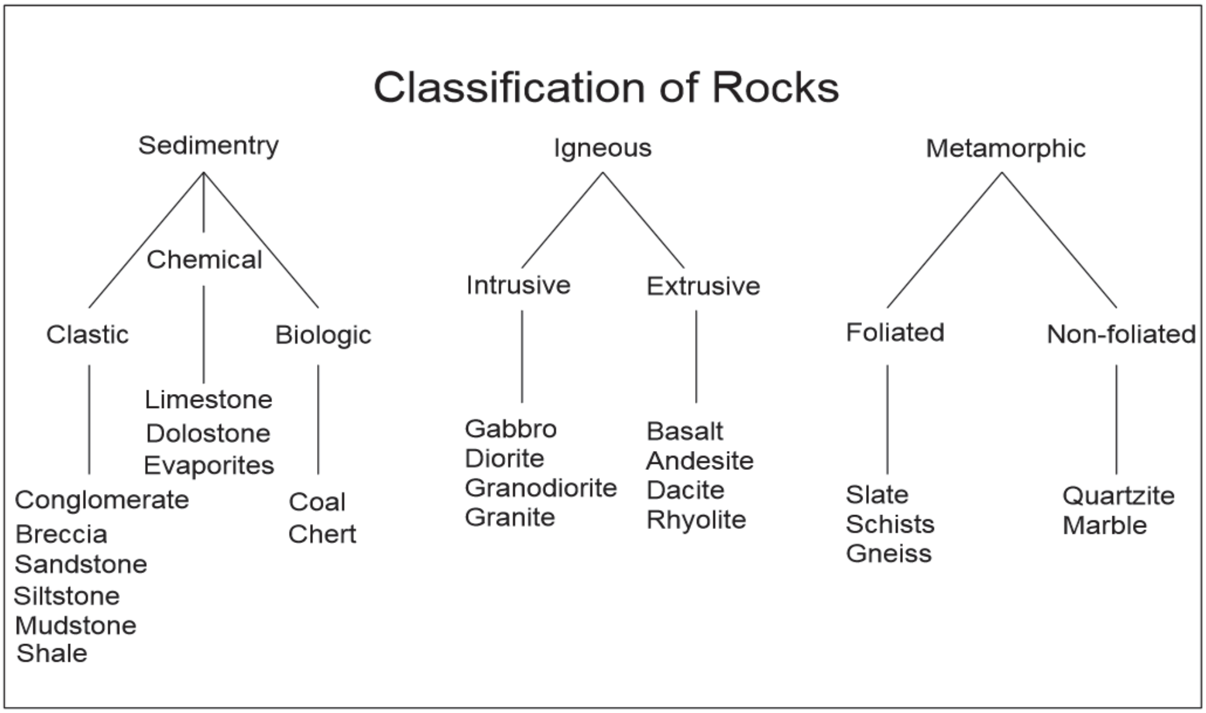

Figure 19. Classification of Rocks (Pellant & Pellant, 2014)

Igneous rocks

Rocks in this broad variety are characterized by a crystalline or, more infrequently, glassy texture with low porosity (usually <2%), except the rock has been weathered. The strongest rocks are recognized among this group. Igneous rocks are made from the solidification of the molten material, which may originate in or under the Earth's crust. Magma may get firm within the crust at depth or near the surface, giving increase to intrusive igneous rocks, or it may fill up into the face of the earth before solidifying totally, giving rise to extrusive igneous rocks. (Clayton et al., 1982).

Sedimentary rocks

In sedimentary rocks group, the majority of combination materials are an aggregate of cement and transported fragments derived from pre-existing rocks. Characteristically, these types of rock contain rock fragments, grains of minerals resistant to weathering similar to quartz. Moreover, minerals derived from the chemical decomposition of pre-existing rocks, such as clay mineral,s and bound together with chemical precipitates, such as calcium carbonate and iron oxide. Other forms of sedimentary rock include accumulations of organic debris a fragmental material derived from volcanic eruptions, and minerals that have been chemically precipitated such as rock salt, gypsum and some limestones (Pellant & Pellant, 2014).

Metamorphic rocks

Metamorphic rocks are derived from pre-existing rocks of all types in response to marked changes in temperature and pressure, or both at the same time. Increasing the temperature or stress can cause the formation of new minerals and r complete recrystallization of the parent rock with the growth of new textures (Pellant & Pellant, 2014).

5.3 Hydraulic Characteristics Consequence on Excavation Performance

The attendance of water not only affects the excavation productivities during the construction time, but it also might add more work such as waterproofing, drainage, etc. Also, it may influence the mining stabilities and the long and short terms of deformation. Therefore, it is important to achieve a comprehensive hydrogeological information about the ground permeability, the water pressure, and tidal variations. To determine the ground permeability, laboratory tests on samples are not sufficient, and field tests are necessary (Faddick & Martin, 1977b; Piramid Consortium, 2003).

5.4 Tunneling Construction Risk Assessment

Tunnels are artificial underground spaces that provide a capacity for particular goals such as storage, underground transportation, mine development, power and water treatment plants, civil defense, and other activities. Therefore, tunneling is a core activity in infrastructure projects. Tunneling imposes risks on all parties involved, as well as on those not directly participating in the project (Eskesen, Tengborg, Kampmann, & Veicherts, 2004). These risks may dramatically impact operation, requiring an unexpected time for renovation resulting in major cost and time delays. To avoid such problems, managers are obliged to carry out a risk management program. Risk management involves a number of approaches, including the identification, evaluation, and control of risk.

Risk assessment is one of the crucial steps for selecting and progressing any tunneling construction methods. A proper risk assessment can presume the damage due to the construction process failures. Damage stands for financial losses related to a delay in construction time and/or exceeding the construction budget. In other words, the risk is defined as “the effect of uncertainty on objectives” (Eskesen et al., 2004). Alternatively, the risk is expressed as an expected utility. In current practice, the tunnel project risks are commonly analyzed on a qualitative basis using different rating systems. Such qualitative analysis is an irreplaceable basis for prioritizing the risks, for the development of risk treatment strategies, and for allocating the responsibilities. However, the major decisions made during planning and construction of the infrastructure should ideally be based on a consistent quantitative basis, i.e. on quantification of the risk.

Risk evaluation is a part of risk management which can help decision makers to rank the existing hazards, and finally, the appropriate reaction is accomplished (Banaitienė et al., 2011). There are various techniques for evaluating risks such as Monte Carlo Simulation, Event Trees, Fault Trees, Failure mode and Effective Analysis, Fuzzy set, game theory, multicriteria verbal analysis, and Grey Systems. Risk evaluation decreases the risk to project goals and objectives for the following reasons (Fouladgar, Yazdani-Chamzini, & Zavadskas, 2012):

- To demonstrate that options were comprehensively and rationally evaluated
- The process will disclose useful information even if threats do not eventuate
- To clarify internal project goals, objectives, and priorities and focus the project team
- The feasible range of cost and schedule can be estimated.

Due to the critical importance of risk in underground construction, different researchers are assigned to evaluate and assess risk.

5.5 Probabilistic Model of Risk Assessment in Tunneling Construction

Probabilistic models for tunnel construction risk assessment is one of the most practical tools for tunneling risk assessment. According to Kova 2013, probabilistic model applied to a case study of 480 m long and varied cross-section around 40 m2 an underground extension project in the Czech Republic.

In the first step of a simple model that has been developed for analyzing the cave impact structure surface, the inference of jointed rock in a compact layer above the tunnel, and the effect of randomly varying depth of the rock, overburden which tended to decrease along the tunnel axis. Therefore, to evaluate the probability of occurrence of failures during the construction of a tunnel, the following parameters have been considered (Špačková, Novotná, Šejnoha, & Šejnoha, 2013).

- The tunnel length
- Failure rate
- A number of failures per a unit length of the tunnel.

Another important factor in tunneling construction was the Human Influence: management, equipment operator, and labor performance

The human factors were also classified into three categories:

- Unfavorable
- Neutral
- Favorable

In step two, after the construction began, more information about the influence of common factors on the construction performance will be provided. This can be done probabilistically by updating the human factor “H”. For example, by observing a failure during the excavation of a short section of the tunnel, the probability of an “unfavorable” human factor increases, indicating a systematic problem in the construction process. With this new information, a prediction of the number of failures for the remaining part of the tunnel construction is updated. Figure (20) represents the equation for estimation of probabilistic risk assessment in tunneling construction.

$$\begin{aligned}\Pr[N_F = k \mid \lambda_{II}, L_{II}, n_{F,OBS}] \\ = \sum_{j=1}^{j=n_H} \Pr[\mathrm{H} = j \mid n_{F,OBS}] \Pr \frac{\left(\sum_{i=1}^{i=n_{Z,II}} \lambda_{ij} L_i\right)^k}{k!} \exp\left(-\sum_{i=1}^{i=n_{Z,II}} \lambda_{ij} L_i\right)\end{aligned}$$

Figure 20.**Probabilistic models for tunnel construction risk assessment (Špačková et al., 2013)**

The impact of these factors is uncertain in the design phase, giving rise to the uncertainty in the selection of the failure rates. This uncertainty decreases once the construction starts and the variable can thus be updated with observed performance as illustrated in the proposed model. The risk is quantified for three cases. By introducing the utility, the version of the contractor to high financial losses can be taken into account. In the next step, demonstrating probabilistic estimates of the construction time/cost ratio obtained from available models should be utilized in the tunnel project management. The optimal quantitative decision concept, possibly based on the utility theory, should be proposed. The decided concept should take into account the measurable criteria, such as construction time and cost or maintenance costs, as well as soft criteria, covering environmental or social impacts. Probabilistic problems related to the failures of surface structures and ensuing from the impacts of the tunnel excavation and mutual interactions are discussed in Section 4 along with other specific tasks.

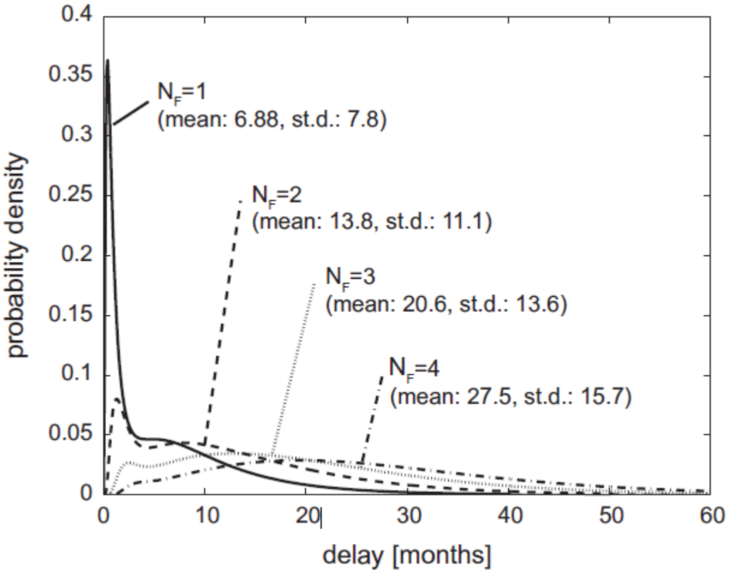

Figure 21**. Estimation of crucial parameters in probabilistic modeling (Špačková et al., 2013)**

To obtain a realistic prediction from the probabilistic models, a systematic analysis of data from construction projects is necessary. To achieve this, the understanding of benefits of probabilistic modeling among stakeholders should be raised to motivate them to manage more systematically and statistically analyzed data from the available project.

5.6 **Productivity of Earthmoving Equipment**

Productivity plays a significant role in the construction field. From a contractor's point of view, the main purpose of carrying on a project is to gain profit from that action. In order to be profitable, the contractor should be able to utilize ways in which the monetary value of output is greater than the value of money injected into the project. In other words, to be competitive and gain more, production should be more than the amount of money spent in each activity related to the project. Productivity can be divided into two main parts. First, productivity is measured as how efficient the labor is in a particular activity. The other measure is how productive the equipment used in a particular activity. Productivity is distinct as "the ratio of the input of an associated resource to real output" (Ahuja, Dozzi, & Abourizk, 1994).

There are many factors that affect productivity that should be taken into consideration while measuring productivity. Some of these factors are projected conditions, market conditions, procurement, construction management, labor, education, and training. Also, there are some specific measures for the productivity of equipment, such as the effectiveness of using the equipment and the relative efficiency of the equipment in doing a specific task.

There are several ways to measure productivity in general. Productivity can be measured through field ratings, field surveys, and work sampling. Also, delay factors can be identified, and corrective actions can be selected.

Earthmoving operations are one of the main activities in each and every construction project. Therefore, it is of vital importance to measure the productivity of the equipment used in such operations to maximize the output and result in more competitive results. According to Smith (1999), a system's maximum productivity depends on the output of the prime mover and this maximum can be changed by altering its characteristics or number of crew utilized. Also, the productivity of certain equipment can be found out using historical data or the manufacturer's handbook. Many factors affect the productivity of earthmoving operations such as the type of rock, versatility, mobility, capital and operational costs, and many other factors that are related to the project.

5.7 Criteria for Tunneling excavation Equipment Selection

Applying one of the three major excavation approaches - road-headers, drill & blast, or TBM - fundamentally depends on the size of the project (Girmscheid & Schexnayder, 2002). According to Girmscheid and Schexnayder (2002), the drill and blast are cost effective if the tunnel length is less than three kilometers. TBM 's hard to set up and very expensive to design, build, and transport to the site. Therefore, it is not reasonable to apply this technique for small projects (Girmscheid & Schexnayder, 2002). Minimum tunnel cross section with respect to TBM was discussed in section 2.9.1, and one of the most important differences between the three types of procedures is performance (Thompson et al., 2011). The performance, and the cost of the equipment is higher for TBM than for other methods. Using TBM will give us an accurate circle cross section; however, in blast and drill method, the cross section can be any shape (Messinella, 2010). According to (Hitachizoosen, 2012), the most important criteria that determine the optimal machine type in tunneling excavation processes are a geological and hydrological situation of the project, as well as its specific requirements. In complex soils, it is much better to use drill and blast rather than TBM. Even though TBM can excavate soils ranging from loose soil to the hardest granite, such as that found in Alp Mountains in Switzerland, kind of soil and condition requires a special device be designed, and a specific cutter header should be used. When unanticipated materials are encountered, a project can face a big problem. An example of that is the Seattle downtown tunnel project which used the massive TBM with 17.8 meters in diameter. The project stopped in December 2013 for more than two months as the excavation came across a dense layer. The machine stopped without any apparent reason. After two months of inspections, the work using the TBM continued (Ehrbar, H. 2008).

5.8 **Analytical Hierarchy Process (AHP)**

Construction management decisions typically involve several conflicting aspects that need to be considered, particularly in tunneling construction projects, known as complex and dynamic projects. Making decisions for projects with such situations can be formulated as multi-criteria optimization problems, where the different aspects of a tunneling project equipment selection constitute the conflicting criteria that are optimized simultaneously.

It is widely recognized that most of the total cost and performance of the tunneling projects are determined by the decision making in the conceptual design phase. In this early stage of the project applying multi-criteria optimization can lead to significant savings in the tunneling project (Mela, Tiainen, & Heinisuo, 2012). Analytical Hierarchy Process (AHP) is a very commonly-used tool for multi-criteria analysis decision making. Analytical Hierarchy Process (T. Saaty, 1980) provides methods of weighing selection criteria with a higher level of objectivity, as items are compared two or more at a time. Decisions are stated either numerically or verbally, as in Table 3.

Table 6. Analytical Hierarchy Process (AHP) (T. Saaty, 1980)

1	**A and B are equally important**
3	A is weakly more important than B
5	A is strongly more important than B
7	A is very strongly more important than B
9	A is absolutely more important than B

Presentations for multi-Criteria Decision making are commonly verified in, n x m matrix scales, where n is represented as a number of items compared. Consistency can be checked by calculating consistency ratio (C.R.), which must be kept under 0.1(R. W. Saaty, 2003). To reach a decision through the AHP method, one constructs a hierarchy of the problem. The top of the hierarchy is the goal of the decision process, the sub-objectives are immediately below, the alternatives or possible outcomes at the bottom, and there may be several intermediate levels (T. Saaty, 1980). Elements are compared to each other within clusters, with respect to elements higher in the hierarchy. Constructing a decision hierarchy or network relies on an understanding of the problem, and a certain level of subjectivity is inherent in the AHP method (T. Saaty, 1980). The AHP considers the elements of each group as only affecting the elements of one other group and being affected by elements of one other group.

AHP utilize mathematical operations with matrices to compute the relative importance of the selection criteria. Exact priorities are obtained by "raising the matrix to arbitrarily large powers and dividing the sum of each row by the sum of elements in the matrix," (T. Saaty, 1980). Software, such as Super Decisions, automates the AHP matrix calculations. Priorities of elements within the same set of comparisons, i.e. the elements that are all compared to each other with respect to another element, are referred to as local priorities. Among the approximate methods for calculating local priorities, a method that represents the best approximation consists in finding the geometric mean of each row of the local decision matrix and normalizing the resulting numbers - the process referred to as 'Good' by Saaty (1980). This approximate method also includes a method for calculating consistency ratio. To calculate the overall priorities of elements, local priorities of items that are connected to each other along the same branch of a hierarchy are multiplied with each other, going from highest to lower levels of hierarchy (R. W. Saaty, 2003).

Most examples of AHP in multi-criteria selection have three levels of hierarchy, including the goal but not including the level of alternatives (Mahdi & Alreshaid, 2005). They have three to seven elements on the second level, of which at least one is related to the owner and one to project.

Analytical network process (ANP) represents a further development of the AHP. The ANP allows interactions and feedback within clusters (inner dependence) and between groups (outer dependence, (Saaty, 2003). The AHP is a special case of the ANP. A network may be generated by adding connections to a hierarchy (Saaty and Vargas, 2006). According to Saaty (2003), both the use of AHP and the ANP has been justified in various examples, based on the validity of the outcomes.

5.9 **TOPSIS**

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a method of multi-criteria decision analysis. It was developed by Hwang and Yoon (1981). It is based on the concept that the alternative with shortest geometric distance from the ideal solution and longest geometric distance from the negative ideal solution should be chosen. Having a defined set of m, alternatives and n criteria, the input information for a TOPSIS analysis are the scores of each alternative with respect to each criterion, as well as the criteria weights. In Step 1 the scores x_{ij} of m, alternatives with respect to n criteria are entered into an evaluation matrix with m columns and n rows. In Step 2, the evaluation matrix is normalized as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i = 1, 2, ..., m, j = 1, 2, ..., n$$

where r_{ij} is a normalized score.

In Step 3, the normalized scores are multiplied by the respective factor weights, to give a weighted normalized decision matrix, with entries t_{ij}. In Step 4 the ideal and the negative ideal solution are determined. The ideal solution A_b is the set of highest weighted normalized scores t_{bj} and the negative ideal solution A_w is the set of lowest weighted normalized scores t_{wj}. In Step 5, the distance from the ideal solution d_{ib} and the distance from the negative ideal solution d_{iw} are determined for each alternative as follows:

$$d_{ib} = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_{bj})^2}, i = 1, 2, ..., m$$

$$d_{iw} = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_{wj})^2}, i = 1, 2, ..., m$$

In Step 6, the relative closeness to ideal solution for each alternative is determined as follows:

$$s_{iw} = d_{iw}/(d_{iw} + d_{ib}), 0 \leq s_{iw} \leq 1, i = 1, 2, ..., m$$

In Step 7, the alternatives are ranked based on relative closeness to the ideal solution. The alternative with the highest value of S_{iw} is chosen. (Hwang and Yoon, 1981).

5.10 Sensitivity analysis

The project decision makers are trying to evaluate the impact of their decisions on the current statues of the production system and its productivities. Also they need to know setting of one of the controllable management variables to be able to evaluate changes. Examine the system and the parameters, statistics may lead to new insights and indicate the need for a system redesign (Halpin and Riggs, 1992). Sensitivity analysis is conducted to get specific information out of the model. Sensitivity analysis is done by selecting an important factor, and changing the value of this factor while the other factors have fixed values. This way it is possible to see which factors have a big impact on the overall performance of the simulation mode (Halpin and Riggs, 1992).

5.11 **Summary**

From reviewing the literature, it was understood that, despite current literature contributions, considering the diversity of tunneling construction in all phases, there still lacks an integrated model or roadmap to compare all variety of equipment based on various project conditions. A selection of the most suitable (near optimum) alternative based on multi-attributed criteria has always been a concern for contractors, design professionals, and owners. Limited work has been carried out in the application of multi-attributed comparison or tunneling equipment, for the purpose of equipment selection. Such a selection model could help decision-makers' team members to choose an optimum alternative. The thesis proposes an automated, integrated model which considers all important selection factors.

The next chapter will focus on this research methodology and the developed model, with full descriptions of all steps, including the identification of selection factors and equipment from the literature, and weighing the importance of factors according to the project conditions based on a survey and the MCA including AHP, ANP, and TOPSIS methods.

Chapter 3 Proposed Methodology

6.1 General

In this chapter, the research methodology is presented, and the proposed model for tunneling equipment selection is described. The research methodology includes identifying the effective factors and the current practices in tunneling excavation. The goal of this study is to circumvent the limitations of current methods, which, in most cases, are comparisons among limited alternatives and factors. The proposed model is intended to help accelerate and simplify the selection of equipment and methods of excavation in tunneling construction.

In this study, information is gathered from literature and interviews with experts. Selection factors and alternatives have been defined and categorized based on possible project conditions. An online questionnaire has been designed and distributed to an extensive range of experts in tunneling industry to weight and score on the factors and alternatives, respectively. The survey data was utilized multi-criteria analyzes for pairwise comparisons and ranking. Three methods of multi-criteria analysis were evaluated: AHP, ANP and TOPSIS. The proposed model was applied to two real case studies to evaluate different scenarios of excavation methods, and select the most suitable alternatives. Figure 22 presents the steps in the research methodology.

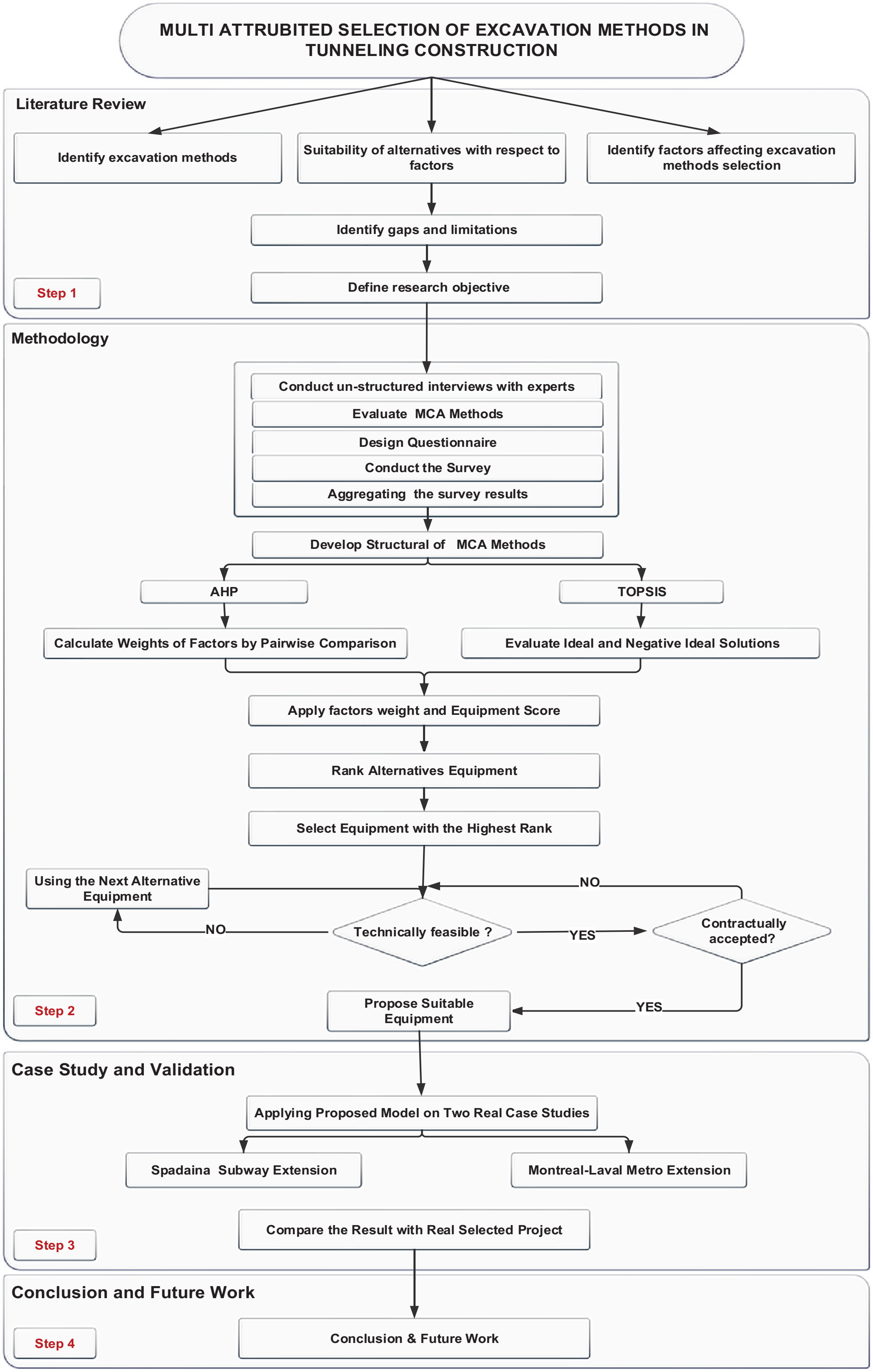

Figure 22. Research Methodology

6.2 Tunneling Excavation Techniques

Current practice in the tunneling construction industry includes different types of TBM, Road-header, and drilling & blasting methods. TBM includes a variety of models and sometimes the equipment is custom designed to suit a specific project. This research focuses on the four most common TBMs: gripper TBM suitable for tough hard rock, single shield TBM for fast tunneling in changing rock conditions, EPB TBM suitable for cohesive soil, rocky, and submerged conditions, and mixed shield TBM, suitable for heterogeneous soil conditions. The drilling and blasting method is suitable for different types of soil and short length tunneling, as it has lower mobilization cost but also low productivity compared to other alternatives. Road-headers also have various shapes and designs, and they are suitable for rocky and hard soils, very efficient for short length tunneling, and also when there is a high variety of geotechnical conditions (Likhitruangsilp, 2003).

6.3 Factors Affecting Tunneling Equipment Selection

The presented study focuses on both quantitative and qualitative factors, affecting productivity calculation and suitability of equipment and tunneling methods, and thus affecting the selection of tunneling methods and equipment alternatives. Therefore, this research provides a comprehensive study of different aspects of tunneling construction.

Current practice in selecting a tunneling excavation method considers technical factors such as tunnel length, tunnel opening, tunnel depth, geotechnical conditions, and level of the water table. The first stage of literature review included collecting data from equipment manufacturers, industry professionals, and researchers, as well as the study of the relevant published sources: papers, journals, theses, and books. The second stage of the literature review included personal interviews with several experts in the tunneling industry, to classify the conditions and circumstances of all effective factors. The aim was to identify the factors that contractors usually consider in order to perform their projects in the most efficient and practical manner.

After studying several cases and interviewing both academic and industrial experts, the following quantitative categories of tunnels have been defined. With respect to length, there are three major groups: short tunnels with a length of under 3000m, average tunnels within the length of 3000m to 6000m, and long tunnels with a length greater than 6000m. With respect to tunnel opening size, diameters smaller than 5 meters are considered to be small opening tunnels. According to previous studies, tunnels with openings of 1.5m or less are considered to be micro, and any tunnels below 5m diameter as small cross sections opening. After deliberating with experts, these two categories are combined as one. Tunnels with diameters between 5 and 12m are considered to be of the average cross-section and any tunnel with a diameter larger than 12m a large opening tunnels. The tunnel depth is also divided into three main categories: very deep tunnels, average tunnels, and almost ground level tunnels that can be seen mainly in urban undergrounds projects.

The most important factor affecting the tunneling equipment selection was found to be the geotechnical conditions. In this study, the large variety of geotechnical conditions have been reviewed, as well as the behavior of each type of equipment in those conditions. In underground excavation, it is quite challenging to estimate the geotechnical conditions accurately all along the tunnel, especially for very deep and long tunnels. In the questionnaire, the tunnel is categorized according to its major state in terms of geotechnical conditions. The classification of rock and soils into six main categories has been adopted: sedimentary rock, igneous rock, metameric rock, sand & gravel, cohesive soil, and highly organic soils (Clayton et al., 1982).

The fifth selected factor was the level of the underground water table, which is one of the most operative elements in the selection of tunneling equipment. The suitability of all alternatives is evaluated with respect to three possible conditions of the water level in excavation zones - dry condition, partially submerged, and fully submerged condition.

6.4 **Questionnaire Design**

To find the weights of alternatives and factors used in the developed model, an online questionnaire survey was designed and distributed to experts. The questionnaire consists of two parts. Part one represents pairwise comparisons between factors, to identify the importance of each factor in relation to the rest of the factors. Judgment of such importance is expressed as absolutely more important, very strongly more important, strongly more important, moderately more important, equally important, moderately less important, strongly less important, very strongly less important, and absolutely less important. In part two, all six alternatives are scored according to each factor condition, one by one. Every survey response was reviewed, and after eliminating the non-practical results, the answers were merged and plotted in the graph.

The questionnaire survey is carried out to better understand the influences of each factor and suitability of each equipment, considering project conditions. In other words, it was designed to find out the weight of each relevant factor, as well as the equipment abilities for the specific project conditions. The questionnaire survey also asked the respondents to score the types of equipment according to their abilities with respect to defined project conditions. The major types of tunneling equipment and the equipment selection factors are listed in Figure 15.

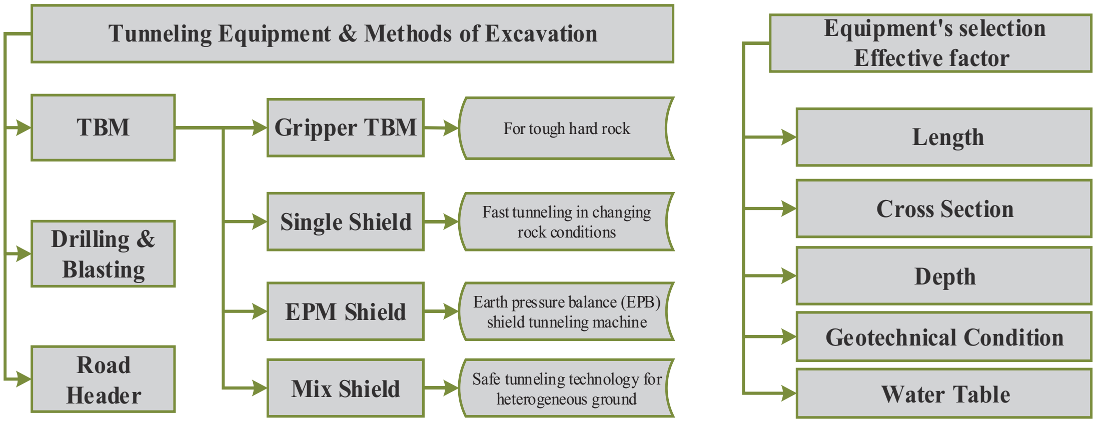

Figure 23. Tunneling Equipment and Selection Factors

6.4.1 Questionnaire Distribution

The questionnaire of the survey was prepared in both paper and web-based formats in the English language. The web-based format was developed in the Qualtircs online application. A copy of the web-based format is included in Appendix I. The questionnaire was sent to approximately 300 experts in tunneling construction, including construction managers, project engineers, construction site superintendents, equipment suppliers, university professors, and other experts with related proficiency, in Canada and worldwide, via email and LinkedIn. The experts were selected based on their qualifications and working experience found in their LinkedIn profiles.

6.4.2 Survey Participation

Overall, 36 responses were received from nine countries. Five responses were discarded as incomplete or invalid, based on the nature of the responses. Therefore, 31 valid responses were used in further analysis. Figure 24 shows the percentage of responses by occupation. Project managers with 32 percent have the highest participation, followed by project engineers and superintendents with 23 percent each.

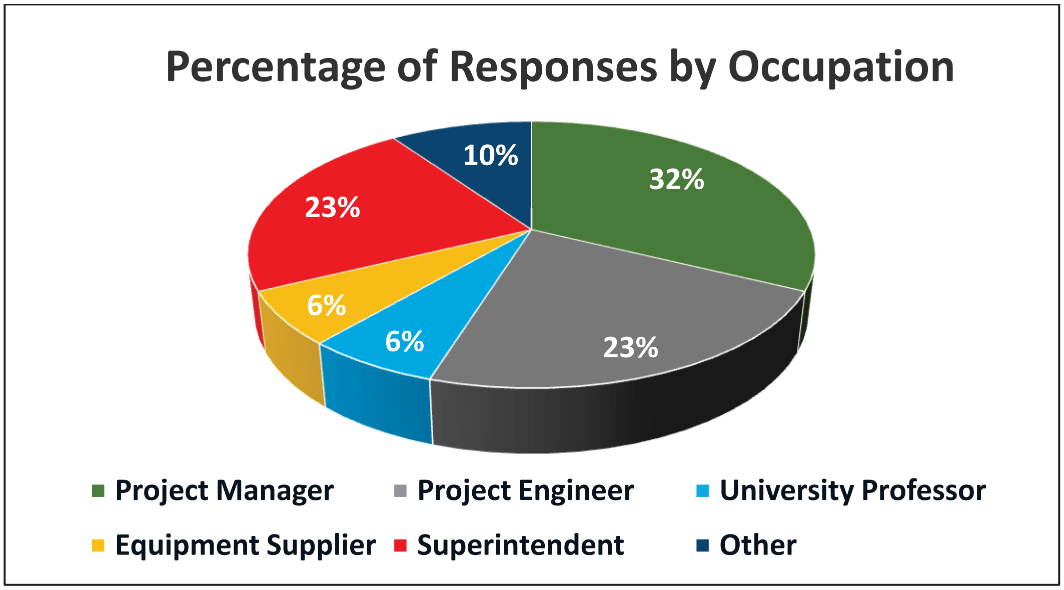

Figure 24. Percentage of Responses by Occupation

Figure 25 represents the percentage of participation in three main regions: North of America, Middle-East and UK & Europe.

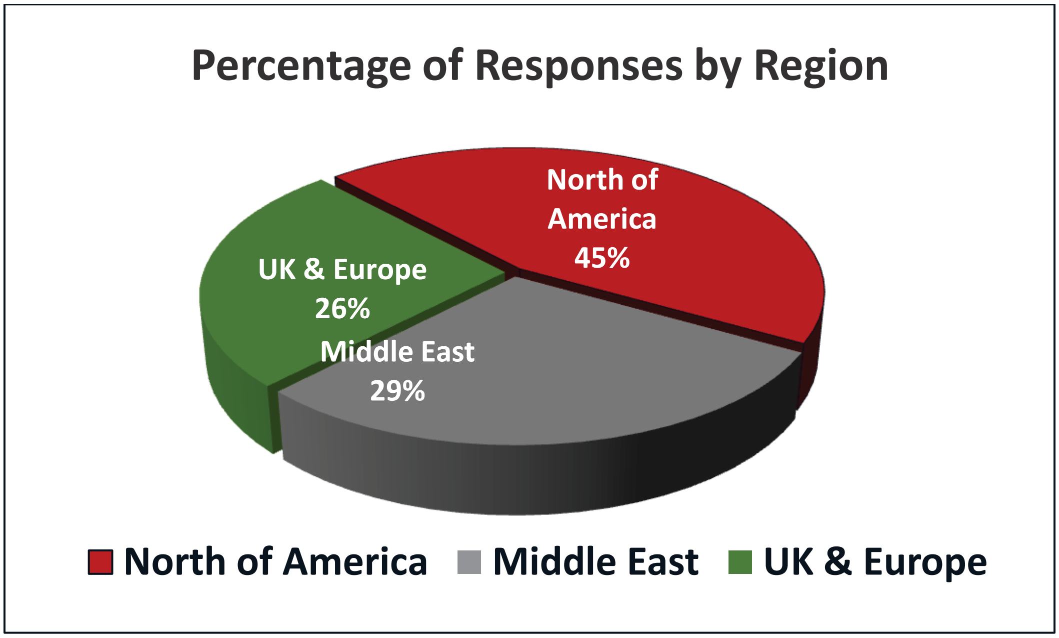

Figure 25. Percentage of Responses by Region

The participants in the survey were seasoned contractors, professionals, and academics in the industry, with experience in tunneling construction projects. Their experience in management of these types of projects ranged from 5 to more than 20 years (see Figure 26). The graph indicates that 32 percent of the respondents had between 10 to 20 years of work experience, 19 percent had more than 20 years of experience, and the remaining 16 percent of participants had 5 to 15 years of work experience in tunneling construction.

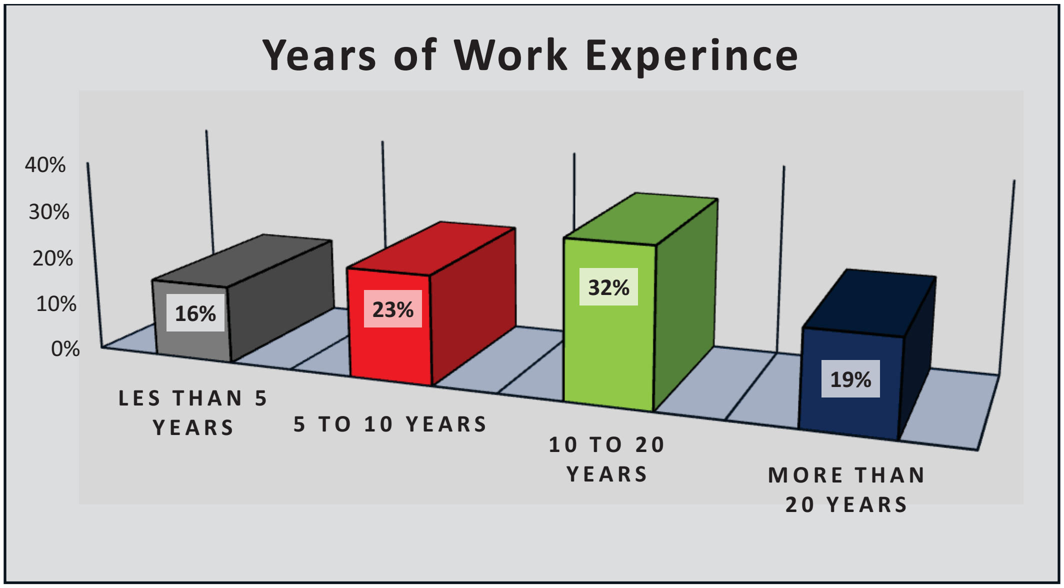

Figure 26. Survey Participation by Years of work Experience

6.5 Survey analysis and the findings

The findings represent the pairwise comparisons among the factors and the scores of alternatives with respect to project conditions, as follows.

6.5.1 Tunnel Length

The tunnel length is one of the most important among the five factors in this study, based on literature review and the experts' opinions. The tunnel length has been divided into 3 main categories: L<3000m as short tunneling, tunnels between 3000m to 6000m as an intermediate tunnel, and tunnels with a length of 6000m and more as long tunnels.

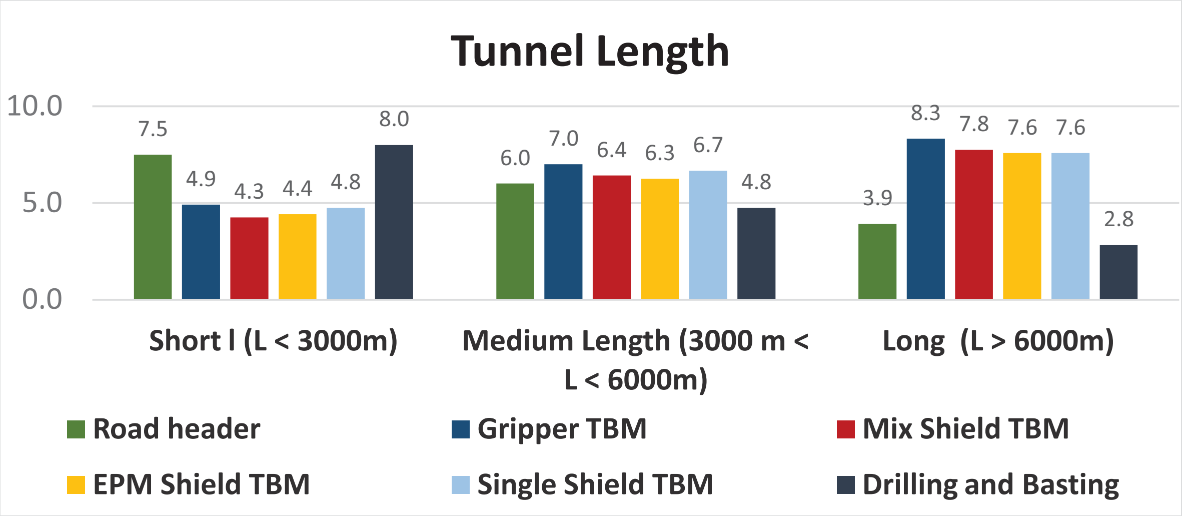

Figure 27. Suitability of Equipment with Respect to Tunnel Length

Figure 27 indicates that in the short tunnels, Drilling and blasting and Road header with scores of 8 and 7.5 and 8 out of 9, respectively, are the most efficient types of equipment. Different types of TBM are with average rates of 4.3 to 4.9 are less suitable. According to the expert opinions, the setup for TBMs is time-consuming and costly, which makes the length categories highly expensive for TBM operation. In average length tunneling (3000m< L <6000m), the suitability of Road-Header is reduced slightly from 7.5 to 6, while there is a significant difference for drilling and blasting - from a score of 8 to 4.8. TBMs are becoming more suitable for the rate of 7. Finally, for long tunnels, TBMs for their high advance rate and consistent rate of cost and time for preparation are the most recommended equipment, while the drilling and blasting and Road-Header are not recognized as an efficient method for these categories of tunneling excavation.

6.5.2 **Tunnel Cross Section**

Tunnel cross section is one of the important factors in tunneling construction equipment selection. Although, compared to the other factors considered in this survey it has the lowest rate, it can still contribute significantly to tunneling equipment selection. In this survey, tunnel cross section sizes have been divided into three main groups: Narrow opening tunneling, including of Micro tunneling (R<5m), average opening size (5m<R<12m), and large opening (R>12m).

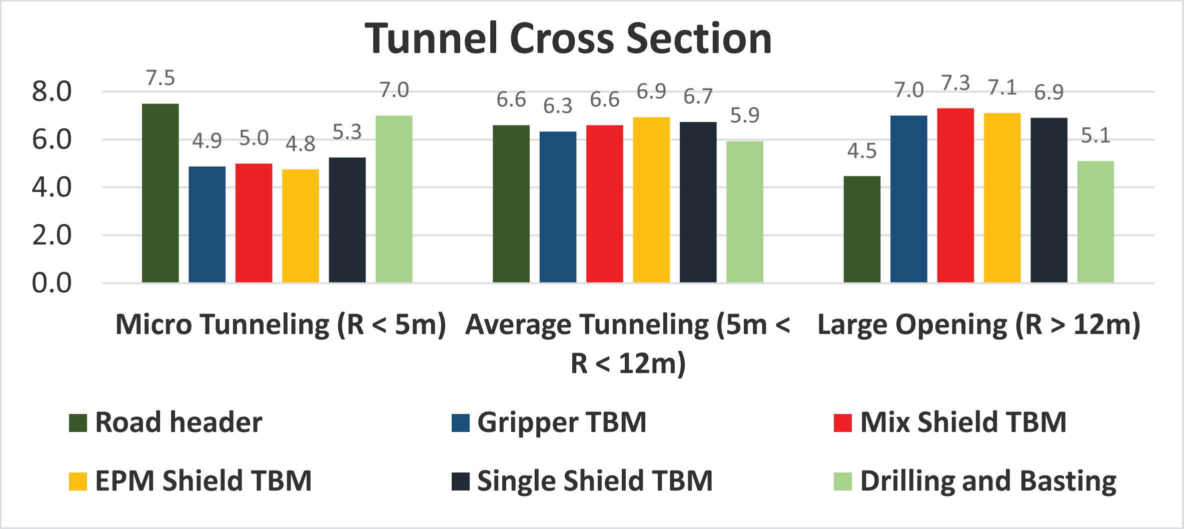

Figure 28. Suitability of Equipment with Respect to Tunnel Cross Section

According to the survey results, in small opening tunnels, road header and drilling and blasting methods are comparably more suitable than TBMs. For average sizes of the cross section, all methods are almost evenly appropriate. For large openings, the varieties of TBM are more appropriate compared to the other two alternatives (Figure 28).

6.5.3 Tunnel Depth

Based on the location and situation of each tunnel, the depths of tunneling excavation vary in a very large range. In this research, after interviewing the experts, three main categories have been defined: very deep (D>200m), average depth (20m<D<200m), and low depth tunnels (D< 20m under the ground level). As Figure 29 shows, for very deep tunnels, TBMs are more recommended, and Road-header and drilling & blasting methods are less recommended. For average depth tunnels, all methods are almost in balance. The major differences appear in low depth tunneling construction, where Drilling and blasting are recognized as the most recommended and TBMs are considered as less suitable methods.

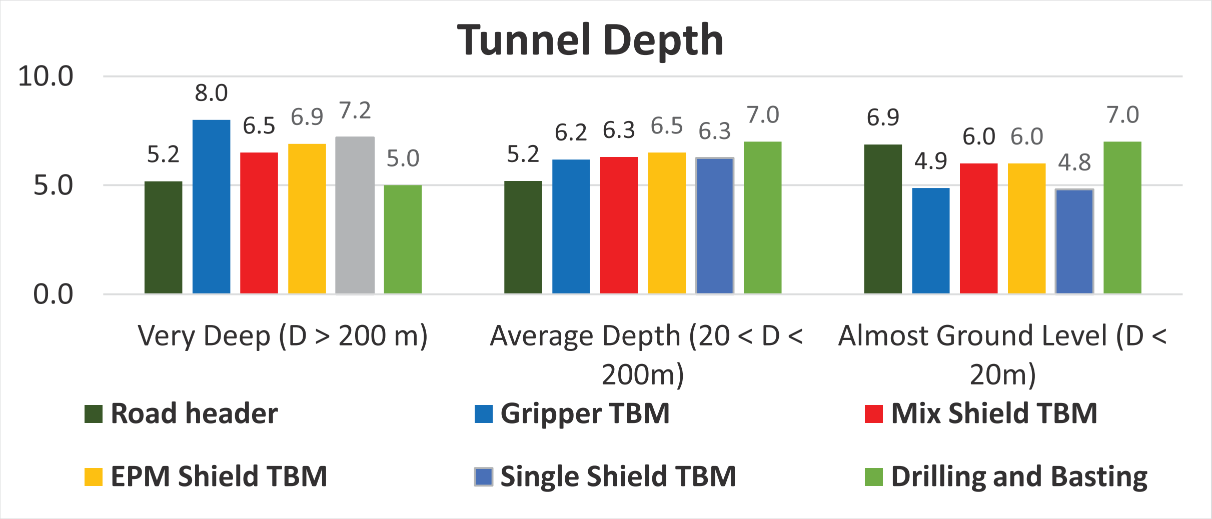

Figure 29. Suitability of Equipment with Respect to Tunnel Depth

6.5.4 Geotechnical Conditions

Geotechnical conditions are one of the most important factors in tunneling selection. Indeed, it is the most important element for tunnel excavation advance rate and productivity. As a result of pairwise comparisons in this survey, geotechnical conditions are the mot effective factor in equipment selection. Considering the large variety of soils and rocks, the six main categories have been defined: sedimentary rock, igneous rock, metamorphic rock, sand & gravel, cohesive soil, and highly organic soils. Each equipment type has been evaluated with respect to each condition.

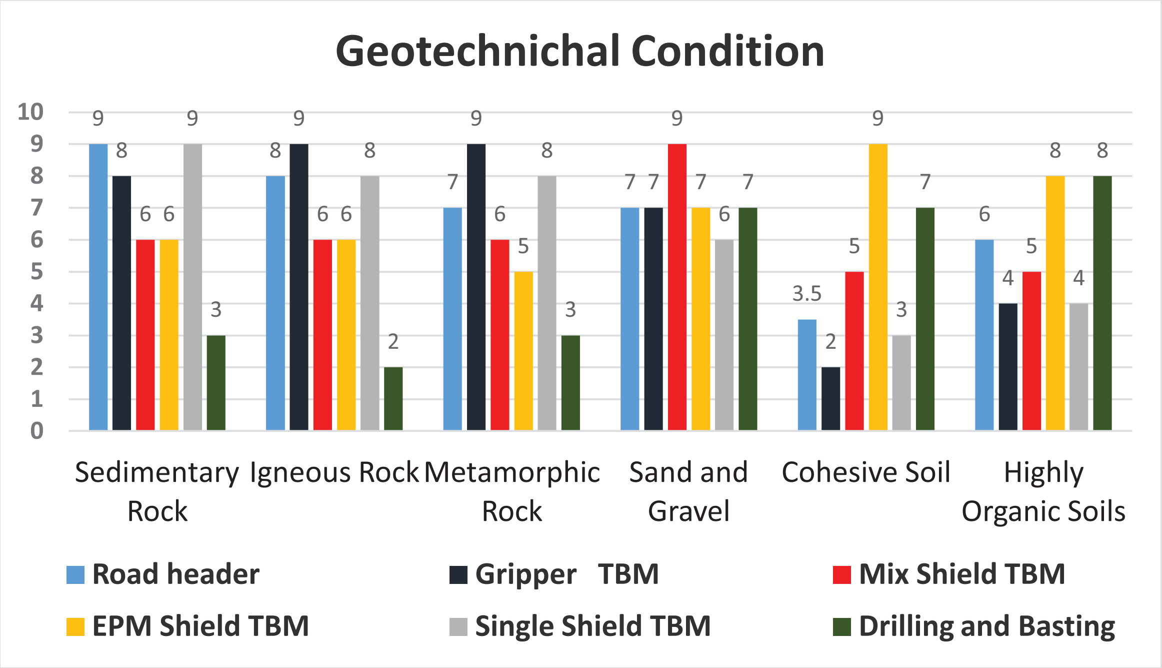

Figure 30. **Suitability of Equipment with Respect to Geotechnical Conditions**

For the excavation with the overall geotechnical condition of sedimentary rock, Road-header and single shield TBM with score 9 is the most suitable, followed by Gripper TBM, with the rate of 8. Drilling & Blasting has the lowest production rate of 3 for this type of rock. For metamorphic rocks and Igneous rocks similarly, Gripper TBM, single shield TBM and road header with the high rating of 9, 8, and 8 respectively are the most suitable, whereas drilling and blasting is recognized as the least suitable method.

In sand and gravel excavation, mixed shield has been rated as the most suitable technique with the score of 9, however the other methods are recognized as quite feasible approaches for this type of geotechnical condition, although, they are not as productive as mixed shield method. Similarly, for cohesive soils, EPB TBM is the most suitable and Drilling and blasting is the second ranked. For highly organic soils, the methods have been evaluated similarly as cohesive soils, by considering road header becomes more efficient compared to cohesive soil (Figure 30).

6.5.5 Water Table Level

Water table level is also a crucial factor for selecting a tunneling method. The water table level has been grouped in three categories: above the water table, partially submerged, and fully submerged in water.

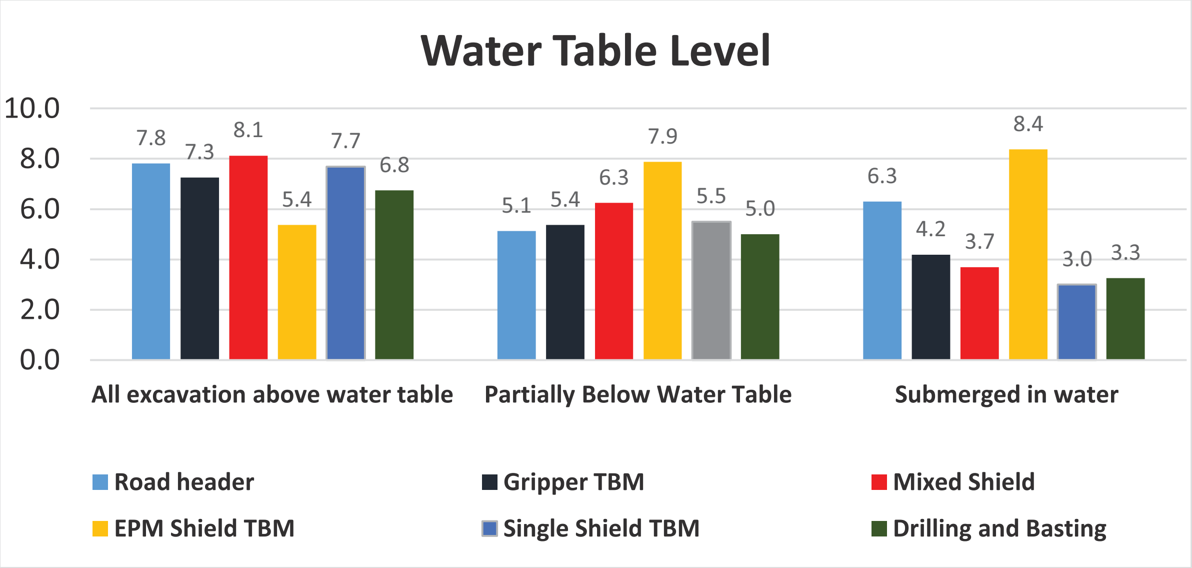

Figure 31. Suitability of Equipment with Respect to Water Table Level

According to the experts' opinions, all techniques have a good performance in dry conditions, but the EPB TBM is highly productive when the excavation is submerged with water (Figure 31). Single shield TBM and mixed shield TBM carry a high risk for submerged cases, and they are not advised to use for submerged tunnel excavation.

6.6 Applying Multi-Criteria Analyzes (MCA)

A multi-criteria analyzes model has been developed. Methods of multi-criteria analysis include analytical network process (ANP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Analytical Hierarchy Process (AHP). According to the findings from the questionnaire, AHP is the suitable technique to weight and compare the factors and alternatives for this study. Therefore decent responds were merged and taken into AHP pairwise comparison application performed the table 7.

Table 7 Tunneling Equipment Selection Weighing by AHP

Factors	Tunnel Cross Section	Depth of Tunnel	Geotechnical Conditions	Length of Tunnel	Water Table Level
Tunnel Cross Section	1	6	2	3	1
Depth of Tunnel	4	1	2	4	2
Geotechnical Conditions	8	8	1	8	6
Length of Tunnel	7	6	2	1	3
Water Table	9	8	4	7	1

6.6.1 Applying Analytic Hierarchy Process (AHP)

The collected data in AHP application has been analyzed once by pairwise manual comparison in Excel, and once more time in super-decision software. The weight result in AHP method represents the relative importance of factors in Figure 32, indicating that geotechnical conditions have the greatest influence in tunneling equipment selection with the weight of 0.30, and that water table level with the weight of 0.28 has the second largest effect on decision making for tunneling excavation. The tunnel length with the weight of 0.18 and the depth and cross-section with the weights of 0.13 and 0.11, respectively, are of less influence.

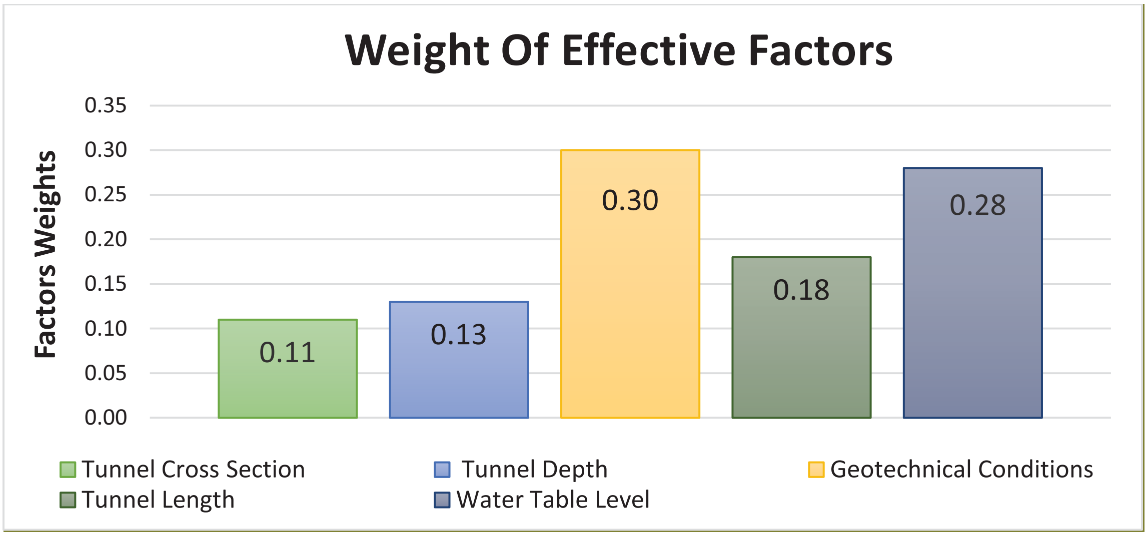

Figure 32. **Weight Effective Factors in AHP**

In the next step of the analysis, the given scores of excavation approaches, according to the project circumstances, are taken onto the developed multi-criteria analysis model for further assessment (Figure 33).

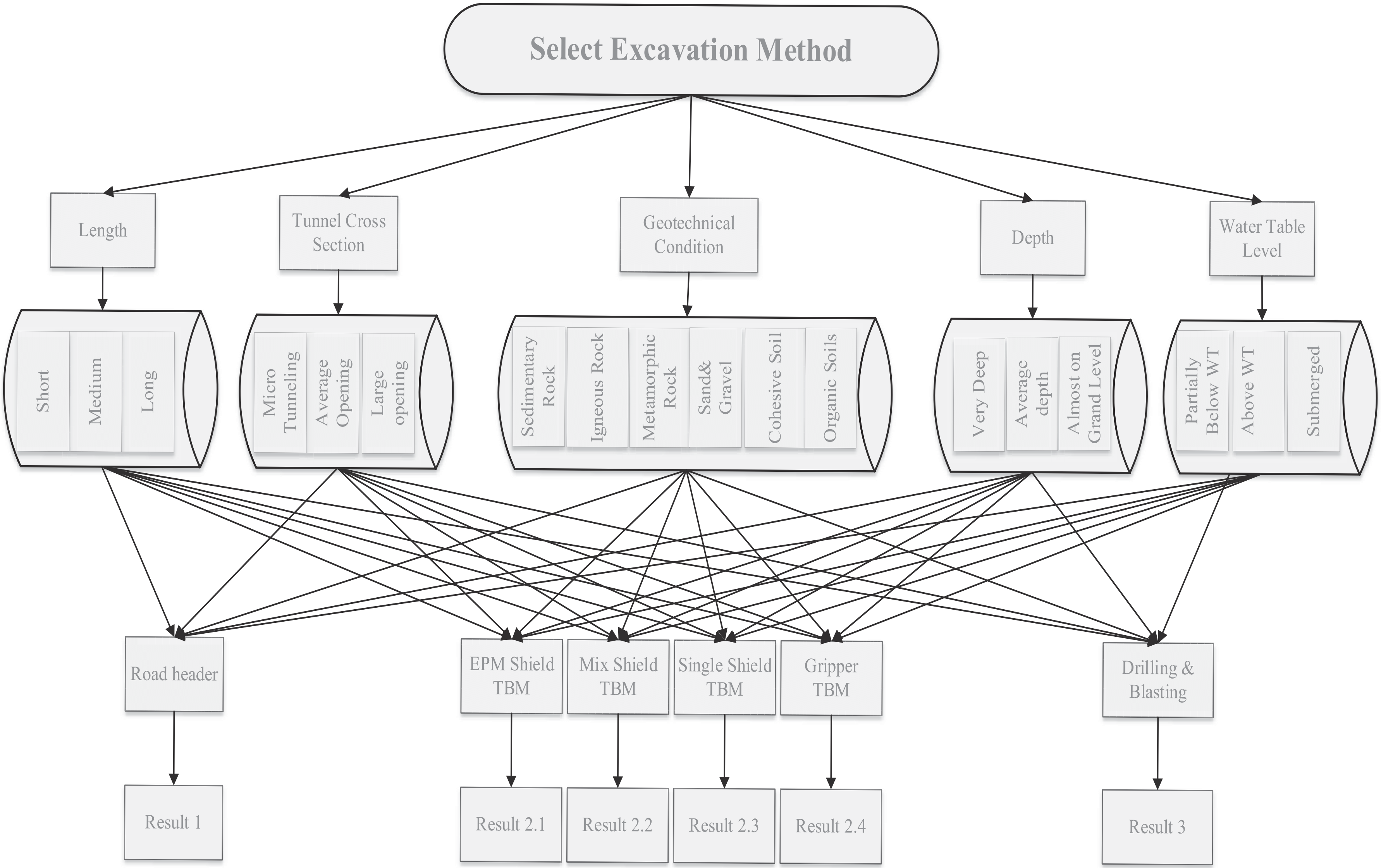

Figure 33. Multi-criteria analysis model for selection of exaction method

In this model, the sustainability of each equipment individually has been assessed with respect to each factor and the condition of the project. The AHP model is applied as follows. For example, if a project is a short tunnel, the scores of all six alternatives with respect to this condition, obtained from the survey, are multiplied 0.18 (weight of the tunnel length factor). The weighted sums of all the scores are calculated for each alternative. The alternative with the highest overall score is recommended as the most suitable for that particular project.

Moreover, a threshold has been designed to eliminate from the selection the equipment that is not practically based on one or more technical feasibility. For example, if the project is located in a submerged situation, the single shield TBM would be eliminated, even though it might have the highest overall score. This equipment would be eliminated by not meeting the minimum acceptable score for all factors.

6.6.2 **Discussion application of Analytical Network Process (ANP)**

The suitability of the analytical network process (ANP) for the problem of selection of tunneling excavation equipment was evaluated. As determined in the previous analysis, there are five selection factors and six alternatives. A set of project conditions corresponds to each selection factor. The ANP would be suitable to represent interdependence and feedback among the criteria and the alternatives, if applicable. Regarding the factors, in tunneling construction, there may be dependence among the selection factors identified. For example the length of tunnel, the water table and the geotechnical conditions, may depend on the depth of tunnel and on the tunnel cross section. The water table may also depend on the geotechnical conditions. However, these conditions and relationships are usually evaluated in defining different design alternatives, and in choosing the optimum design alternative. In the scope of this research, in analyzing the problem of equipment selection, it will be assumed that the design is fixed, which means that a set of project conditions in terms of tunnel geometry (cross section, depth, and length) as well as the geotechnical conditions and the water table are fixed, i.e. they do not depend on one another. Regarding the alternatives, they are being evaluated against one another with respect to the selection criteria, but it does not make sense to evaluate the alternatives with respect to other alternatives. Therefore, there are no meaningful interdependencies among the alternatives. Based on this, the ANP was not included in the developed decision model.

6.6.3 **Applying TOPSIS**

The principle of TOPSIS method was described in section 5.9. The TOPSIS method was applied by utilizing the same set of factors, the ranges of project conditions for each factor, and the scores of each alternative with respect to each project condition, that were previously developed in this work and that were also used in AHP. Also, the weights of the factors obtained by AHP, as described in the previous section were applied. From this, the ideal solution and the negative ideal solution for each project condition were calculated, as shown in Table 8, as well as the distance from the ideal solution and the distance from the negative ideal solution for each alternative for each project condition. For a specific project, the ratings and ranking of the alternatives are determined as follows. The actual categories of project conditions are selected for each factor. Based on this, for each alternative, separation from ideal solution for the project and separation from negative ideal solution for the project are calculated, as well as the relative closeness to the ideal solution. The relative closeness to ideal solution represents the rating of each alternative.

Table 8 TOPSIS analysis using survey results

Factors	Project conditions	Ideal solution	Negative ideal solution
Tunnel Cross Section	Micro Tunneling (R < 5m)	0.05	0.04
	Average Tunneling (5m < R < 12m)	0.05	0.04
	Large Opening (R > 12m)	0.05	0.03
Depth of Tunnel	Very Deep (D > 200 m)	0.06	0.04
	Average Depth (20 < D < 200m)	0.06	0.04
	Almost Ground Level (D < 20m)	0.06	0.04
Geotechnical Conditions	Sedimentary Rock	0.15	0.05
	Igneous Rock	0.16	0.04
	Metamorphic Rock	0.17	0.06
	Sand and Gravel	0.15	0.10
	Cohesive Soil	0.20	0.04
	Highly Organic Soils	0.16	0.08
Length of Tunnel	Short l (L < 3000m)	0.10	0.05
	Medium Length (3000 m < L < 6000m)	0.08	0.06
	Long (L > 6000m)	0.09	0.03
Water Table	All excavation above water table	0.13	0.09
	Partially Below Water Table	0.15	0.10
	Submerged in water	0.19	0.07

6.7 Applying Sensitivity Analysis to select the most Sensitive Factors

Sensitivity analysis is done by selecting an important factor, and changing the value of this factor while the other factors have permanent values. By performing the sensitivity analysis the effect of each individual variable on equipment suitableness. This information is important to evaluate the applicability of the model and determining parameters for which it is important to have more accurate values, as well as understanding the behavior of the system being modelled. The variables that are relevant regarding the MCA model of the Montreal-Laval metro extension and Spadaina Subway extension tunnel project actual values of the variables collected from the tunneling expert. Therefore sensitivity analysis was carried out on each of the case studies, to identify and analyze the most sensitive tunneling variables affecting equipment selection in both case studies.

6.8 Applying Different Scenarios on Case Studies

Finding an optimum solution for any construction project requires examining a variety of projects. In tunneling construction, assessing the different technique is particularly valuable. In this research, two different cases with real industry data have been studied, and the proposed model was applied on each. The information of both case studies are collected by direct communication of the operative companies and previous studies.

The Toronto-York Spadina Subway Extension project started in 2011, and it is expected to be completed within five years. The project is being operated out by Kiewit. By applying the model and creating different scenarios of start to finish, the most suitable equipment (EPB TBM) was selected.

Similarly, the Laval Extension of Montreal's Metro project, completed by SNC-Lavalin, has been reviewed. Different scenarios have been considered, and the developed model was applied and compared to the actual method used for selecting the equipment. The results and analyzes are discussed in Chapter 4 in greater detail.

6.9 **Summary**

An industry-wide questionnaire survey was carried out to understand and capture the nature of current practices pertinent to the decision environment, including factors and methods used for tunneling excavation. The results of this survey highlighted the importance of the equipment selection in practice. Also, these results revealed that despite the wide range of methods, which are available in the literature, none of the respondents refer to the use of these methods. These results also show that factors such geotechnical condition and water table level are highly important for selecting any method in tunneling excavation. Moreover, in this chapter the proposed model has been described and the multi-criteria analysis method was implemented to the survey result to identify sustainability of each equipment respective to existing factors and checking that the selected equipment is feasible for the project.

Chapter 4 Analysis and Implementation on Case Studies

7.1 Montreal-Laval Metro Extension Case Study (1):

The Montreal to Laval metro extension project with total length of the 5.2 kilometer, involved tunneling for almost a kilometer under a river des Prairies and burrowing deep under buildings constructed by SNC-Lavalin Company (SNC-Lavalin, 2010). According to SNC-Lavalin report, the biggest challenges for the engineers in extending the Line 2 of Montreal's Metro Northwest towards the suburb of Laval was the excavation of the section under the riverbed. It started from a new platform constructed at the existing Henri-Bourassa station on the Montreal side of the river. From there, it tunnels for 400 meters below the river to arrive at Laval where there are three new underground stations, named, Cartier, De la Concorde, and Montmorency metro station (SNC-Lavalin, 2010).

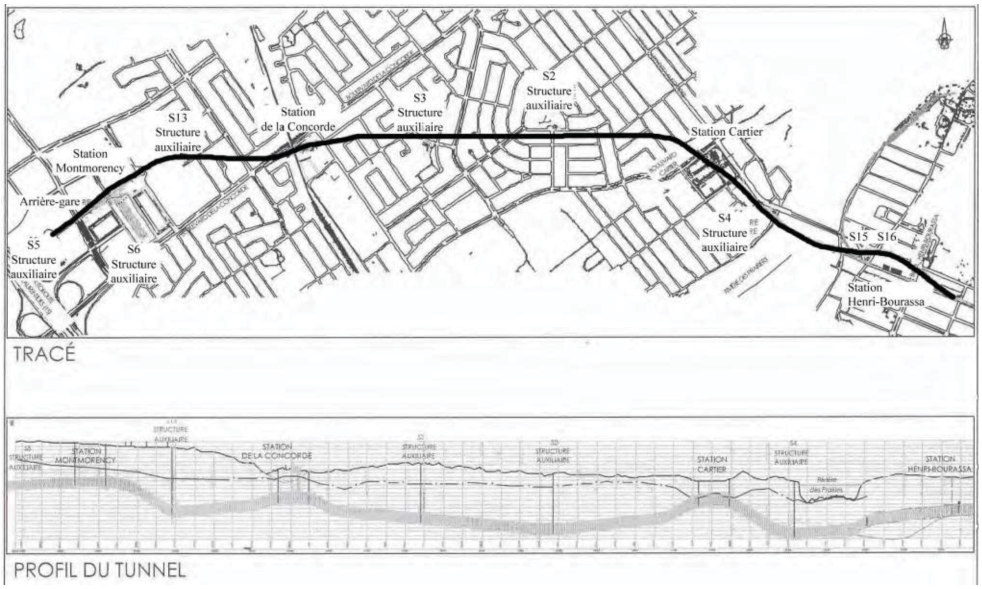

Figure 34. Laval tunnel metro extension profile (SNC-Lavalin, 2010)

The tunnel cross-section was 7.5 meters wide in section, with a rectangular profile and low arched roof which is considered in the averaged tunnel opening group. Figures 35 and 36 show the sketch of the Montreal metro extension cross section including the support details.

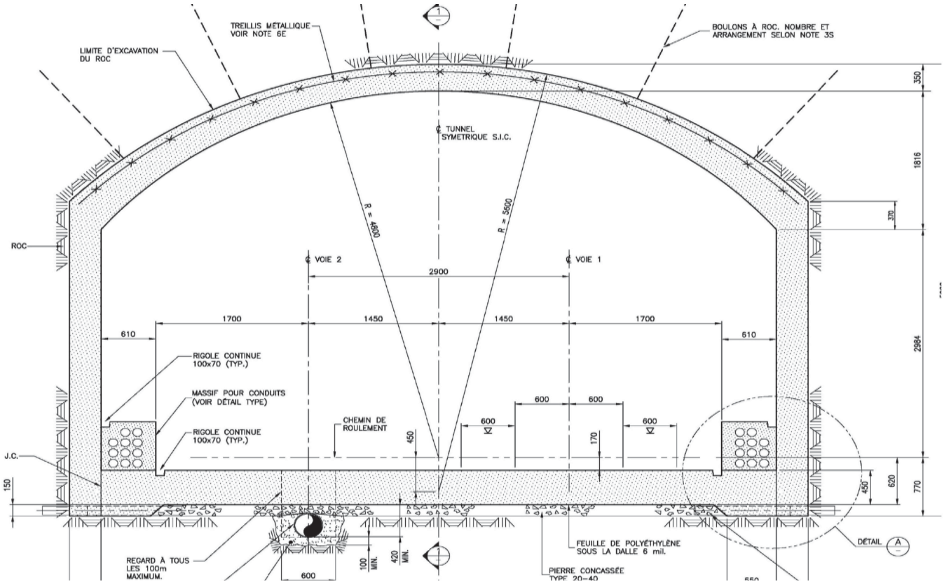

Figure 35.Montreal metro extension cross section (SNC-Lavalin, 2010)

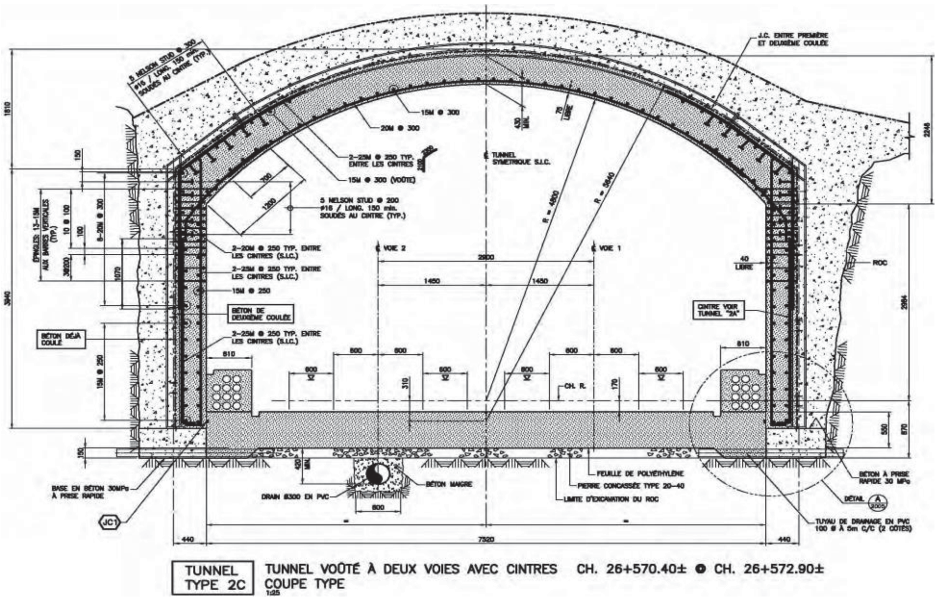

Figure 36.Montreal-Laval metro extension cross section and support details (SNC-Lavalin, 2010)

7.1.1 **Project Geotechnical Condition**

The geological conditions along the route were mainly limestone (sedimentary rock), hard rock types which are normally considered an appropriate geotechnical condition for tunneling excavation. However, to support and reduce the excavation risk under the river, reinforcing was applied before excavations could begin. Crews were working on floating platforms on the river to insert 35-mm steel bolts measuring up to 6 meters long into the bedrock to strengthen it. Two road headers and two crews worked simultaneously from opposite ends of the tunnel, each advancing approximately 6 meters every day (SNC-Lavalin, 2010).

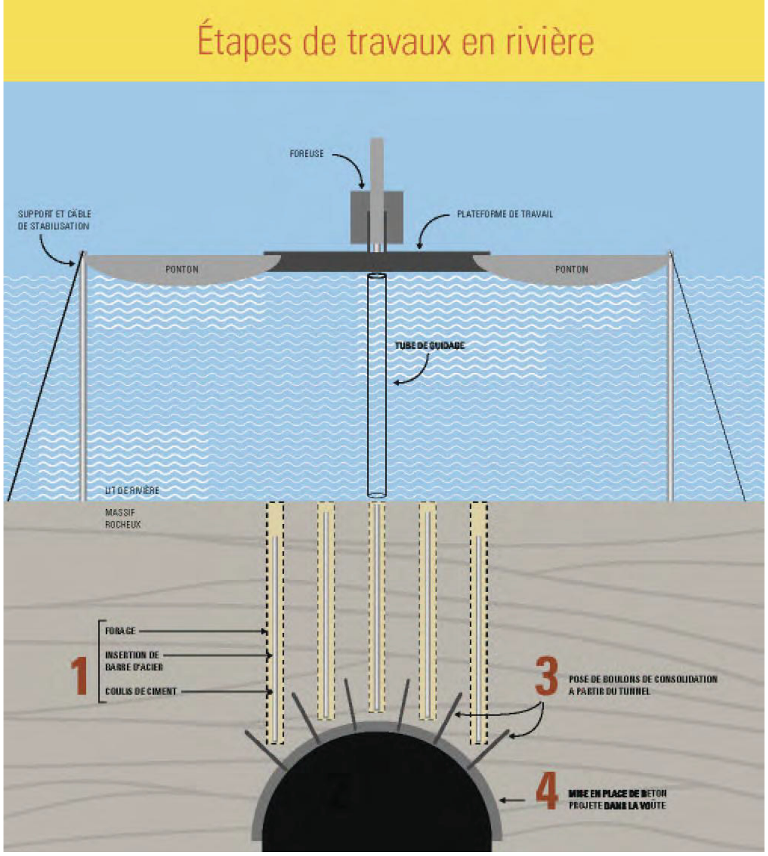

Figure 37.Montreal- Laval metro extension 400 meters under the river (SNC-Lavalin, 2010)

7.1.2 Excavation Methods

In this project, a combination of two tunneling excavation methods was applied. The major part of the project was completed by mechanical excavation (Road-header). To improve productivity and accelerate the project excavation time, the Drilling and Blasting method was used, mostly in the Montmorency stations zone, which was around 0.8 km long (SNC-Lavalin, 2010).

The conventional technique was implemented in drilling and blasting excavation method. Table 9 shows the general condition of the project for Drilling and blasting methods by considering the advantages and disadvantages during the construction process

Table 9 Drilling & Blasting project information Montreal metro extensions ((SNC-Lavalin, 2010).

Manpower Per Shift	Equipment per Shift	Advantages	Disadvantages	Safety Measures
1 Foreman	2 Drilling Equipment	Good Production	Over Break	Blast plan prepared by the contractor and approved by the engineer
7 Underground Workers	1 Loader	Proven Technique	Vibration	On time delivery of explosive for each blast
1 Blaster	6 Trucks (10 Wheels)	Can Be Used Even If The Rock Is In Bad Condition	Risk Of Damage To Existing Structures	Work zone established by the blaster during preparation
1 Loader Operator and 6 Truck Drivers		Efficient In The Case Of Hard Rock	Noise	Security zone before the blast
2 Surveyors		Need Less Water	Safety	Sound signal before the blast & leaflets distributed to inform residents

In Drilling and Blasting excavation method, the advance rate of one crew working alternately with two faces and two shifts, was 12m per day on average.

The second and foremost method used in the project was excavation with Road-Header (mechanical excavation). Road-Header is suitable for the hard rock geotechnical condition, and is also known to be quite productive in wet excavation. Although another assessed method for excavation this area was EBP TBM, which after furthers study in production, site investigation and availabilities of excavation materials, the management team decided to select road header as the main method in the Montreal-Laval metro extension. Table 10 presents a summary of groups and production as well as the advantages and disadvantages of this method during the project running.

Table 10 Road Header project information Montreal metro extension (SNC-Lavalin, 2010).

Manpower per Shift	Equipment per Shift	Advantages	Disadvantages	Safety Measures
1 Foreman	2 Road-headers	Less over-break	Limited production	Dust Removal Equipment
4 Underground Workers	1 Man-lift	Reduced Vibration and Noise	Sensitive to Rock Hardness	Watering
2 Road-header operators & 4 truck drivers		No impact on exterior properties	Generate much dust	Scaling
One loader operator & 2 Mechanics	1 Loader Four trucks (12 wheels)	Reduced risk in sensitive areas	Need much water during excavation	Rock Reinforcement
2 Surveyors		Productive in wet condition	Can be used in solid rock only.	Wire mesh

The actual production obtained, resources and facilities is shown in Table 10. Apparently the advance rate for Road-Header was 6m per day. In addition, to secure and reduce the risk of the exaction by Road-Header for under the river area, anchor bolt, short-creating, and wire mesh methods were used to give additional support (SNC-Lavalin, 2010).

7.1.3 Montreal-Laval Metro extension project statistic

The project data for this case study is summarized below:

- The total length of the tunnel is 5.2 km (average tunneling length)

- The tunneling excavation zone starts 20m below ground and under the river bed it reaches 400m below ground in the major part of the project.
- The tunnel cross section is R=7.5m,
- The tunnel is below the undergrad water table level.
- The geotechnical conditions vary, but the overall condition is in the hard rock group, specifically in the sedimentary rock category.

7.2 Applying the AHP model on Montreal- Laval metro extension

The developed AHP model described in Chapter 3 has been applied to this case study by considering two scenarios. In Scenario 1, excavation starts on one end of the tunnel and continues in one direction to reach the other end. In Scenario 2, excavation starts from both ends simultaneously, and the two sections meet in the middle. It was determined that both scenarios are feasible, as access is possible on both ends. All equipment alternatives are being assessed with each of the two scenarios. The weight of each factor is multiplied by each equipment's score with respect to that factor to provide the influences of that factor on each equipment alternative. For each factor, the equipment scores depend on the applicable project condition. Figure 38 shows the weights of factors and the project conditions for each factor in this case study. By summing the influence of all factors on every alternative, the total suitability rating of each alternative is determined. In Scenario 1, the overall length of the project is 5.4 km, which categorizes it as average length tunneling. According to the survey analysis described in Chapter 3, Road Header has a score of 6 out of 9 in average length tunneling. By multiplying this score by the weight of the length factor (0.18), the influence of length in evaluating the road header suitable for this project is calculated as 1.08. The same procedure is applied to the other factors:

Tunnel Cross section, Geotechnical Condition, Tunnel Depth, and Water Table Level. The sum of all factors' influences represents the suitability rating for each equipment alternative. Considering only the Scenario 1 for each equipment, Road header with the highest rating of 7.2 was recommended as the most suitable method, as shown in Figure 38.

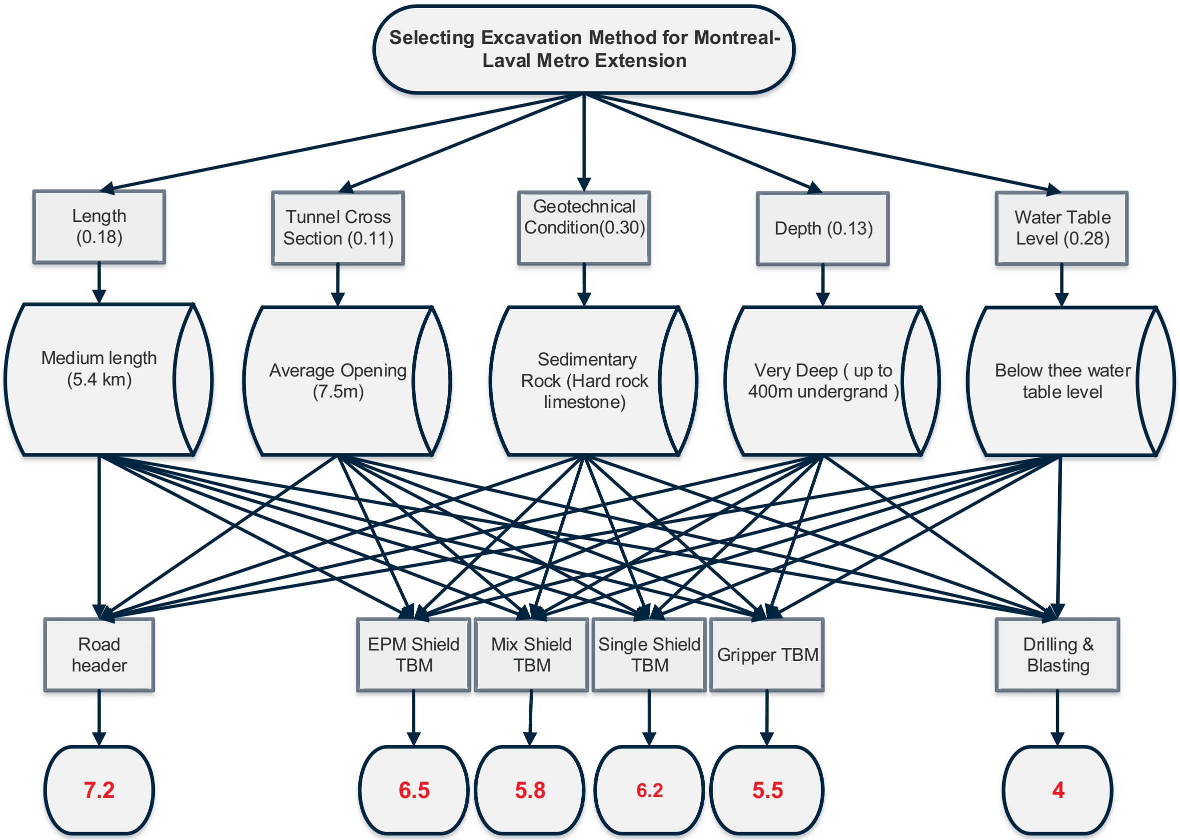

Figure 38.**Applying the AHP model into the Montreal Laval metro extension equipment selection, Scenario 1**

EPB TBM with the rating of 6.5 ranked as the second most suitable equipment. Single Shield TBM and Mixed Shield TBM have ratings of 6.2 and 5.8 respectively. Because of the submerged condition, the type of the rock and the variabilities in geotechnical conditions, these two types of equipment are considered not suitable for this project. Drilling and Blasting has a rating of 4. This method is not considered suitable for the entire project. However, according to the SNC-

Lavalin report (SNC-Lavalin, 2010). for certain areas such as the 0.8 long Montmorency Station zone, which is located in partially submerged zones and which has appropriate geotechnical conditions for Drilling and Blasting, it is practical to use this method.

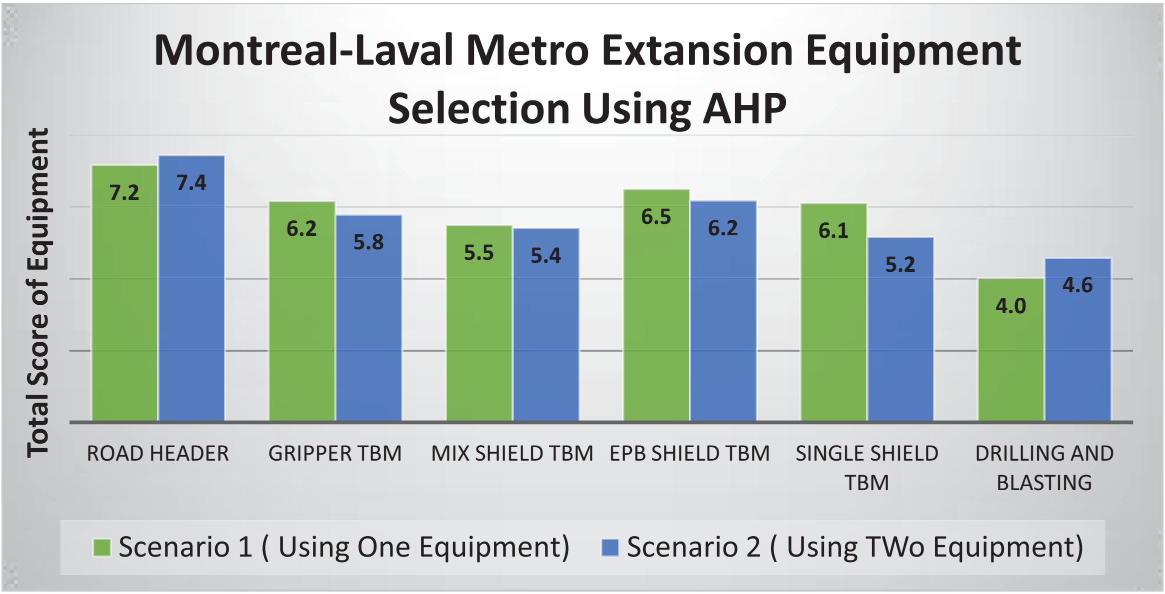

Figure 39 Applying AHP on Metro Montreal-Laval extension Equipment Selection

In Scenario 2, it is assumed that excavation is started from two ends simultaneously, using two pieces of equipment of the same type. In this scenario, the project was divided into two 2.6km long sections. This time, in applying the AHP model, the project is considered to be of the short length. The ratings for both Scenario 1 and Scenario 2 are summarized in . In the Scenario 2, the highest rated alternative is again the Road Header. Its suitability rating increased to 7.4. Therefore, the Rad Header with Scenario 2 is the highest rated alternative overall. The Drilling and Blasting method, as well as the four TBM methods become less suitable for Scenario 2, as neither of them is an expert choice for shorter distances.

7.3 Applying TOPSIS on Montreal-Laval metro extension

The TOPSIS model of the developed method is applied as described in Section 6.6.3. In applying this method to a specific case, the appropriate category of project conditions for each selection factor must be selected, in the same way as in applying the AHP. The categories of project conditions for this case have been identified in the previous section. In applying TOPSIS, the ideal solution and the negative ideal solution are determined based on the specific set of project conditions. Then, the distances from the ideal solution and the negative ideal solution are calculated for each equipment alternative, and from this the rating of each alternative is calculated. The same two scenarios are considered for each equipment, as described in the previous section.

The results are summarized in Figure 40. The highest rated alternative is Road Header with Scenario 2, with a rating of 0.73, followed by the Road Header with Scenario 1 and the EPB Shield TBM with Scenario 1, which both have a rating of 0.71. The lowest rated alternative is Drilling and Blasting with Scenario 1, with a rating of 0.1.

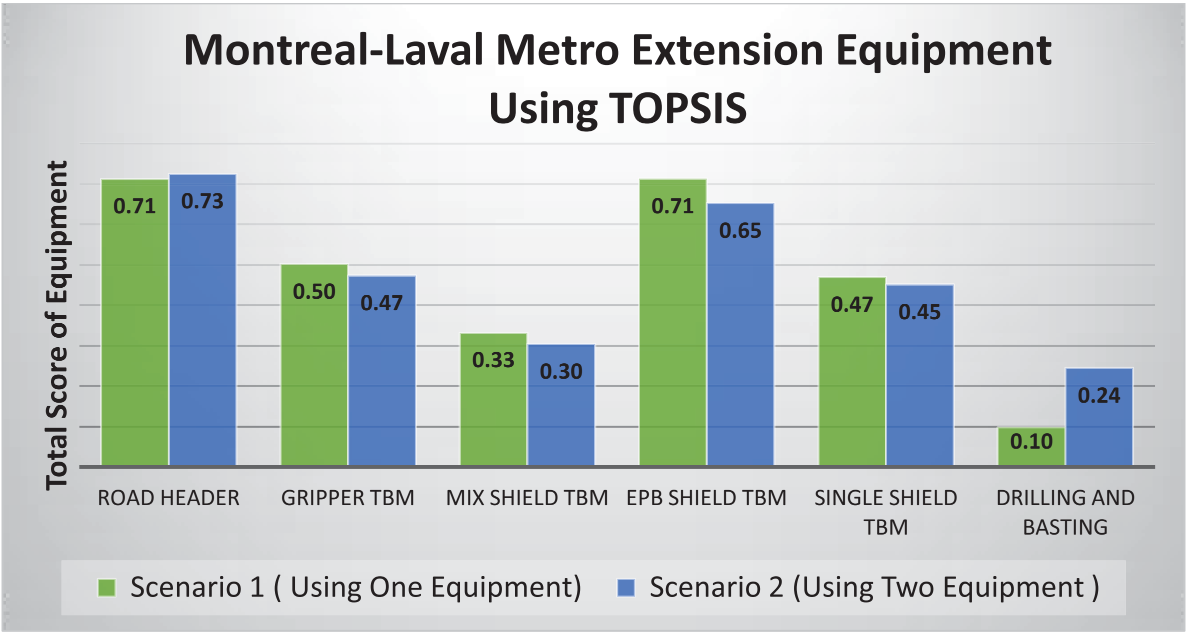

Figure 40 Applying **TOPSIS on Metro Montreal-Laval extension Equipment Selection**

7.4 Sensitivity Analysis Montreal –Laval metro extension

In Figure 41 the graph is presented showing the relationship between the variables of the MCA model and the suitability of equipment of the tunnel excavated by road header. By increasing the values of the variables, the suitability of using road header increases. A value of 0% on the x-axis indicates the actual state of the tunneling construction system; the state in which the variables have values as described in as an effective factors.

The graph shows that the variable ‘geotechnical condition, has the highest influences on tunneling equipment selection, and the biggest impact on changes in equipment suitability. On the other hand the impact of the variables ‘level of underground water is the second sensitive factors.

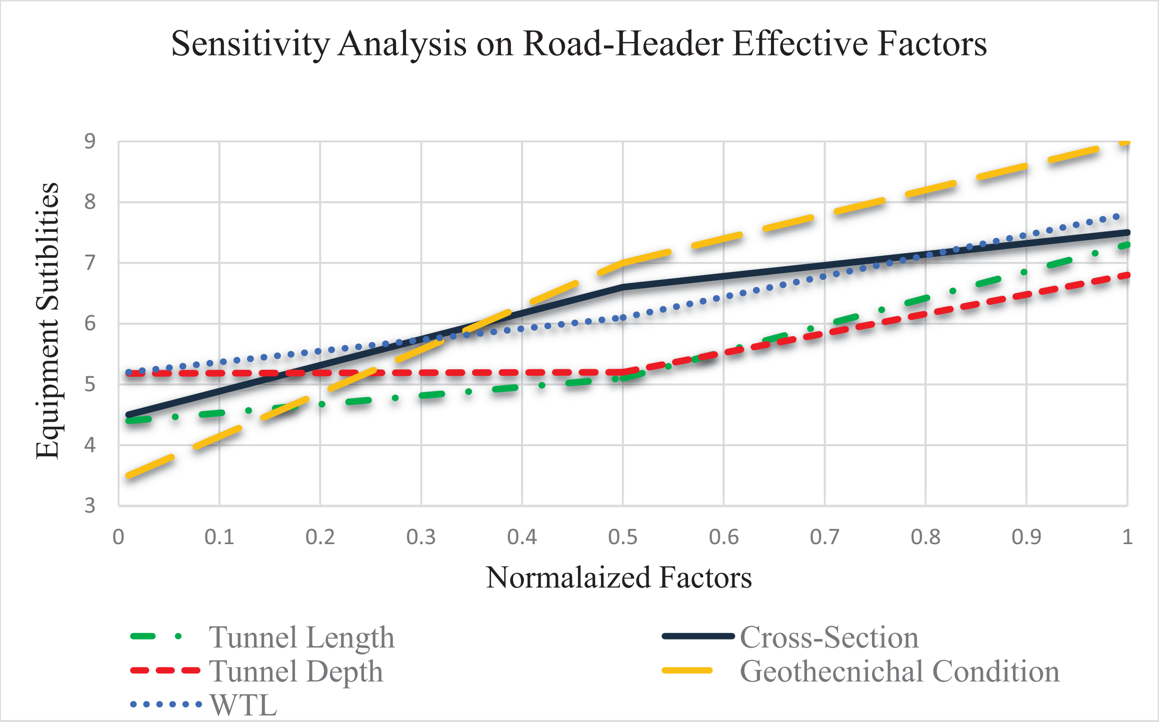

Figure 41 Applying Sensitivity Analysis on Road header suitability in Montreal- Laval Metro extension

The graph shows that the variables 'geotechnical condition with a sensitivities in changes from 3.5 to 9 is the most sensitive factor in equipment selection.

7.5 Toronto-York Spadina Subway Extension case study (2)

Toronto-York subway extension twin tunnels start from Spadina station toward North with a total length of 6.4 kilometers. The project started in 2011 (Under Construction) and has an expected completion date of 2016. Kiewit and McNally were two operator companies. The selected method for tunneling project was Earth Pressure Balance tunnel boring machines (EPB TBM). EPB is a powerful machine with circular cutting that bores a tunnel in soil or rocky conditions with minimal interruption to the surface above (Kiewit, 2015).

Figure 42.Tunnel Boring Machine "Torkie" (Kiewit, 2015)

In the Spadina Metro extension project, during the TBM excavation, the material is removed by rail cars and a conveyor system to the launch shaft and then transported away by dump trucks. Two methods are used to build the Toronto-York Spadina Subway Extension: EPB TMB technology and cut and over construction. (Kiewit, 2015).

Figure 43 Downs-view Park Station Launch Shaft (Kiewit, 2015)

In this project, the tunnel boring machine operates in three shifts during 24 hours a day, seven days a week. A construction staging area, or worksite, was equipped at the launch shaft prior to the entrance of TBM and the tunnel facings. In addition, an alternative extraction shaft was prepared before the tunnel boring machine reaches its destination. Figure 44 shows the Spadina metro extension plan.

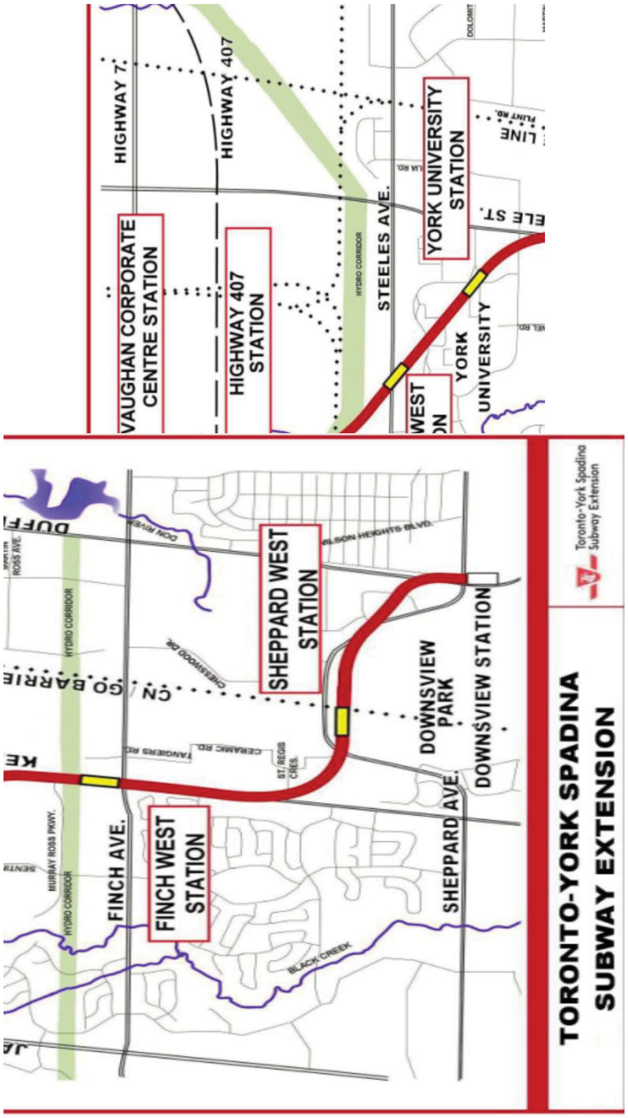

Figure 44 Spadina metro extension plan (Kiewit, 2015)

7.5.1 Site Geology and Subsurface Conditions

In the Quaternary period deposits of the Toronto, region contains mostly glacial till, glaciolacustrine and glacis fluvial sand, silt, clay deposits, beach sands, and gravels. These deposits are laid down by glaciers and associated glacial rivers and lakes. Recent deposits of alluvium are found in river and stream valleys and their floodplains (Bidhendi, Mancini, Lashley, & Walters, 2011). The Quarternary soil is deposited over the Ordovician age bedrock of the Georgian Bay Formation, which consists predominantly of shale with interbeds of limestone and siltstone. This bedrock formation is about 250 m thick and has a regional dip to the southeast of about 5 m/km. The Quaternary soil deposits overlying the bedrock are believed to have been deposited over the course of at least two glaciations and one interglacial stage.

7.5.2 Spadaina Subway Extension Project Statistics

The overall condition and advance rate for the tunnel excavation is as follows:

- The major part of the project contains sand, silt, and clay.
- Total project length is 6.4 km.
- The project is located in a wet geotechnical condition.
- A tunnel boring machine advance rate is 15 meters per day.
- The average tunnel cross section is 6.1m.
- The EPB TBM was named Holey, Moley, Yorkie.
- The assembly weights for tunnel boring machine cutter head is 50.6 tons.
- The EPB TBM weight 430,000 kg.
- The total weight of a TBM including all components is 568 tons.
- The number of precast tunnel liners includes 9,000 rings comprised of 54,000 segments.

- The total excavation of material (bulked up) is more than fill the Rogers Centre.
- The project has used 400,000 m3 of concrete, the amount equal to 10 CN Towers.
- The subway track requires 11,000 precast double ties.
- The project requires 70,000 tons of rebar.

7.5.3 **Applying AHP on Spadina Metro Extension Case Study**

In the Spadina Metro extension case study, the multi-criteria analysis was implemented to assess the degree of usability of each equipment alternatives and select the most suitable alternative. In this project, the geotechnical conditions include sand, silt, and clay. Therefore, the project does not belong to only one category with respect to geotechnical conditions, but other two categories are applicable: sand & gravel, and cohesive soil. Precise data regarding the location and extents of particular geotechnical conditions are not available. In applying the multi-criteria analyzes of the proposed model, it is assumed that the two types of conditions have equal weights, as shown in Figure 45.

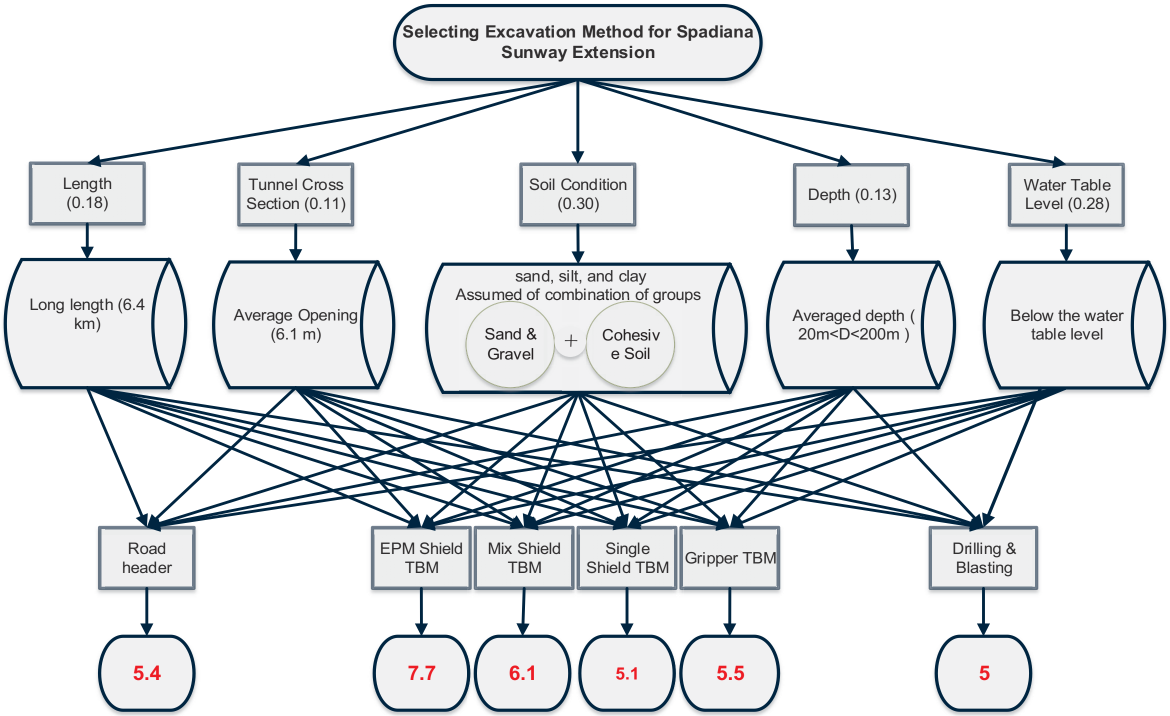

Figure 45 Applying AHP model on Spadaina Subway extension equipment selection, (Scenario 1)

The developed AHP model is applied by considering two scenarios for each equipment alternative. In Scenario 1, excavation starts from one end, whereas in Scenario 2 the excavation starts from the two ends of the tunnel, using two pieces of equipment of the same type. In Scenario 2, it is assumed that two pieces of equipment are working at the same time, one from the south entrance towards the north and the other from the north entrance towards the south, as shown in Figure 44.

EPB TBM with Scenario 1 ranked highest with the rating of 7.7, as shown in 46, and it is recommended as the most suitable alternative. The second most suitable alternative is EPB TBM with Scenario 2 with a rating of 7.2. In Scenario 2, EPB TBM becomes less efficient and highly costly to operate. These two alternatives are followed by Mix Shield TBM with Scenario 1, and Road Header with Scenario 2, both of which have a rating of 6.1.

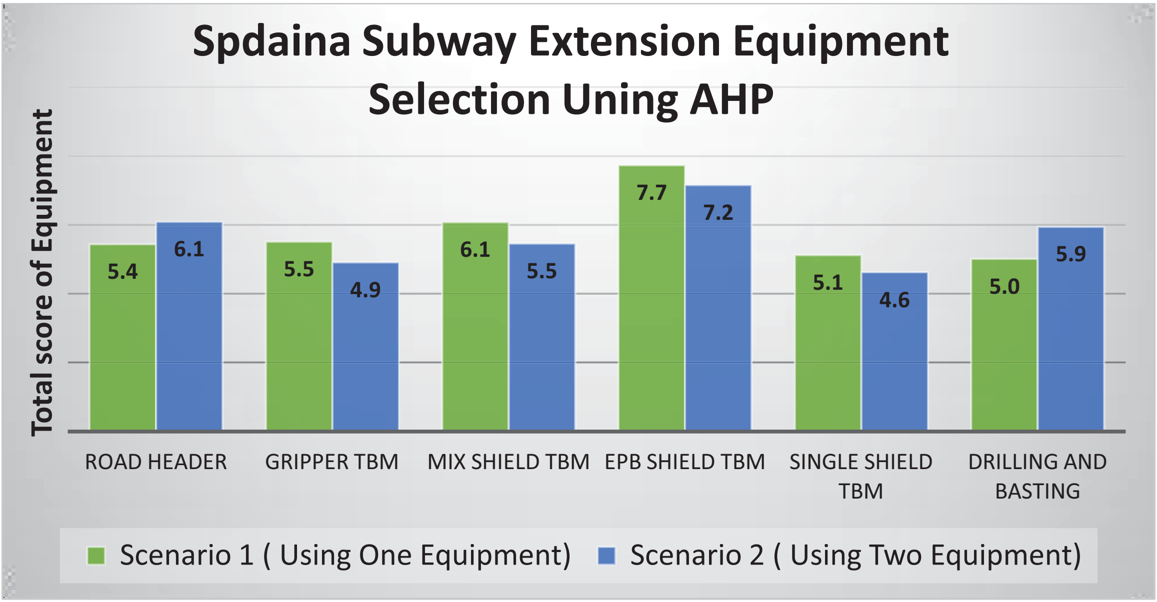

Figure 46 Applying AHP on Spadina Subway extension Equipment Selection

Based on the Hydrology and Geotechnical Conditions, Gripper TBM, and Single Shield TBM, are considered as little efficient and not feasible alternatives for this project. The suitability of all four types of TBM drops from Scenario 1 to Scenario 2. Drilling & Blasting and Road Header, become more suitable in Scenario 2 than in Scenario 1, but this does not affect the highest rated alternative.

7.5.4 Applying TOPSIS on Spadina Metro Extension Case Study

TOPSIS model of the developed method is applied as described in section 6.6.3. The appropriate category of project conditions is identified for each factor, and the corresponding scores for each alternative are used in calculating the ideal solution and the negative ideal solution. As discussed in the previous section, two types of geotechnical conditions occur on this project. In applying the TOPSIS model, the score of each alternative with respect to the factor Geotechnical Conditions is calculated as the average value of the two scores, for each of the two applicable categories of geotechnical conditions. Also, two scenarios are considered for each equipment alternative, as described in the previous section. The results are summarized in Figure 47.

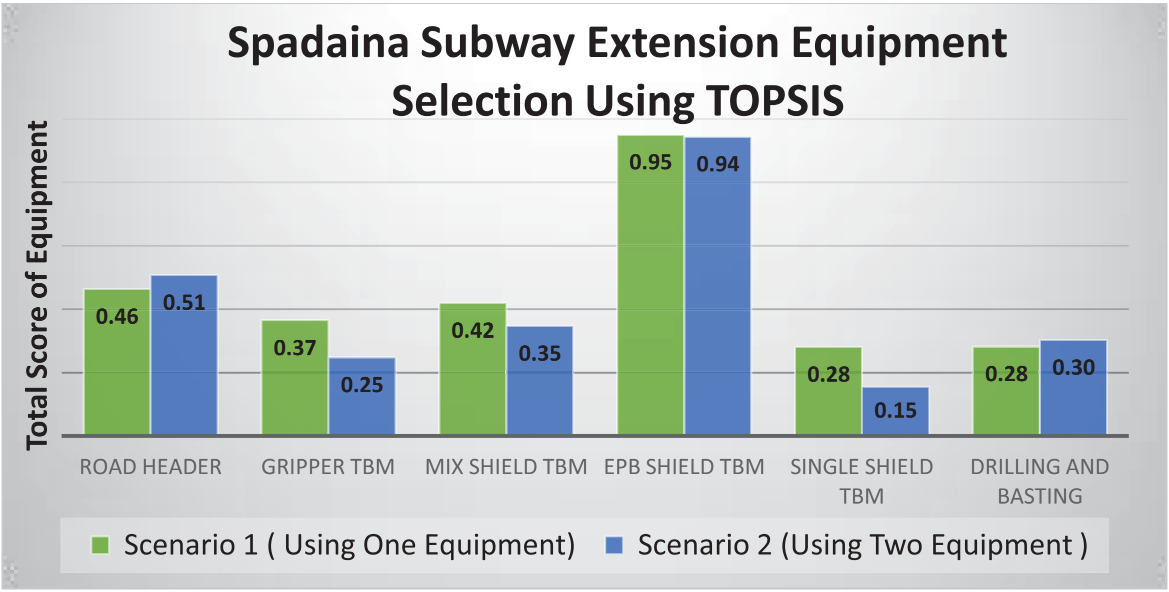

Figure 47 Applying TOPSIS on Spadina Subway Extension Equipment Selection

The highest ranking alternative is EPB Shield TBM with Scenario 1 with a rating of 0.95, followed by EPB Shield TBM with Scenario 2 with a score of 0.94. These two alternatives are followed by Road Header with Scenario 2 with a rating of 0.5 and Road Header with Scenario 1 with a rating of 0.46. The lowest ranking alternative is Single Shield TBM with Scenario 2, with a rating of 0.15, and the second lowest ranked alternative is the Gripper TBM with Scenario 2, with a rating of 0.24.

7.6 **Sensitivity Analysis on Factors affecting on Spadaina Subway extension**

The Figure 48 indicates the relationship between the variables in the developed MCA model and the suitability of equipment of the tunnel excavated by in selecting EBP TBM for Spadaina subway extension. By increasing the values of the variables, the suitability of using EPB TBM increases. A value of 0% on the x-axis indicates the actual state of the tunneling construction system; the state in which the variables have values as described in as an effective factors. The graph shows that the variable Tunnel length and geotechnical condition has the highest influences on tunneling equipment selection as well as larger impact on changes in equipment suitability.

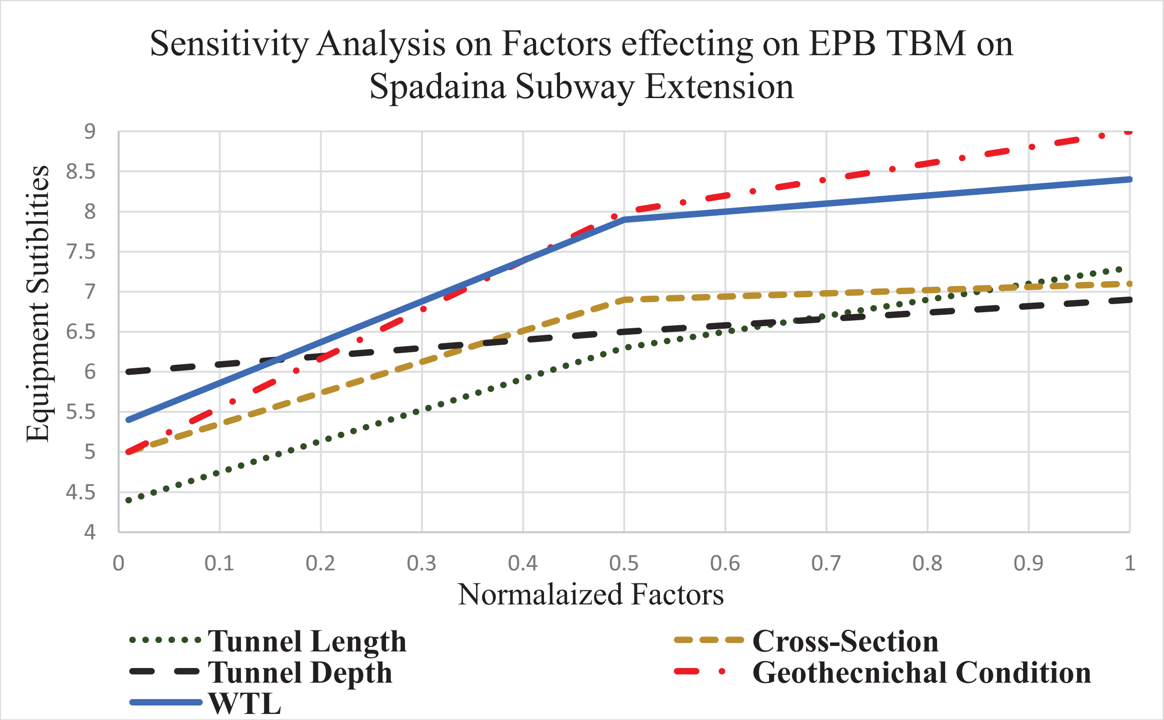

Figure 48 Applying Sensitivity Analysis on EPB suitability Spadaina subway extension

7.7 Compression of AHP Results, the TOPSIS results, and Actually Selected Alternatives

The two methods of multi-criteria analysis – AHP and TOPSIS, have been applied to the two case studies, to select the most suitable equipment alternatives. For each case study, two scenarios are considered for each type of equipment. In AHP, the ratings are on a scale of 1 to 9, where 9 is the highest rating. In TOPSIS, the ratings are from 0 to 1, where 1 is the highest rating. The results of the two methods for Case Study 1 - Montreal-Laval Metro Extension, are summarized in Table 11. Road Header with Scenario 2 ranked highest by both AHP and TOPSIS. The second and third ranked alternatives according to AHP are Road Header with Scenario 1, and EPB Shield TBM respectively. In TOPSIS, the second and third-ranked alternatives are reversed when compared to the rankings by AHP, but in TOPSIS these two alternatives have very close ratings. The two lowest ranked alternatives are also equal for the two methods. Those are Drilling and Blasting with Scenario 2 and Drilling and blasting Scenario 1. The rankings of 4 to 10, are also similar for the two methods.

Table 11 Case Study 1 - Montreal Laval Metro Extension: Comparison of AHP and TOPSIS

Case Study 1 - Montreal Laval Metro Extension					
	AHP			TOPSIS	
Rank	Alternative	Rating	Rank	Alternative	Rating
1	Road Header Scenario 2	7.4	1	Road header Scenario 2	0.73
2	Road Header Scenario 1	7.2	2	EPB Shield TBM Scenario 1	0.71
3	EPB Shield Scenario 1	6.5	3	Road header Scenario 1	0.71
4	Gripper TBM Scenario 1	6.2	4	EPB Shield TBM Scenario 2	0.65
4	EPB Shield Scenario 2	6.2	5	Gripper TBM Scenario 1	0.50
6	Single Shield TBM Scenario 1	6.1	6	Gripper TBM Scenario 2	0.47
7	Gripper TBM Scenario 2	5.8	7	Single Shield TBM Scenario 1	0.47
8	Mix Shield TBM Scenario 1	5.5	8	Single Shield TBM Scenario 2	0.45
9	Mix Shield TBM Scenario 2	5.4	9	Mix Shield TBM Scenario 1	0.33
10	Single Shield TBM Scenario 2	5.2	10	Mix Shield TBM Scenario 2	0.30
11	Drilling and Blasting Scenario 2	4.6	11	Drilling and Basting Scenario 2	0.24
12	Drilling and Blasting Scenario 1	4.0	12	Drilling and Basting Scenario 1	0.10

The result of the analysis – corresponds to the equipment actually used on the project by the SNC-Lavalin Company. Road-Header was selected as the most suitable equipment. According to SNC-Lavalin, in the process of equipment selection, out of all alternatives EPB TBM, with one entry, and Road Headers with two entries, were proposed as two strong candidates for this project (SNC-Lavalin, 2010). It was considered that EPB TBM could be highly productive and that geotechnical conditions were suited to the specifications of this machine, but also that there was a high variation of soil material along the tunnel length, which made the TBM a high-risk method. On the other hand, the Road-Header has a lower advance rate than the EPB TBM, but it is more suitable for varying soil conditions. Furthermore, it was determined that introducing the drilling method to specific areas of the project was the most appropriate (SNC-Lavalin, 2010). The results of the methods developed in this research are consistent with the actually selected methods of excavation.

The results of AHP and TOPSIS for the Case Study 2 - Spadiana Subway Extension are represented in Table 12. According to both methods, EPB TBM, starting from one end (Scenario 1) is recommended as the most suitable method for the project. The second, third, sixth, and seventh, as well as the lowest two rankings, are also equal for the two methods, whereas the remaining rankings are similar. The equipment actually used on the project is EPB Shield TBM with a single entry point (SNC-Lavalin, 2010). which corresponds to the recommendation of the developed selection method.

Table 12 Case Study 2 - Spadaina Subway Extension: Comparison of AHP and TOPSIS

Case study 2 - Spadaina Subway Extension				
	AHP		TOPSIS	
Rank	Alternative	Rating	Alternative	Rating
1	EPB Shield TBM Scenario 1	7.7	EPB Shield TBM Scenario 1	0.95
2	EPB Shield TBM Scenario 2	7.2	EPB Shield TBM Scenario 2	0.94
3	Road Header Scenario 2	6.1	Road header Scenario 2	0.51
3	Mix Shield TBM Scenario 1	6.1	Road header Scenario 1	0.46
5	Drilling and Blasting Scenario 2	5.9	Mix Shield TBM Scenario 1	0.42
6	Gripper TBM Scenario 1	5.5	Gripper TBM Scenario 1	0.37
6	Mix Shield TBM Scenario 2	5.5	Mix Shield TBM Scenario 2	0.35
8	Road Header Scenario 1	5.4	Drilling and Basting Scenario 2	0.30
9	Single Shield TBM Scenario 1	5.1	Drilling and Basting Scenario 1	0.28
10	Drilling and Blasting Scenario 1	5.0	Single Shield TBM Scenario 1	0.28
11	Gripper TBM Scenario 2	4.9	Gripper TBM Scenario 2	0.25
12	Single Shield TBM Scenario 2	4.6	Single Shield TBM Scenario 2	0.15

The two models of multi-criteria analysis developed in this research, one based on AHP and the other based on TOPSIS are developed based the same set of selection factors, the same categories of project conditions, the same weights of factors and the same scores of alternatives. The main difference between these two models is the mathematical method for calculating the ratings of alternatives. Therefore, it is expected that these two models would have a high degree of agreement in recommending an excavation equipment for a project. Based on the analysis of the two case studies, it can be stated that the developed AHP and TOPSIS models are likely to agree regarding the highest ranked and the lowest ranked alternatives, whereas the other rankings are likely to differ between the two methods, but they should not vary drastically. It can also be noted that in the to case studies, the relative differences in ratings between the highest and lowest ranked alternatives are higher in TOPSIS than in AHP, whereas the relative differences in ratings between the highest two alternatives are higher in AHP than in TOPSIS for Case Study 1 and approximately equal for Case Study 2. The differences in ratings among the highest two alternatives would be more important than the differences between the highest and lowest alternatives, in evaluating the accuracy of a method. Analysis of additional cases would provide a better understanding regarding the suitability of TOPSIS versus that of AHP.

7.8 **Summary**

In this chapter, two real projects are examined as case studies for implementation of the developed method, including both the AHP and the TOPSIS as multi-criteria analysis methods. The information on the case studies was gathered through direct email communication and interviews with representatives of operator companies, who had knowledge of the projects in question, and from the literature review. The developed models were implemented in both case studies, and the results were compared to the actual selection of excavation method for each of the projects. In both case studies, two scenarios are considered for each equipment alternative. In scenario one, it is assumed that the excavation is completed with one piece of equipment, starting from one end, and in scenario two - with two pieces of the same type of equipment starting from both ends of the tunnel.

In the Montreal-Laval Metro Extension (Case Study 1), two Road Headers, starting from each end of the tunnel were selected as the most suitable excavation alternative, according to both the

AHP and TOPSIS analysis. This was also the alternative actually selected for the project, in combination with Drilling and Blasting for specific areas, which enabled a higher productivity overall.

In the Spadiana Metro Extension project (Case study 2), the excavation was located in a very sandy zone with a high percentage of moisture. The length of the tunnel is just over 6 km. Both the AHP and the TOPSIS models recommended EPB TBM with one entry as the most suitable excavation alternative, which was actually selected for the project. The results of the developed AHP and TOPSIS models, in terms of the rankings of all alternatives are compared for the two case studies.

Chapter 5 Summary and Conclusion

8.1 **Summary**

This research aims to develop and present a new model for selection of excavation methods in tunneling projects. A comprehensive study was conducted to understand the excavation methods and their suitability for various project conditions and to design an integrated model for tunneling equipment selection. This model assesses the technical feasibility of various excavation methods. The research methods included a thorough literature review and an industry-wide questionnaire survey, conducted to understand the current academic work and industry practices.

The questionnaire of the survey was prepared in both paper and web-based format and was distributed to experts through email and LinkedIn social media professional network. 31 valid responses were received from construction managers, project engineers, construction site superintendents, equipment suppliers, university professors, and other experts with related proficiency in the field. The findings of the survey were used in the developments made in this research.

To address the limitations of current methods of tunneling equipment selection, a structured multi-criteria analysis method was developed, utilizing the results of the questionnaire survey. This is done in a formal qualitative and quantitative manner. The proposed model considers a series of selection factors significant in selection of tunneling excavation methods: length, cross-sectional area, geotechnical characteristics, depth of the tunnel, and the level of the water table. Pairwise comparisons between these factors were used to determine their relative weights. A range of technical conditions specific to each project corresponds to each factor. The excavation methods were assigned scores of suitability for each technical condition. The excavation methods considered as alternatives include four types of tunnel boring machines (TBMs), Road-header, and drilling & blasting methods. Two methods of multi-criteria analysis – AHP and TOPSIS are used to rank and rate the alternatives.

The proposed method was implemented in two real case studies: the Montreal-Laval Metro Extension and Toronto-York Spadaina Subway Extension, by applying both the AHP and the TOPSIS models. In each of the case studies, the AHP and TOPSIS models had the same results regarding the most suitable excavation methods and recommended the excavation methods actually selected for these two projects. The generated result indicates that the proposed model can objectively assess the equipment appropriateness in tunneling excavation method selection.

8.2 Conclusion

Appropriate selection of excavation method is among the key factors of tunneling project success. Previous studies in selecting the most suitable technique for tunneling excavation assigned priorities based on highest productivity rate as well as the availability of resources. These methods assessed each excavation method individually. Examples of previous academic work considered two alternatives for specific projects. The widespread industry practice has been to select the excavation method based on experience and expert knowledge.

In this research, a new method for selecting the most suitable excavation methods for tunnels is developed. The developed method is based on the multi-criteria analysis. The effective selection factors were identified from literature and expert survey questionnaires. Those factors are; tunnel length, the size of the tunnel opening, geotechnical conditions, how deep tunnel is located, and the level of ground water in the excavation area. The excavation method alternatives were identified from literature and interviews with industry experts.

By applying the multi-criteria analysis model based on AHP, the weight of each factor and the influence of each project condition on the suitability of each equipment alternative are assessed. The geotechnical conditions with the weight of 0.3 and water table level with the weight of 0.28 are the most important factors in tunneling excavation method selection. The tunnel length with the weight of 0.18 also has a high impact in decision making, whereas the tunnel depth with the weight of 0.13 and the tunnel cross section area with the weight of 0.11 have lesser impact among the identified selection factors. All excavation alternatives are assessed individually against the project conditions. Also sensitivity analysis was carried out on each of the case studies, to identify and analyze the most sensitive tunneling variables affecting equipment selection. Based on sensitivity analysis geotechnical condition is the most sensitive factors among all effective variables in both case studies. The developed method was implemented in two real case studies to demonstrate its effectives and highlight its essential features. In the Montreal-Laval Metro Extension, the selected method was Road Header, and in the Spadina Subway project EPB Mixed Shield was selected as the most favorable method of excavation. These results confirm the actually selected excavation methods on the two projects and indicate that the developed method is reliable.

After the multi-criteria analysis assessment, the thresholds for each equipment, for particular project conditions are applied. The threshold values of specific project parameters when particular excavation methods become technically unfeasible, ensure that technically unfeasible solutions are not selected, even if they rank high based on the multi-criteria analysis calculations, or due to an error. The developed method is intended to be used by contractors and project owners of tunneling projects and by academics. It can be used in preliminary cost estimates and budgets, milestone schedule, and risk analysis.

The advantage of the multi-criteria analysis model is that it represents a straightforward and quick method of assessment of technical feasibility. To apply the multi-criteria analysis model, the user needs to know the major project parameters but does need to have thorough knowledge of tunneling construction and excavation methods.

8.3 Contributions

The contributions of this work can be summarized as follows:

- Providing a knowledge base for a technical feasibility assessment of tunneling equipment, by gathering information from literature and expert questionnaires.
- Developing a novel multi-criteria model for selection of the most suitable (near optimum) tunneling methods and for planning tunneling construction processes in an extensive range of applications.
- Developing a set of influential factors, categories of project conditions for each factor, and excavation method alternatives have been identified. Relative weights of factors and the scores of all alternatives for each project condition were determined.
- Providing method and implementation in MS Excel to facilitate its use.
- Comparing AHP and TOPSIS as methods of multi-criteria analysis, based on two real case studies.

8.4 Limitations

The following are the limitations of this research:

- In designing the questionnaire, in defining the ranges of project conditions for the selection factors, the research relied on the judgment of experts interviewed. As an example in categorizing the tunnel opening size, according to the literature review, tunnels with an opening less than 1.5 meters are considered as micro-tunnels. However, to limit the number of categories, in order to have a more manageable number of questions in the questionnaire, all tunnels with the opening of less than 5m were grouped as small tunnels.

- Limited information was available on the case studies, and as a result, in analyzing the case studies certain assumptions were made regarding the geotechnical conditions and variability of materials. Having more precise information about the project, such as the geotechnical report and the design specifications, would help to select the method more precisely.

8.5 Recommendations for Future Work

- Studying only technical factors is not sufficient to select excavation methods for tunneling projects. Other relevant criteria include management impact, risk assessment, and availability of equipment and materials. Therefore, quantitative and qualitative studies of such additional aspects of tunneling method selection are recommended for future work.
- By expanding the research through ANP for identifying the interdependence and feedback among the factors in tunneling construction
- An automated user-friendly software tool, to facilitate the implementation of the developed method could be developed.

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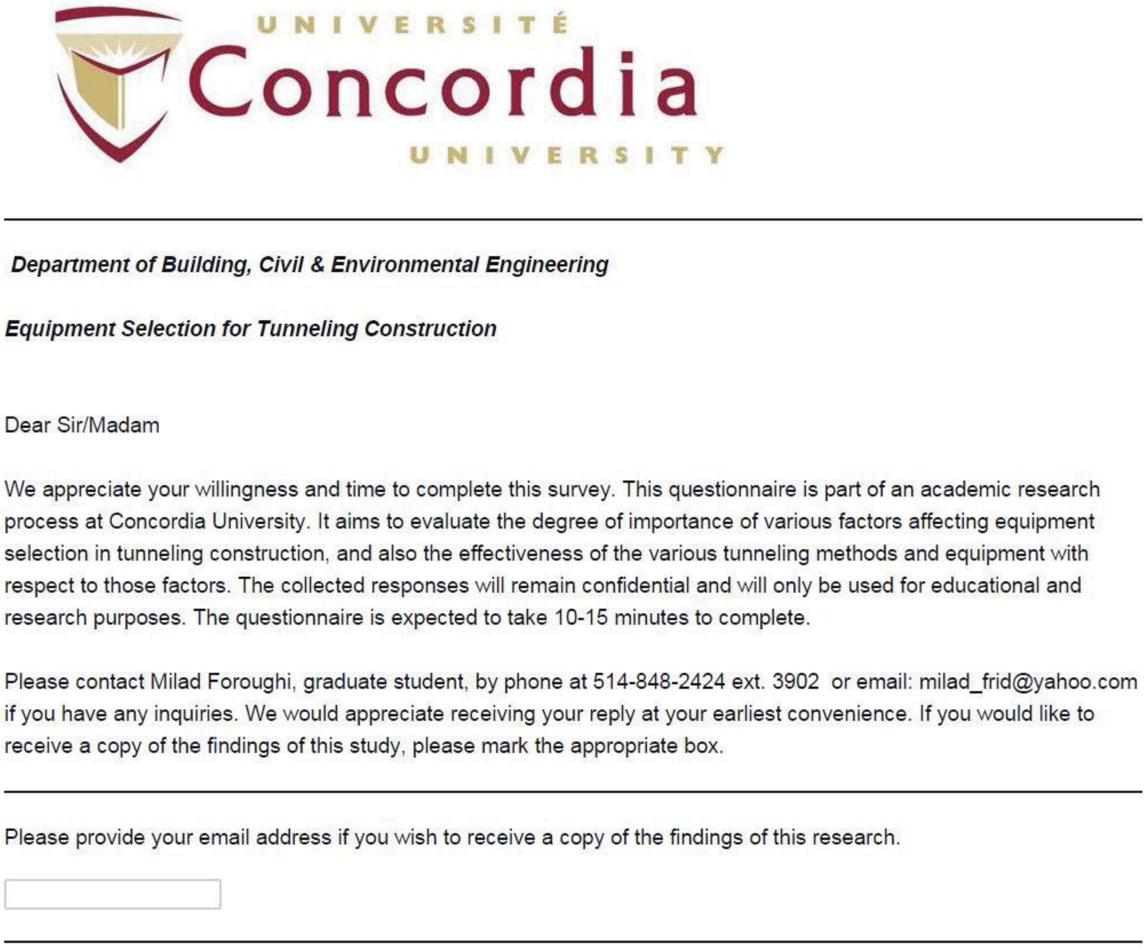
Appendix I (The Questionnaires)

Questionnaire of the survey-English Format



UNIVERSITÉ
Concordia
UNIVERSITY

Department of Building, Civil & Environmental Engineering

Equipment Selection for Tunneling Construction

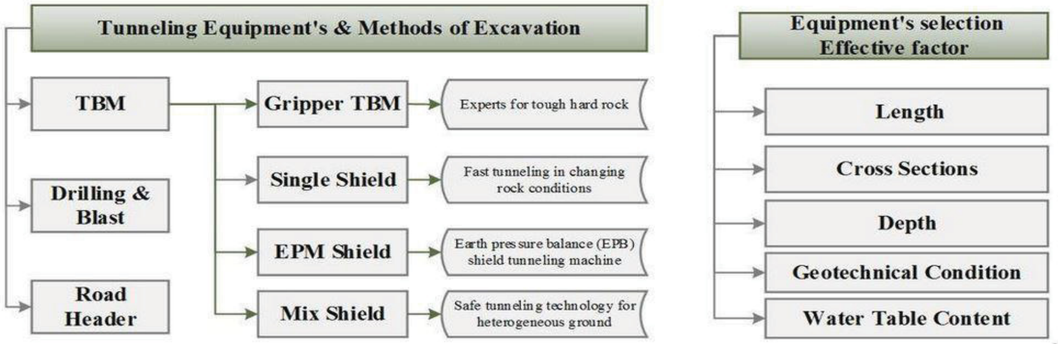
Dear Sir/Madam

We appreciate your willingness and time to complete this survey. This questionnaire is part of an academic research process at Concordia University. It aims to evaluate the degree of importance of various factors affecting equipment selection in tunneling construction, and also the effectiveness of the various tunneling methods and equipment with respect to those factors. The collected responses will remain confidential and will only be used for educational and research purposes. The questionnaire is expected to take 10-15 minutes to complete.

Please contact Milad Foroughi, graduate student, by phone at 514-848-2424 ext. 3902 or email: milad_frid@yahoo.com if you have any inquiries. We would appreciate receiving your reply at your earliest convenience. If you would like to receive a copy of the findings of this study, please mark the appropriate box.

Please provide your email address if you wish to receive a copy of the findings of this research.

Based on literature review and limited number of interviews with experts, the factors that affect equipment selection for tunneling construction were identified. Those factors and the tunneling excavation methods are presented in Figure 1:



After reviewing the main factors and equipment listed; please fill in parts (1) to (3) of this questionnaire.

PART (1) : GENERAL INFORMATION

1) What is your occupation?

○ Project Manager
○ Project Engineer
○ University Professor
○ Equipment Supplier
○ Superintendent
○ Other (Please Specify)

2) How many years of work experience do you have in tunneling construction?

○ Les than 5 years
○ 5 to 10 years
○ 10 to 20 years
○ more than 20 years

PART (2): PAIRWISE COMPARISON BETWEEN FACTORS

In an attempt to determine the degree of importance of factors affecting equipment selection for tunneling construction. Please compare each factor on the left-hand side to the factor on the right-hand side, one pair at a time, in terms of how important is the factor on the left compared to the factor on the right, in selecting the most suitable equipment for tunnel excavations.

The example below means that geotechnical conditions are very strongly more important than the tunnel cross section.

	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	
Geotechnical Conditions	○	●	○	○	○	○	○	○	○	Tunnel Cross Section

	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	
Tunnel Cross Section	○	○	○	○	○	○	○	○	○	Depth of Tunnel
Tunnel Cross Section	○	○	○	○	○	○	○	○	○	Geotechnical Conditions
Tunnel Cross Section	○	○	○	○	○	○	○	○	○	Length of Tunnel
Tunnel Cross Section	○	○	○	○	○	○	○	○	○	Water Table
Depth of Tunnel	○	○	○	○	○	○	○	○	○	Geotechnical Conditions
Depth of Tunnel	○	○	○	○	○	○	○	○	○	Length of Tunnel
Depth of Tunnel	○	○	○	○	○	○	○	○	○	Water Table
Geotechnical Conditions	○	○	○	○	○	○	○	○	○	Length of Tunnel
Geotechnical Conditions	○	○	○	○	○	○	○	○	○	Water Table
Length of Tunnel	○	○	○	○	○	○	○	○	○	Water Table

PART (3): IMPORTANCE OF EACH EQUIPMENT ACCORDING TO THE CIRCUMSTANCES OF THE FACTORS

Please fill the following tables by assigning a value from 1 to 9, according to the suitability of each equipment with respect to each of the five factors considered (Sections a, b, c, d, e).
This part is intended to rank the methods and equipment in terms of time and cost effectiveness.

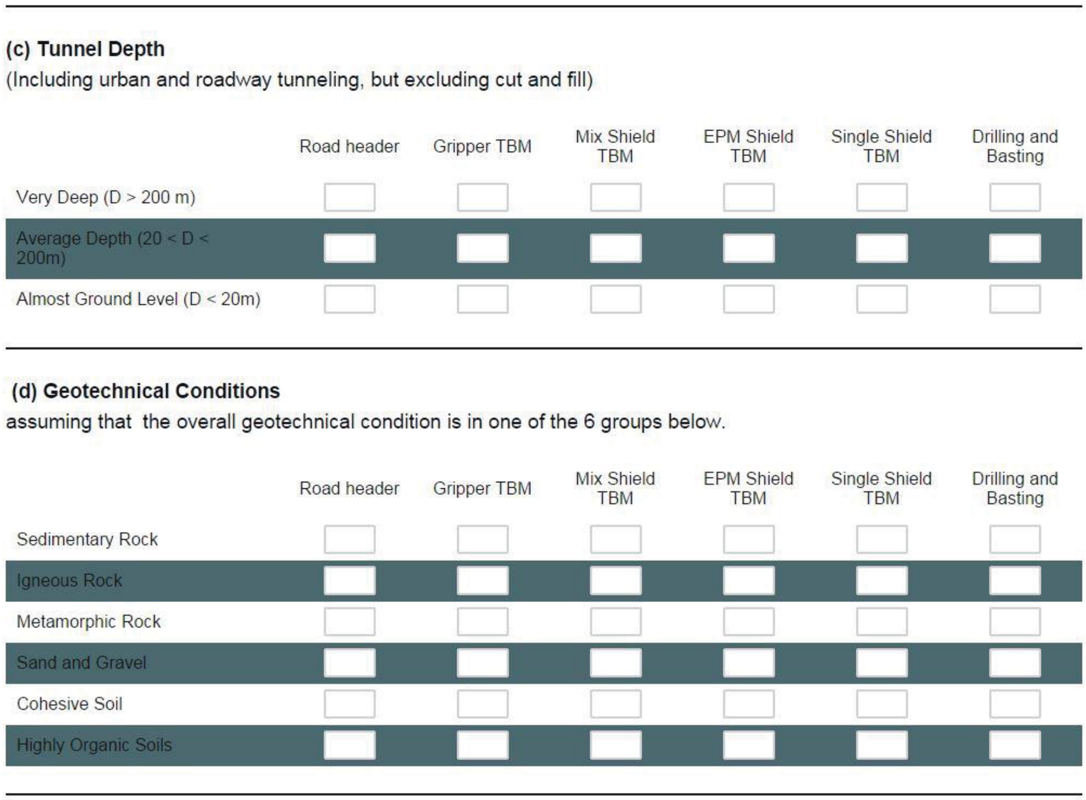
(9) is the most suitable method and (1) is least suitable method.

(a) Tunnel Length

	Road header	Gripper TBM	Mix Shield TBM	EPM Shield TBM	Single Shield TBM	Drilling and Basting
Short l (L < 3000m)	☐	☐	☐	☐	☐	☐
Medium Length (3000 m < L < 6000m)	☐	☐	☐	☐	☐	☐
Long (L > 6000m)	☐	☐	☐	☐	☐	☐

(b)Tunnel Cross Section

	Road header	Gripper TBM	Mix Shield TBM	EPM Shield TBM	Single Shield TBM	Drilling and Basting
Micro Tunneling (R < 5m)	☐	☐	☐	☐	☐	☐
Average Tunneling (5m < R < 12m)	☐	☐	☐	☐	☐	☐
Large Opening (R > 12m)	☐	☐	☐	☐	☐	☐



(c) Tunnel Depth

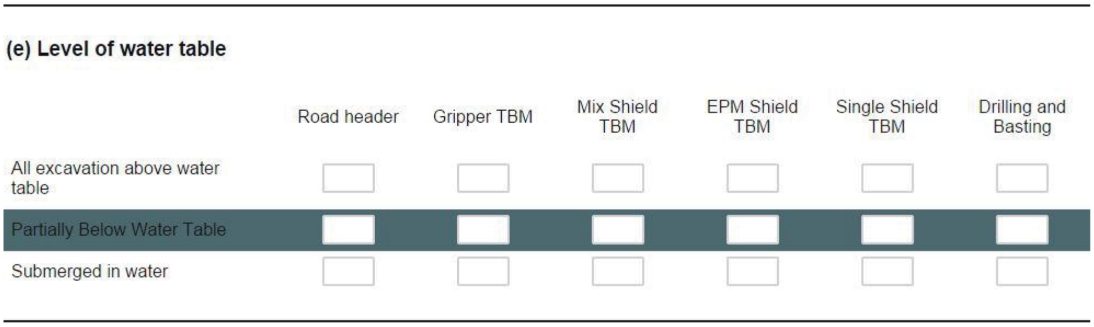
(Including urban and roadway tunneling, but excluding cut and fill)

	Road header	Gripper TBM	Mix Shield TBM	EPM Shield TBM	Single Shield TBM	Drilling and Basting
Very Deep (D > 200 m)	☐	☐	☐	☐	☐	☐
Average Depth (20 < D < 200m)	☐	☐	☐	☐	☐	☐
Almost Ground Level (D < 20m)	☐	☐	☐	☐	☐	☐

(d) Geotechnical Conditions

assuming that the overall geotechnical condition is in one of the 6 groups below.

	Road header	Gripper TBM	Mix Shield TBM	EPM Shield TBM	Single Shield TBM	Drilling and Basting
Sedimentary Rock	☐	☐	☐	☐	☐	☐
Igneous Rock	☐	☐	☐	☐	☐	☐
Metamorphic Rock	☐	☐	☐	☐	☐	☐
Sand and Gravel	☐	☐	☐	☐	☐	☐
Cohesive Soil	☐	☐	☐	☐	☐	☐
Highly Organic Soils	☐	☐	☐	☐	☐	☐



(e) Level of water table

	Road header	Gripper TBM	Mix Shield TBM	EPM Shield TBM	Single Shield TBM	Drilling and Basting
All excavation above water table	☐	☐	☐	☐	☐	☐
Partially Below Water Table	☐	☐	☐	☐	☐	☐
Submerged in water	☐	☐	☐	☐	☐	☐

Thank You.

Appendix II (Scores of Alternative)

Scores of alternatives		Alternatives					
Factors	**Project conditions**	Road header	Gripper TBM	Mix Shield TBM	EPM Shield TBM	Single Shield TBM	Drilling and Basting
Tunnel Cross Section	Micro Tunneling (R < 5m)	6.5	4.9	5	4.8	5.3	5.3
	Average Tunneling (5m < R < 12m)	6.6	6.3	6.6	6.9	6.7	5.9
	Large Opening (R > 12m)	4.5	8	7.3	7.1	6.9	5.1
Depth of Tunnel	Very Deep (D > 200 m)	5.2	7.4	6.4	6.3	6.5	7.1
	Average Depth (20 < D < 200m)	5.2	6.2	6.3	6.6	6.4	6.4
	Almost Ground Level (D < 20m)	6.9	4.9	6	6	4.8	5.2
Geotechnical Conditions	Sedimentary Rock	9	8	6	6	9	3
	Igneous Rock	8	9	6	6	8	2
	Metamorphic Rock	7	9	6	5	8	3
	Sand and Gravel	7	7	9	7	6	7
	Cohesive Soil	3.5	2	5	9	3	7
	Highly Organic Soils	6	4	5	8	4	8
Length of Tunnel	Short l (L < 3000m)	7.5	4.9	4.3	4.4	4.8	8
	Medium Length (3000 m < L < 6000m)	6	7	6.4	6.3	6.7	4.8
	Long (L > 6000m)	3.9	8.3	7.8	7.6	7.6	2.8
Water Table	All excavation above water table	7.8	7.2	8.1	5.4	7.7	6.8
	Partially Below Water Table	5.2	5.4	6.25	7.9	5.5	5
	Submerged in water	6.3	4.2	3.7	8.4	3	3.3

Appendix III (Factors influences weight)

	Tunnel Length			
Tunnel Condition	Method	Weight	Given Score	Influence Rate
Short l (L < 3000m)	Road header	0.18	7.5	1.35
	Gripper TBM	0.18	4.9	0.882
	Mix Shield TBM	0.18	4.3	0.774
	EPM Shield TBM	0.18	4.4	0.792
	Single Shield TBM	0.18	4.8	0.864
	Drilling and Basting	0.18	8	1.44
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Medium Length (3000 m < L < 6000m)	Road header	0.18	6	1.08
	Gripper TBM	0.18	7	1.26
	Mix Shield TBM	0.18	6.4	1.152
	EPM Shield TBM	0.18	6.3	1.134
	Single Shield TBM	0.18	6.7	1.206
	Drilling and Basting	0.18	4.8	0.864
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Long (L > 6000m)	Road header	0.18	3.9	0.702
	Gripper TBM	0.18	8.3	1.494

	Mix Shield TBM	0.18	7.8	1.404
	EPM Shield TBM	0.18	7.6	1.368
	Single Shield TBM	0.18	7.6	1.368
	Drilling and Basting	0.18	2.8	0.504
	Tunnel Cross Section			
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Small Tunneling (R < 5m)	Road header	0.11	6.5	0.72
	Gripper TBM	0.11	4.9	0.21
	Mix Shield TBM	0.11	5	0.55
	EPM Shield TBM	0.11	4.8	0.53
	Single Shield TBM	0.11	5.3	0.58
	Drilling & Blasting	0.11	5.5	0.61
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Average Tunneling (5m < R < 12m)	Road header	0.11	6.6	7
	Gripper TBM	0.11	6.3	0.69
	Mix Shield TBM	0.11	6.6	0.73
	EPM Shield TBM	0.11	6.9	0.76
	Single Shield TBM	0.11	6.7	0.74
	Drilling and Basting	0.11	5.9	0.65

Tunnel Condition	Method	Weight	Given Score	Influence rate
Average Tunneling (5m < R < 12m)	Road header	0.11	4.5	0.5
	Gripper TBM	0.11	8	0.88
	Mix Shield TBM	0.11	7.3	0.8
	EPM Shield TBM	0.11	7.1	0.78
	Single Shield TBM	0.11	6.9	0.76
	Drilling and Basting	0.11	5.1	0.56
	Tunnel Depth			
Tunnel Condition	**method**	**Weight**	**given Score**	**Influence Rate**
Very Deep (D > 200 m)	Road header	0.13	5.2	0.68
	Gripper TBM	0.13	7.4	0.96
	Mix Shield TBM	0.13	6.4	0.83
	EPM Shield TBM	0.13	6.3	0.82
	Single Shield TBM	0.13	6.5	0.85
	Drilling & Blasting	0.13	7.1	0.92
Tunnel Condition	**method**	**Weight**	**given Score**	**Influence Rate**
Average Depth	Road header	0.13	5.2	0.68
	Gripper TBM	0.13	6.2	0.81
	Mix Shield TBM	0.13	6.3	0.82
	EPM Shield TBM	0.13	6.6	0.86

	Single Shield TBM	0.13	6.4	0.83
	Drilling and Basting	0.13	6.4	0.83
Tunnel Condition	**method**	**Weight**	**given Score**	**Influence Rate**
Almost Ground Level	Road header	0.13	6.9	0.9
	Gripper TBM	0.13	4.9	0.64
	Mix Shield TBM	0.13	6	0.78
	EPM Shield TBM	0.13	6	0.78
	Single Shield TBM	0.13	4.8	0.62
	Drilling and Basting	0.13	5.2	0.68
	Tunnel Geotechnical Condition			
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Sedimentary Rock	Road header	0.3	9	2.7
	Gripper TBM	0.3	8	2.4
	Mix Shield TBM	0.3	6	1.8
	EPM Shield TBM	0.3	6	1.8
	Single Shield TBM	0.3	9	2.7
	Drilling and Blasting	0.3	3	0.9
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Igneous Rock	Road header	0.3	8	2.4

	Gripper TBM	0.3	9	2.7
	Mix Shield TBM	0.3	6	1.8
	EPM Shield TBM	0.3	6	1.8
	Single Shield TBM	0.3	8	2.4
	Drilling and Basting	0.3	2	0.6
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Metamorphic Rock	Road header	0.3	7	2.1
	Gripper TBM	0.3	9	2.7
	Mix Shield TBM	0.3	6	1.8
	EPM Shield TBM	0.3	5	1.5
	Single Shield TBM	0.3	8	2.4
	Drilling and Basting	0.3	3	0.9
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Sand and Gravel	Road header	0.3	7	2.1
	Gripper TBM	0.3	7	2.1
	Mix Shield TBM	0.3	9	2.7
	EPM Shield TBM	0.3	7	2.1
	Single Shield TBM	0.3	6	1.8
	Drilling and Blasting	0.3	7	2.1

Tunnel Condition	Method	Weight	Given Score	Influence Rate
Cohesive Soil	Road header	0.3	3.5	1.05
	Gripper TBM	0.3	2	0.6
	Mix Shield TBM	0.3	5	1.5
	EPM Shield TBM	0.3	9	2.7
	Single Shield TBM	0.3	3	0.9
	Drilling and Basting	0.3	7	2.1
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Highly Organic Soils	Road header	0.3	6	1.8
	Gripper TBM	0.3	4	1.2
	Mix Shield TBM	0.3	5	1.5
	EPM Shield TBM	0.3	8	2.4
	Single Shield TBM	0.3	4	1.2
	Drilling and Basting	0.3	8	2.4
	Water Level			
Tunnel Condition	Method	Weight	Given Score	Influence Rate
All excavation above water table	Road header	0.28	7.8	2.2
	Gripper TBM	0.28	7.2	2
	Mix Shield TBM	0.28	8.1	2.3
	EPM Shield TBM	0.28	5.4	1.5

	Single Shield TBM	0.28	7.7	2.2
	Drilling & Blasting	0.28	6.8	1.9
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Partially Below Water Table	Road header	0.28	5.2	1.5
	Gripper TBM	0.28	5.4	1.5
	Mix Shield TBM	0.28	6.25	1.8
	EPM Shield TBM	0.28	7.9	2.2
	Single Shield TBM	0.28	5.5	1.5
	Drilling and Basting	0.28	5	1.4
Tunnel Condition	**Method**	**Weight**	**Given Score**	**Influence Rate**
Submerged in water	Road header	0.28	6.3	1.8
	Gripper TBM	0.28	4.2	1.2
	Mix Shield TBM	0.28	3.7	1
	EPM Shield TBM	0.28	8.4	2.4
	Single Shield TBM	0.28	3	0.8
	Drilling and Basting	0.28	3.3	0.9

Appendix IV (TOPSIS Weighted Standardized Decision Matrix)

TOPSIS weighted standardized decision matrix		Road header				
Factors	**Factors**	Score	Standardized score	Weighted standardized score	Separation from ideal solution	Separation from negative ideal solution
Tunnel Cross Section	Micro Tunneling (R < 5m)	6.50	0.49	0.05	0.0000	0.0002
	Average Tunneling (5m < R < 12m)	6.60	0.41	0.05	0.0000	0.0000
	Large Opening (R > 12m)	4.50	0.28	0.03	0.0006	0.0000
Depth of Tunnel	Very Deep (D > 200 m)	5.20	0.33	0.04	0.0003	0.0000
	Average Depth (20 < D < 200m)	5.20	0.34	0.04	0.0001	0.0000
	Almost Ground Level (D < 20m)	6.90	0.50	0.06	0.0000	0.0004
Geotechnical Conditions	Sedimentary Rock	9.00	0.51	0.15	0.0000	0.0106
	Igneous Rock	8.00	0.47	0.14	0.0003	0.0114
	Metamorphic Rock	7.00	0.43	0.13	0.0014	0.0055
	Sand and Gravel	7.00	0.40	0.12	0.0012	0.0003
	Combination sand, gravel and cohesive	5.25	0.35	0.00	0.0000	0.0000
	Cohesive Soil	3.50	0.26	0.08	0.0151	0.0011
	Highly Organic Soils	6.00	0.40	0.12	0.0016	0.0016
Length of Tunnel	Short l (L < 3000m)	7.50	0.52	0.09	0.0000	0.0016
	Medium Length (3000 m < L < 6000m)	6.00	0.39	0.07	0.0001	0.0002
	Long (L >	3.90	0.24	0.04	0.0023	0.0001

	6000m)					
Water Table	All excavation above water table	7.80	0.44	0.12	0.0000	0.0014
	Partially Below Water Table	5.20	0.36	0.10	0.0027	0.0000
	Submerged in water	6.30	0.50	0.14	0.0021	0.0053

TOPSIS weighted standardized decision matrix		Gripper TBM				
Factors	**Factors**	Score	Standardized score	Weighted standardized score	Separation from ideal solution	Separation from negative ideal solution
Tunnel Cross Section	Micro Tunneling (R < 5m)	4.90	0.37	0.04	0.0002	0.0000
	Average Tunneling (5m < R < 12m)	6.30	0.40	0.04	0.0000	0.0000
	Large Opening (R > 12m)	8.00	0.49	0.05	0.0000	0.0006
Depth of Tunnel	Very Deep (D > 200 m)	7.40	0.46	0.06	0.0000	0.0003
	Average Depth (20 < D < 200m)	6.20	0.41	0.05	0.0000	0.0001
	Almost Ground Level (D < 20m)	4.90	0.35	0.05	0.0003	0.0000
Geotechnical Conditions	Sedimentary Rock	8.00	0.46	0.14	0.0003	0.0073
	Igneous Rock	9.00	0.53	0.16	0.0000	0.0155
	Metamorphic Rock	9.00	0.55	0.17	0.0000	0.0123
	Sand and Gravel	7.00	0.40	0.12	0.0012	0.0003
	Combination sand, gravel and cohesive	4.50	0.30	0.00	0.0000	0.0000
	Cohesive Soil	2.00	0.15	0.04	0.0245	0.0000
	Highly Organic Soils	4.00	0.27	0.08	0.0065	0.0000

Length of Tunnel	Short l (L < 3000m)	4.90	0.34	0.06	0.0015	0.0001
	Medium Length (3000 m < L < 6000m)	7.00	0.46	0.08	0.0000	0.0007
	Long (L > 6000m)	8.30	0.51	0.09	0.0000	0.0037
Water Table	All excavation above water table	7.20	0.41	0.11	0.0002	0.0008
	Partially Below Water Table	5.40	0.37	0.10	0.0023	0.0001
	Submerged in water	4.20	0.33	0.09	0.0086	0.0007

TOPSIS weighted standardized decision matrix		Mix Shield TBM				
Factors	**Factors**	Score	Standardized score	Weighted standardized score	Separation from ideal solution	Separation from negative ideal solution
Tunnel Cross Section	Micro Tunneling (R < 5m)	5.00	0.38	0.04	0.0002	0.0000
	Average Tunneling (5m < R < 12m)	6.60	0.41	0.05	0.0000	0.0000
	Large Opening (R > 12m)	7.30	0.45	0.05	0.0000	0.0004
Depth of Tunnel	Very Deep (D > 200 m)	6.40	0.40	0.05	0.0001	0.0001
	Average Depth (20 < D < 200m)	6.30	0.41	0.05	0.0000	0.0001
	Almost Ground Level (D < 20m)	6.00	0.43	0.06	0.0001	0.0001
Geotechnical Conditions	Sedimentary Rock	6.00	0.34	0.10	0.0026	0.0026
	Igneous Rock	6.00	0.36	0.11	0.0028	0.0051
	Metamorphic Rock	6.00	0.37	0.11	0.0031	0.0031
	Sand and Gravel	9.00	0.51	0.15	0.0000	0.0026

	Combination sand, gravel and cohesive	7.00	0.46	0.00	0.0000	0.0000
	Cohesive Soil	5.00	0.37	0.11	0.0080	0.0045
	Highly Organic Soils	5.00	0.34	0.10	0.0037	0.0004
Length of Tunnel	Short l (L < 3000m)	4.30	0.30	0.05	0.0022	0.0000
	Medium Length (3000 m < L < 6000m)	6.40	0.42	0.08	0.0000	0.0004
	Long (L > 6000m)	7.80	0.48	0.09	0.0000	0.0030
Water Table	All excavation above water table	8.10	0.46	0.13	0.0000	0.0018
	Partially Below Water Table	6.25	0.43	0.12	0.0010	0.0006
	Submerged in water	3.70	0.29	0.08	0.0107	0.0002

TOPSIS weighted standardized decision matrix		EPM Shield TBM				
Factors	**Factors**	Score	Standardized score	Weighted standardized score	Separation from ideal solution	Separation from negative ideal solution
Tunnel Cross Section	Micro Tunneling (R < 5m)	4.80	0.37	0.04	0.0002	0.0000
	Average Tunneling (5m < R < 12m)	6.90	0.43	0.05	0.0000	0.0000
	Large Opening (R > 12m)	7.10	0.44	0.05	0.0000	0.0003
Depth of Tunnel	Very Deep (D > 200 m)	6.30	0.39	0.05	0.0001	0.0001
	Average Depth (20 < D < 200m)	6.60	0.43	0.06	0.0000	0.0001
	Almost Ground Level (D < 20m)	6.00	0.43	0.06	0.0001	0.0001

Geotechnical Conditions	Sedimentary Rock	6.00	0.34	0.10	0.0026	0.0026
	Igneous Rock	6.00	0.36	0.11	0.0028	0.0051
	Metamorphic Rock	5.00	0.31	0.09	0.0055	0.0014
	Sand and Gravel	7.00	0.40	0.12	0.0012	0.0003
	Combination sand, gravel and cohesive	8.00	0.53	0.00	0.0000	0.0000
	Cohesive Soil	9.00	0.67	0.20	0.0000	0.0245
	Highly Organic Soils	8.00	0.54	0.16	0.0000	0.0065
Length of Tunnel	Short l (L < 3000m)	4.40	0.31	0.06	0.0020	0.0000
	Medium Length (3000 m < L < 6000m)	6.30	0.41	0.07	0.0001	0.0003
	Long (L > 6000m)	7.60	0.46	0.08	0.0001	0.0028
Water Table	All excavation above water table	5.40	0.31	0.09	0.0018	0.0000
	Partially Below Water Table	7.90	0.54	0.15	0.0000	0.0031
	Submerged in water	8.40	0.66	0.19	0.0000	0.0142

TOPSIS weighted standardized decision matrix		Single Shield TBM				
Factors	**Factors**	Score	Standardized score	Weighted standardized score	Separation from ideal solution	Separation from negative ideal solution
Tunnel Cross Section	Micro Tunneling (R < 5m)	5.30	0.40	0.04	0.0001	0.0000
	Average Tunneling (5m < R < 12m)	6.70	0.42	0.05	0.0000	0.0000
	Large Opening (R > 12m)	6.90	0.43	0.05	0.0001	0.0003

Depth of Tunnel	Very Deep (D > 200 m)	6.50	0.41	0.05	0.0001	0.0001
	Average Depth (20 < D < 200m)	6.40	0.42	0.05	0.0000	0.0001
	Almost Ground Level (D < 20m)	4.80	0.34	0.04	0.0004	0.0000
Geotechnical Conditions	Sedimentary Rock	9.00	0.51	0.15	0.0000	0.0106
	Igneous Rock	8.00	0.47	0.14	0.0003	0.0114
	Metamorphic Rock	8.00	0.49	0.15	0.0003	0.0085
	Sand and Gravel	6.00	0.34	0.10	0.0026	0.0000
	Combination sand, gravel and cohesive	4.50	0.30	0.00	0.0000	0.0000
	Cohesive Soil	3.00	0.22	0.07	0.0180	0.0005
	Highly Organic Soils	4.00	0.27	0.08	0.0065	0.0000
Length of Tunnel	Short l (L < 3000m)	4.80	0.34	0.06	0.0016	0.0000
	Medium Length (3000 m < L < 6000m)	6.70	0.44	0.08	0.0000	0.0005
	Long (L > 6000m)	7.60	0.46	0.08	0.0001	0.0028
Water Table	All excavation above water table	7.70	0.44	0.12	0.0000	0.0013
	Partially Below Water Table	5.50	0.38	0.11	0.0021	0.0001
	Submerged in water	3.00	0.24	0.07	0.0142	0.0000