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Comparison of two different tunnelling methods in hard rock -With a focus on the geological parameters

*Master of Science Thesis in the Master's Programme Infrastructure and Environmental
Engineering*

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MASTER'S THESIS

Comparison of two different tunnelling methods

Infrastructure and Environmental Engineering

Department of Civil and Environmental Engineering
Chalmers University of Technology
Göteborg, Sweden **Error! Reference source not found.**

Comparison of two different tunnelling methods in hard rock
Infrastructure and Environmental Engineering

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Cover:
Two different Excavation tunnelling methods, TBM and D&B (Tunnel talk 2014)

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Comparison of two different tunnelling methods in hard rock

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ABSTRACT

This report aimed to study two tunnelling excavation methods, Tunnelling Boring Machine (TBM) and Drilling and Blasting (D&B), to provide a decision basis to determine which excavation method is more suitable in hard rock.

First, the two different excavation methods have been described, and the main factors that have influenced the choice of tunnelling method have been identified. To find these factors, the two excavations method was compared, focusing on how the geological parameter affects the tunnelling method.

The most important parameters and factors have been presented to describe how they influence the two tunnelling methods. The lists of parameters are based on the performed literature study.

A recently designed project, the Oslo–Skien railway tunnel, has been used as an example of a tunnelling project. This tunnel has been studied to find which factors affect the tunnelling method and why the TBM method was selected. This study will provide a practical example of TBM and an opportunity to investigate the suggested tunnelling method.

A planned water tunnel between Vättern and Hallsberg has been investigated as a case study. A pre-study of this planned water tunnel based on identified parameters are used to suggest a primary excavation method. A definitive answer to the question about which driving method should be chosen is complicated.

Concerning the geological condition of the water tunnel use, the TBM method seems to be a suitable option for water tunnels. For example, the estimated average advance rate for the water tunnel using the TBM method is about 65m/week and about 39m/week with the D&B method.

Investigating other factors that influenced the tunnelling method, such as equipment parameters and construction processes, recommended increasing the probability of which tunnelling method is most suitable.

Key words: Excavation, TBM, D&B, geological parameter and advance rate.

Comparison of two different tunnelling methods in hard rock

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SAMMANFATTNING

Målet med denna rapport var att studera två olika tunneldrivningsmetoder, Tunnel Borr Maskin (TBM) och Borring/Sprängning (D&B) för att ge ett beslutsunderlag till att avgöra vilken tunneldrivningsmetod är lämpligare i hårt berg.

Först har två olika uttagsmetoder beskrivits för tunnlar i hårt berg och hitta viktiga faktorer som har påverkar valet av tunneldrivningsmetod. För att hitta dessa faktorer har de två olika uttagsmetoderna jämförts med fokus på hur de geologiska parametrarna påverkar tunneldrivningsmetoden.

De identifierade viktigaste parametrarna och faktorerna har presenterats för att beskriva hur de påverkar de två olika tunneldrivningsmetoder. Detta har baserat på den genomförda litteraturstudien.

Ett nyligen designat projekt, Oslo – Skien järnvägs tunnel har använts som en exempel på ett tunnel-projekt, denna tunnel har studerat för att hitta vilka faktorer har påverkat val av tunneldrivningsmetod och varför har TBM metod valts. Denna studie kommer att ge den praktisk exempel på TBM och en möjlighet för utredning av den föreslagna tunnelmetoden.

En planerade vatten tunnel mellan Vättern och Hallsberg har undersökts som en fallstudie. En förstudie av den planerade vattentunneln utifrån identifierade parametrar används för att föreslå en primär uttagsmetod. Ett definitivt svar på frågan om vilken drivningsmetod ska väljas är väldigt svårt.

Med avseende på geologiska förhållanden för vatten tunnel användning av TBM metod verkar vara ett lämpligt alternativ för vattentunnel. Den beräknade framdrifhastigheten för vattentunnel vid användning av TBM är ungefär 65 m/vecka och 39 m/vecka med D&B metod.

Undersökning av andra faktorer som påverkar tunneldrivningsmetod såsom utrustning parameter och byggprocess rekommenderas för att öka sannolikheten att vilken metod är mest lämplig.

Nyckelord: Utagsmetod, TBM, D&B, Geologiska parameter och framdrifhastighet.

Contents

2	Introduction.....	11
2.1	Background.....	11
2.2	Aim	12
2.3	Method	13
2.4	Limitation and focus	14
3	Driving method.....	15
3.1	Tunnelling Boring Machine.....	15
3.1.1	Gripper TBM	16
3.1.2	Single shield TBM	16
3.1.3	Double shield TBM	17
3.1.4	TBM performance	17
3.1.5	TBM Limitation	25
3.2	Drilling and Blasting Method	25
3.2.1	Drilling	27
3.2.2	Explosive	28
3.2.3	Ventilation	28
3.2.4	Rock Support	28
3.2.5	Grouting.....	29
3.2.6	Drill and blast Limitation	30
3.3	Calculation of cost and time for tunnelling project.....	31
3.4	Excavated material from tunnel.....	33
4	Geological Parameters	34
4.1	Mineralogy.....	35
4.1.1	Equivalent quartz content	36
4.2	Rock Types.....	36
4.3	Rock Mass Properties	38
4.3.1	Strength	40
4.3.2	Deformation	41
4.3.3	Discontinues	44
4.3.4	Groundwater	44
5	Summary of literature review	46

5.1	Comparison of two tunnelling methods.....	48
5.1.1	The Geometry factors.....	48
5.1.2	The Geological factors	49
5.1.3	The Economic factors	52
5.1.4	The environmental factors	53
5.2	Effect on operation's cost and time	54
6	Oslo - Skien Railway tunnel	56
6.1	Background.....	Error! Bookmark not defined.
6.2	Geometry.....	Error! Bookmark not defined.
6.3	Geological condition.....	Error! Bookmark not defined.
6.4	Factors affecting the choice of tunnelling method for Follo Line Project.....	56
6.4.1	The geometrical factors.....	56
6.4.2	The geological factors.....	57
6.4.3	The economic factors	57
6.4.4	The environmental factors	58
7	Vättern water tunnel.....	59
7.1	Geological condition.....	59
7.2	Comparison of tunnelling method for Vättern water tunnel.....	62
7.2.1	The geometry factors	62
7.2.2	The Geological factors	62
7.2.3	The time and cost factors	63
7.2.4	The environmental factors	67
7.2.5	Suggestion to primary excavation method	67
8	Conclusion and Recommendation	69

Table of Figures

Figure 1.1. The main parameters that influence the excavation method in tunnelling (Thuro, 2003).....	12
Figure 1.2. Different part of this thesis	
Figure 2.1. Two driving methods; TBM and D&B (Nyqvist, 2005)	15
Figure 2.2. Gripper TBM (2014).....	16
Figure 2.3. Single shield TBM (2014)	17
Figure 2.4. Double shield TBM (2014).....	17
Figure 2.5. Single disc cutter with steel ring (Bruland, 1998)	20
Figure 2.6. CLI for various rock types (Skawina, 2013).....	22
Figure 2.7. Drill and Blast cycle (Nath, 2014)	26
Figure 2.8. Activity cycle (Skawina, 2013)	26
Figure 2.9. Unit excavation cost, tunnel length 3 km (Zare, 2007)	31
Figure 2.10. Weekly advance rate, tunnel length 3 km (Zare, 2007).....	32
Figure 2.11. Hypothetical comparison of drill-and-blast and TBM advance rates in m/week (solid curves). Dotted curves represent monthly and yearly rates (Isaksson, 2002).....	33
Figure 3.1. Composition of igneous acid rock based on present quartz, feldspar and plagioclase (Iaden, 2008).....	35
Figure 3.2. Classification diagram enclosing 25 case studies of different rock types from 9 tunnel projects (Rundsch, 1997).....	38
Figure 3.3. Tangential stress in the roof of tunnel	43
Figure 3.4. Tangential stress in the wall of tunnel	43
Figure 4.1. Tunnel line between Oslo and Ski (2013)	46
Figure 4-2. Double tracks with cross-connection every 500 meters (2013) .Error! Bookmark not defined.	
Figure 5.1. Topography of rock tunnel from Vättern lake to the south of Hallberg (Ferbe, 2013).....	59
Figure 5.2. Geological map for the rock tunnel (Wallroth, 2012)	60
Figure 5.3. Advance rate of two tunnelling methods for Vättern tunnel	67

Preface

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Hanieh Aria

Notation

Roman upper case letters

TB	The Torque	[kNm]
UB	Applied operation voltage of the cutter head drive motors	[V]
RPM	Cutter head revolutions	[rev/min]
M_t	Applied thrust	[kN/cutter]
N_{tbm}	Number of the cutter on the cutter head	[-]
R_i	Radius to position of cutter number j	[m]
CLI	Cutter life index	[-]
I_m	Average net penetration rate	[m/h]
I_{nj}	Net penetration rate for subsection j	[m/h]
I_j	Length of subsection j	[m]
T_{bj}	Net time used to bore subsection j	[h]
M_{Bm}	Gross average thrust over a given tunnel length	[kN/cutter]
M_{Bj}	Gross average thrust over subsection j	[kN/cutter]
P	Penetration rate	[m/hr]
S_c	Rock compressive strength	[MPa]
W	Pulldown weight of drill	[t]
R	Drill rotary speed	[rpm]
D	Blasthole diameter	[mm]
$L_{b,roof}$	Rock bolt length in roof	[m]
$L_{b,wall}$	Rock bolt length in wall	[m]
D_t	Diameter or span of tunnel	[m]
D_b	Block diameter	[m]
W_t	Tunnel well height	[m]
I_u	Weekly advance rate	[m/week]
I_n	Average net penetration rate per week	[m/week]
T_b	Net time for boring	[h/week]
T_{ex}	Available time for tunnel excavation	[h/week]
T_{sh}	Shift hours	[h/week]
T_{rs}	Time for rock support work	[h/week]
V_{ch}	Chip size	[mm ³]
AR	Advance rate	[m/week]
PR	Penetration rate	[m/week]
U	Utilisation	[%]
I_s	Point load index	[MPa]
F	Applied load	[MPa · m ²]
D_e	Equivalent core diameter	[m]
E_m	Young's modulus	[GPa]
GSI	Geological strength index	[-]
A, B	Roof and wall coefficient for various excavation shape	[-]
K	Ratio horizontal/vertical stress	[-]

Roman lower case letters

$\cos \varnothing \cdot \eta$	Efficiency of the motors at the given amperage	[-]
n_m	Number of motors on the cutter head	[-]
k_c	The cutter coefficient	[-]
$d_{t_{bm}}$	TBM diameter	[m]
r_{mc}	Relative radius to the position of the average cutter position	[-]
y	Driving cost	[money]
k	The derivate of the function	[cost/m]
x	Tunnel length	[m]
m	Investments before driving	[currency]
u_a	Achieved machine utilisation per week	[%]
t_1	Machine hours at the start of the actual week	[h]
t_2	Machine hours at the end of the actual week	[h]
l_{ch}	Average length of the largest chip	[mm]
w_{ch}	Average width of the largest chip	[mm]
h_{ch}	Average thickness of the largest chip	[mm]
σ_c	Uniaxial compressive strength	[MPa]
σ_{or}	Tangential stress in the roof	[MPa]
σ_{ow}	Tangential stress in the wall	[MPa]
σ_z	Vertical virgin stress	[MPa]

1 Introduction

1.1 Background

Nowadays, the demand for tunnel projects is increasing. This increase is mainly due to increased demand for travel, and tunnels can also be used to transport water, sewage, and so mainly in urban areas. A tunnel is an efficient way to reduce traffic noise and high use of the urban site. There are different methods to excavate a tunnel in hard rock. The most commonly used method is the Drilling and blasting method (D&B). The Boring tunnel Machine (TBM) technic is another driving method mainly used during the 1970-1990s in Scandinavia. The development of the TBM method makes excavation easier, especially for a long tunnel with various rock conditions. TBM method was used in different tunnel projects in Scandinavia in hard rock. This method can overcome the most challenging rock condition, such as water-bearing and different ground rock masses (Rundsch, 1997).

TBM method has not been used in many years, but now it is on the way back, and it will be used in Norway for a railway tunnel between Oslo and Skein. In this project, the Oslo-Skien tunnel will be studied as an example of a tunnelling project that was recently designed and will be excavated by the TBM method. This tunnel will be about 35 km for a high-speed twin-track railway.

Excavation in underground and tunnelling depends on different parameters. The key parameters that influence the tunnelling method are the geological parameter, equipment parameter and working process. Planning and investigation of these parameters are required to make a preliminary choice of tunnelling method. The geological and hydrogeological conditions determine which tunnelling method is best to use (Isaksson, 2002). The other essential parts of tunnelling that consider the tunnelling method are the project's time and cost (Rundsch, 1997).

Figure 1.1 shows the main parameters which influence the excavation method in the tunnelling process; equipment parameters such as drilling bit, bit power, net penetration rate, applied cutter thrust, torque, machine utilisation, etc. (Thuro, 2003). The geological parameters include mineral, rock and rock mass, and construction parameters such as construction time, cost, maintenance, risk distribution between the parties, tunnel length, cross-section shape, and size (Rundsch, 1997).

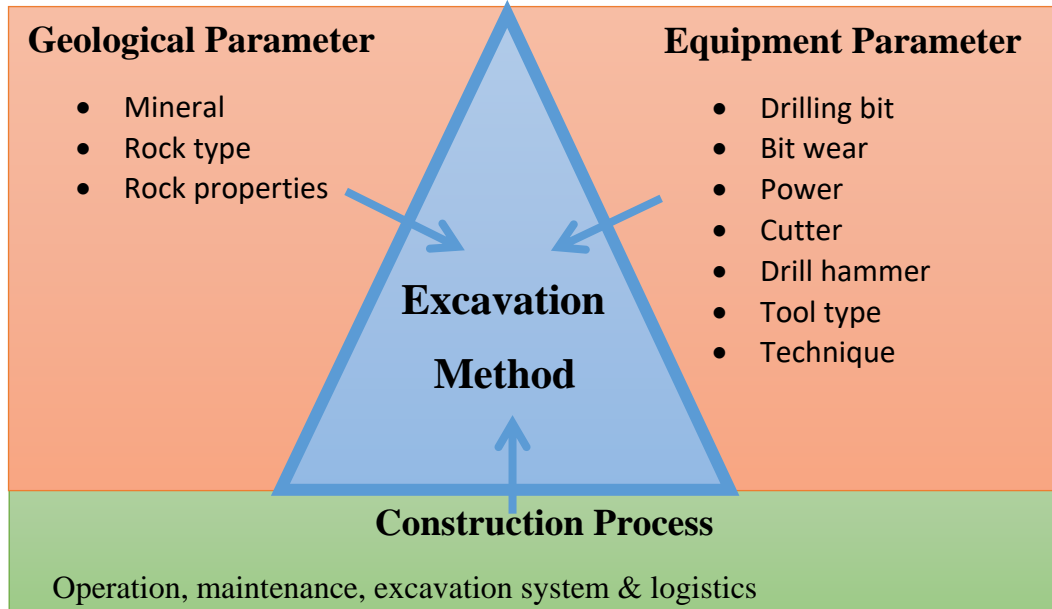


Figure 1.1. The main parameters that influence the excavation method in tunnelling (Thuro, 2003)

Geological parameter, Equipment parameter, and constructions process are terms that influence excavatability, all these parameters presented in figure 1.1 affect the performance of the tunnelling method. This thesis will study how geological parameters influence the preliminary choice of tunnelling method and how a suitable excavation method depends on the geological condition.

The most critical factors that should be considered in determining the tunnelling method are geological parameters. The other essential elements are environmental and economic. The timing of the tunnelling method includes some uncertainties that can affect the whole tunnel project. These uncertainties are known from previous projects and based on gained experiences, i.e. there is no exact value for these uncertainties (Nyqvist, 2005).

A water distribution tunnel is planned from lake Vättern to the south of Hallberg with about 35 km. The comparison of the tunnelling method will be used in this thesis to suggest the most suitable primary excavation method for this water tunnel concerning the geological condition.

1.2 Aim

This project aims to provide a decision basis to suggest the most suitable method to excavate a tunnel in hard rock. There are thus three overall objectives of this thesis:

- A comparison between two driving methods, Drilling and blasting (D&B) and Tunnel Boring Machine (TBM), with a focus on the geological parameter
- Study of a recently designed Oslo-Skien tunnel project that TBM will excavate to learn how and why the choice is.

- We are applying the findings on a planned water tunnel excavated from Vättern lake to Hallsberg to suggest the primary excavation method based on the geological condition. The comparison of the two tunnelling methods will be based on a performed literature review. The literature study was carried out to provide basic and advanced knowledge about these tunnelling methods to create a list of the most critical parameters influencing the tunnelling method.

In this thesis, the Oslo-Skien tunnel will be used as a practical example of the TBM method to discuss the choice of tunnelling method and the reason behind why the TBM method was chosen for this specific project.

The water tunnel between Vättern lake and Hallsberg will be used as a case study in this thesis. The key parameters that resulted from comparing two excavations methods plus discussion of the tunnelling method of the Oslo-Skien tunnel in pre-study will suggest a primary excavation method for this planned water tunnel.

The result of this report should give the key parameters that have to be decided to determine the most suitable excavation method.

1.3 Method

To fulfil the purpose of this thesis, a literature review and a deductive study on a case study appear to be the best method. The methodology parts of this thesis are presented in Figure 1.2.

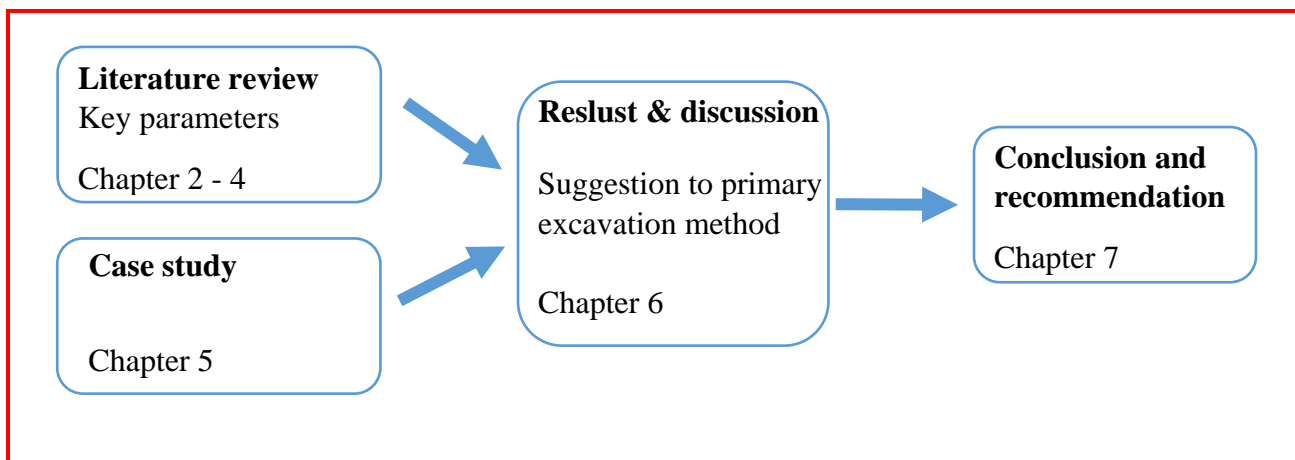


Figure 1.2. Different part of this thesis

The central part of this thesis is a literature review about the two driving methods to clarify and define these two methods and compare them with each other. This is to define these two methods and compare them with each other. This is to gain more understanding of the various processes involved for the two methods. The comparison is made by identifying the most critical parameters that affect the tunnelling method. Geometry, geological, environmental, time and cost are assumed to be the essential parameters and the literature study thus focus on these parameters

in this project.

In chapter 2 describes how to calculate excavation time and cost. These mathematical methods require all values/ data. In this thesis, all values are not available, and in this case, the comparison will be based on the experience of some tunnelling projects and the study of the geological condition.

The outcome of the literature study and case study will provide a theory about how the choice of tunnelling method is made and lists of critical parameters focusing on geological conditions.

1.4 Limitation and focus

This thesis will analyse geological parameters such as mineral, rock types, and rock mass properties. The rock types that will be reviewed in this thesis are the most common Scandinavia rock types. The selected parameters are chosen based on the expected influence on the tunnelling method. The study is limited to tunnelling in hard rock only.

The tunnelling method for the Vättern tunnel will be a preliminary suggestion due to limited data collection. However, the recommended excavation method will be based on available information regarding geometry, geological, environmental and economic factors.

2 Driving method

There are different methods for excavating tunnels in hard rock. These methods can be divided into conventional drilling and blasting (D&B) and full-face boring machine (TBM).

The conventional method is the traditional method that is driven by drilling and blasting. This method has been used and developed for more than 350 years (Nyqvist, 2005).

TBM was a development of the tunnelling method at the start of the 19th century, which is a machine for driving tunnels in hard rock and bore the whole face of the tunnel in the circular cross-section (Maidl, 2008).

Figure 2.1 presents these two driving methods; TBM and D&B (Nyqvist, 2005). TBM is a single machine with different parts such as grouting, support, and ventilation, but the D&B method has other devices for these different parts.

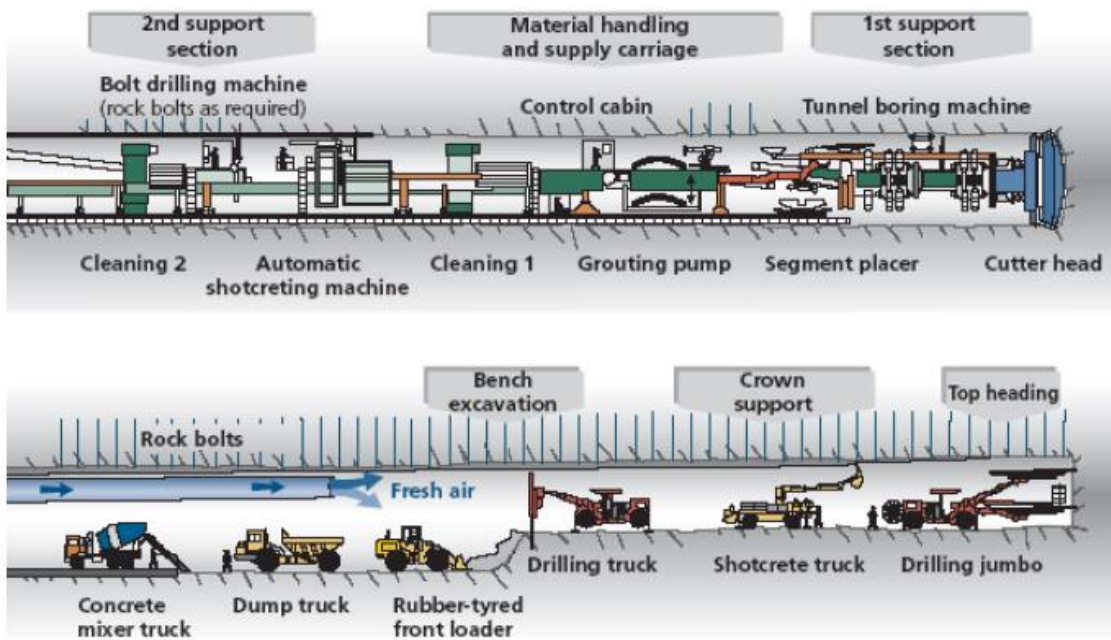


Figure 2.1. Two driving methods; TBM and D&B (Nyqvist, 2005)

2.1 Tunnelling Boring Machine

TBM is a vast machine and works by boring the entire tunnel area in the hard rock. This machine bore circular through with rotary full-cut cutter head. TBM machine uses the rotation of the cutter head and the blade pressure to excavate the stone.

The essential element of the TBM machine is the cutter head with driving motors (Maidl, 2008). This method bore the entire tunnel section in one step and worked without explosion (Lindblom, 2010). Today different types of these machines are in use for tunnelling projects. Additional

classification and geology conditions require other tunnel boring machines. The most commonly used machines in hard rock are; the Gripper TBM, single- and double shield TBM (Maidl, 2008).

2.1.1 Gripper TBM

This machine presses the grippers against the wall of the excavated tunnel and pushes the cutter head frame against the rock surface, which showed in Figure 2.2. This machine can bore a tunnel from 2 up to 12,5m diameter (2014). The gripper loosened during moving operation by hydraulic cylinder and required a free tunnel wall (Maidl, 2008).

Tunnelling with Gripper TBM has been an efficient solution for tunnelling in hard rock. This TBM machine is a good choice when the face is self-supporting. Like other TBM machines, the Gripper TBM has a rotating cutter head with disc cutters to excavate a tunnel. The cutter head is forced against the rock with a series of pressure up to 32 tones per disc. The cutters head break the rock into single pieces called chips. The falls are then transported by the number of buckets, which are installed behind the cutter head. The buckets take up the excavation material out of the tunnel into the final transportation system (2014).

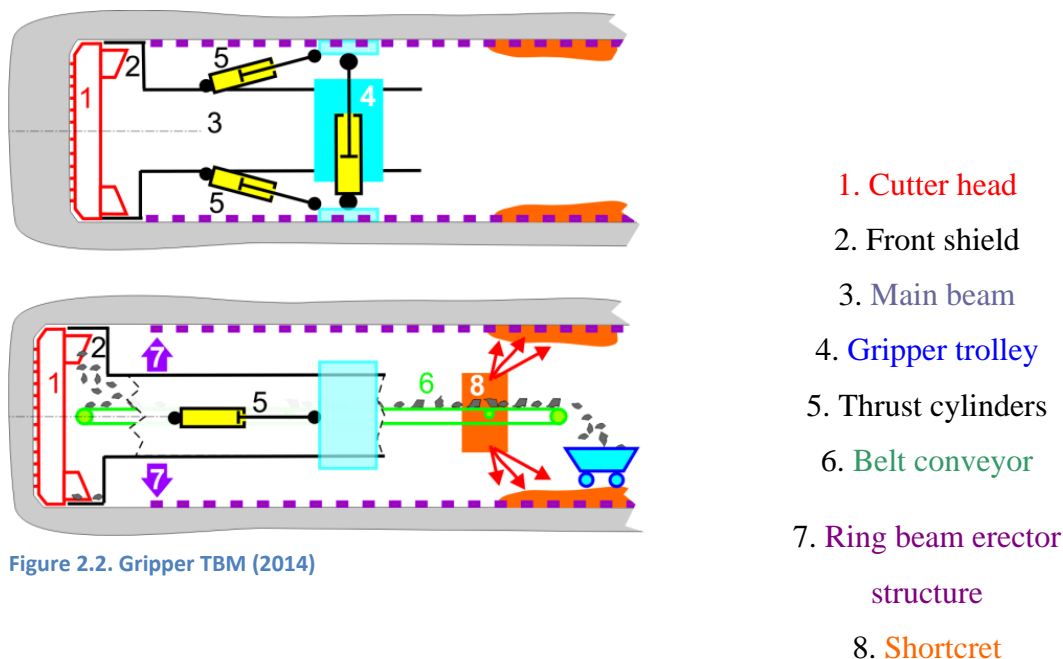
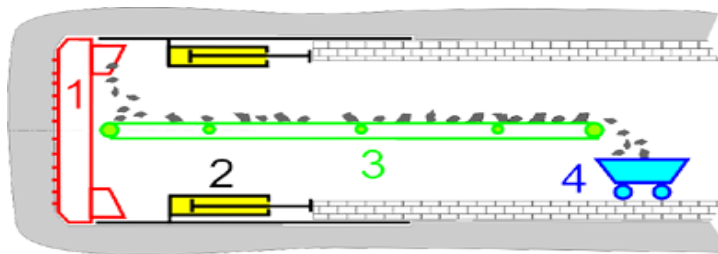


Figure 2.2. Gripper TBM (2014)

2.1.2 Single shield TBM

The single shield machine is usually used for hard rock with a short stand-up time. This machine can bore a tunnel from 1,5 to 14 meter, and the cutter head, excavation tool and transport system is not different from Gripper TBM. This method uses usually reinforced concrete segments for a support system. As shown in Figure 2.3, the thrust jacks in this machine thrust forward directly against the existing support in a tunnel, which is in contract with the gripper TBM. Applying backfill in both shield machines is essential to ensure stability (Herrenknecht, 2014).



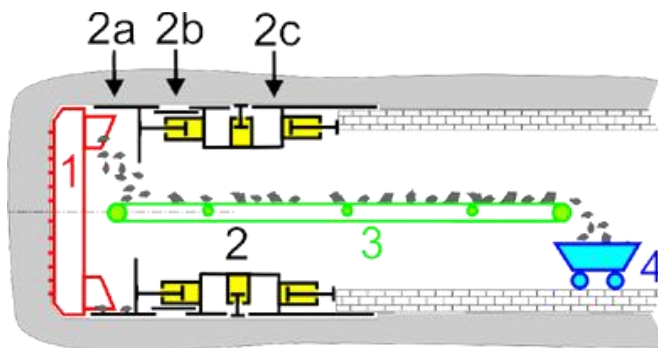
1. Cutter head
2. Shield
3. Belt conveyor
4. Excavated material removal trolley

Figure 2.3. Single shield TBM (2014)

2.1.3 Double shield TBM

The double shield TBM is used in fractured rock with low stand-up time. The excavation diameter with this machine is 2,8 to 12,5 meters and consists of two main components; the front shield and gripper shield, which is on the rear part of the machine. These two shield parts are connected by telescopic jacks (2014).

As shown in Figure 2.4, this machine is driven by using clamp units from gripper shield clamps itself and helping the front shield thrust forward the machine, and these two shields work without influencing each other. The gripper shield may block by using the fractured rock with high strength because the material can be getting in the telescopic joint, but the blocking and jamming are different (Herrenknecht, 2014).



- 1) Cutter head
- 2) Shields
 - a) Front shield
 - b) Double shield
 - c) Rear shield and gripper
- 3) Belt Conveyor
- 4) Excavated material removal trolley

Figure 2.4. Double shield TBM (2014)

2.1.4 TBM performance

The performance of TBM machine has four systems; boring system, thrust and clamping system, muck removal system and support system (Maidl, 2008).

2.1.4.1 Boring System

The boring system is the most critical part of the machine performance. The boring system consists of a disc cutter and cutter head. There are different types of discs and cutting tracks depending on the rock type. The cutter head presses the discs against the rock with high pressure to cut the rock (Maidl, 2008). When the cutter head rotates and, at the same time, demands the rock, the forces from discs become high until they cross the rock (Lindblom, 2010).

The net penetration rate is calculated using the total machine hours that bore the actual tunnel length and is influenced mainly by rock properties and machine parameters. Calculating penetration rate may help determine the time needed for excavation of tunnel and determine which excavation method will have the shorter operation time. In this project, the operation time will be calculated in a pre-study using the same old projects and the graph described in the next chapter. By the following equation, the net penetration rate is calculated in case of the available value or data that is needed to decide the net penetration time (Bruland, 1998):

$$I_m = \frac{\sum l_j}{\sum T_{bj}} = \frac{\sum l_j}{\sum (l_j / I_{nj})} \quad (m/h) \quad (2.1)$$

Where

I_m = average net penetration rate (m/h)

I_{nj} = net penetration rate for subsection j (m/h)

l_j = length of subsection j (m)

T_{bj} = net time (machine hours) used to bore subsection j (h)

Table 1 shows the output for scheduling of a typical TBM tunnel. The data are from CSM/EMI computer model for hard rock with TBM. The model utilized the semi-theoretical formulas (Cigla, 2011). Tables 2.1 and 2.2 present the typical output of the tunnelling project with the TBM method. These values showed how different factors such as rock type and geometry of the tunnel influence the advance rate of the technique. According to Table 2.1, the tunnel with rock type sandstone has a higher advance rate than the other tunnels. The geometry of the tunnel also has an impact on the advance rate. For example, according to Table 2.1 1, two tunnels with the same rock type has a different advance rate, and this may be based on the length of the tunnels that affect the machine utilisation and the advance rate. The tunnel with a longer length has a higher advance rate, and usually, the TBM method is more suitable for long tunnels.

Table 2.1. An example of CSM/EMI model output for a typical TBM tunnel (Cigla, 2011)

Rock type	Length [m]	Slope [%]	Machine utilisation [%]	Advance rate [m/day]
Sandstone	2550	1	35	16.3
Granite	1563	1	30	5.0
Gneiss	447	1	25	3.8
Gneiss	1524	1	30	4.5

Table 2-2 present the details of TBM operation in granitic rock. This project's main delay and breakdown were from cutter replacement and conveyor (Delisio, 2012). The present of Table 2-2 is an overview of the usual output data of the TBM method for typical Scandinavian rock types.

Table 2.2. Details of the TBM operations (Delisio, 2012)

TBM performance	
Total excavated length (m)	176.1
Total time (h)	430.0
Excavation time (h)	130.6
Utilization factor (%)	30
Net advance rate (m/h)	1.3
Standstill time (h)	175.5
Time for rock supporting (h)	123.8
Total advance rate (m/day)	9.8

2.1.4.2 Cutter

The quality of cutter material influence the penetration time and cutter life, and by developing cutter material and cutter head design, the penetration time and cutter life will improve. Cutter geometry as diameter and tip width are also important parameters.

The most used cutter is the single disc cutter with a constant cross-section steel ring and about 394 mm. As presented in Figure 2.5, a typical single disc cutter consists of a removable cutter ring with split ring, hub, two conical bearings, sealing and shaft with retainers.

The number of the cutter depends on TBM diameter and cutter diameter, and by smaller TBM diameter, the available cutting space is less on the cutter head (Bruland 1998).

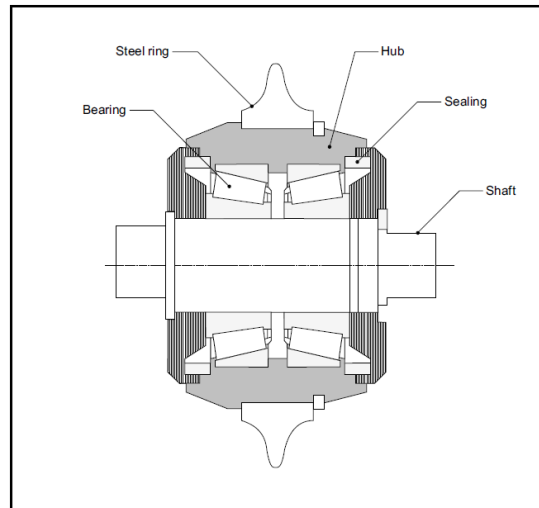


Figure 2.5. Single disc cutter with steel ring (Bruland, 1998)

2.1.4.2.1 Torque

The required torque to rotate the cutter head depends on the diameter of the cutter head, the number and position of the cutter, the gross trust and cutter coefficient. Calculation of torque and cutter coefficient will determine TBM performance, i.e. how long (time) and cost the method will take depending on the geological condition. In this project, the performance of TBM will be determined using some old TBM projects. The following Equations, 2.2 and 2.3, present how to calculate the torque and cutter coefficient for the project the value and data are accessible (Bruland, 1998).

$$T_B = \frac{U_B \cdot I_B \cdot \sqrt{3} \cdot (\cos \phi \cdot \eta) \cdot 60 \cdot n_m}{T_{wo} \cdot \pi \cdot 1000 \cdot RPM} \quad (kNm) \quad (2.2)$$

Where

U_B = applied operation voltage of the cutter head drive motors (V)

I_B = applied amperage (A)

$\cos \phi \cdot \eta$ = efficiency of the motors at the given amperage

n_m = number of motors on the cutter head

RPM = cutter head revolutions (rev/min)

The cutter coefficient is the ratio between the thrust and drag force on the cutter. The following equation calculates the cutter coefficient.

$$k_c = \frac{U_t \cdot I_t \cdot \sqrt{3} \cdot (\cos \phi \cdot \eta) \cdot 60 \cdot n_m \cdot 2}{TWO \cdot \pi \cdot d_{tbn} \cdot r_{mc} \cdot M_t \cdot 1000 \cdot N_{tbn} \cdot RPM} \quad (2.3)$$

Where

d_{tbn} = TBM diameter (m)

r_{mc} = relative radius to the position of the average cutter position

M_t = applied thrust (kN/cutter)

N_{tbn} = number of the cutter on the cutter head

$$r_{mc} = \frac{\frac{\sum_{i=1}^{N_{tbn}} r_i}{N_{tbn}}}{0.5 \cdot d_{tbn}} \quad (2.4)$$

Where

R_i = radius to position of cutter number j (m)

TBM cutter wear influence the advance rate by causing more time and cost, cutter wear is usually determined mainly through rock abrasiveness and rock mass fractures measured by CLI (Cutter Life Index), mineral content and parameter. CLI influences the rock drillability and changing the disc cutter affect the cycle time and the cutter wear, which controls the advance rate. Figure 2.6 shows the CLI for some rock types (Skawina, 2013). CLI parameter defines the rocks potentiality to wear the cutter disks. Together with the quartz content of the rock, CLI can obtain an accurate estimation of the time and cost of the tunnel project (Oggeri, 2012).

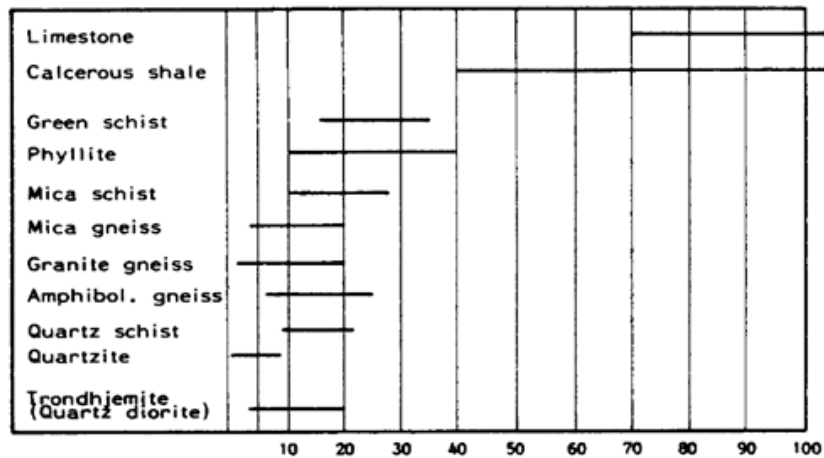


Figure 2.6. CLI for various rock types (Skawina, 2013)Cutter Life Index CLI

The CLI expresses the life of the TBM cutter in drilling hours, as presented in Figure 2.6. The typical range of variation of CLI for gneiss is relatively tiny, between 15 ± 25 . At the same time, it is much more significant for phyllite or mica-schists. With low CLI, it would have been possible to reduce the drilling time of tunnel construction, which also influences the cost of the tunnel (Oggeri, 2012). The cutter's life also depends on the quartz content, and in the calculation of cutter life derived from CLI, the quartz content has to be included as a correction factor. Estimation of Equivalent quartz content will be presented in the next chapter (Bruland, 2000).

In this thesis, calculation of torque and cutter coefficient is not possible because required values are not available, but by use of Figure 2.6, the performance of TBM will be determined.

2.1.4.3 Thrust and Clamping System

The thrust and clamping system consists of a drive unit, which thrust forward the cutter head with the required pressure by hydraulic cylinder, and the thrust must resist the moments created by drilling progress. The gross average thrust can be estimated as a function of cutter diameter and TBM diameter. The thrust level is limited by the cutter ring, i.e. the cutter quality influences the thrust capacity. The low gross thrust provides low cutter penetration against the rock, which affects the cost and delay (Bruland, 1998). This system involves the performance of the TBM machine and is responsible for the drilling process (Lindblom, 2010).

The gross thrust force is calculated from hydraulic pressure in the proper cylinder. The gross thrust should be calculated at the same period and the same tunnel section as the net penetration rate (Bruland, 1998). Calculation of gross thrust also helps to determine the performance of TBM.

$$M_{Bm} = \frac{\sum(M_{Bj} \cdot T_{bj})}{\sum T_{bj}} \quad (kN/cutter) \quad (2.5)$$

$$T_{bj} = \frac{l_j}{I_{nj}} \quad (h) \quad (2.6)$$

Where

M_{bm} = gross average thrust over a given tunnel length (kN/cutter)

M_{Bj} = gross average thrust over subsection j (kN/cutter)

T_{bj} = net time machine hours for boring subsection j (h)

l_j = length of subsection j(m)

I_{nj} = net penetration rate of subsection j (m/h)

2.1.4.4 Muck and Removal System

The cross rock material collected in front of the TBM machine must be transported out of the tunnel. The buckets are monitored on the cutter head to pick up the excavation. Different muck removals systems depend on local conditions. These other removal systems are such as rail system, conveyor system and trackless system. The area that needed for these different removal systems applications vary according to the location. After the investigation the contractor chose the one due to the tunnel's properties. The removal system should not lead to any interruption of the advance rate (Maidl, 2008).

The gradient is essential in the rail system, and the maximum slope is 3% (Maidl, 2008). If the gradient increases, the performance reduces sharply. Rail transport is vulnerable to interruptions in the system but it is still a useful method for small cross-sections with long lengths. The muck cars used in the rail system have a capacity from 2,5-20 m³ (Maidl, 2008).

In some locations that rail or conveyor systems are not possible a trackless system will be chosen and this system simplifies several processes for the operation, larger dump trucks are used instead

as an alternative solution. This system requires increased attention for daily preparation. Other transportation vehicles can be used in this system. However, it should be considered that the vehicles constructed for the tunnelling projects have suitable engine performance and do not require high ventilation equipment, which may benefit the project performance. The haul road should have an asphalt surface (which is not usual in an ordinary project) to enhance the cars' performance, i.e., increased operation time. (Maidl, 2008)

To ensure continued operation without interruption, the stacking silos must be installed in the TBM backup for the muck's temporary stacking. The loading equipment should be prepared with adequate equipment to reduce the dust cloud from the loading of dry material (Maidl, 2008).

The conveyor system can be even tunnelled up to a 5% gradient (Maidl, 2008), but this method has a low belt speed. The breadth of the belt should be more significant than 800 mm to reduce the probability for blockage of large chunks of rock, and about 650 mm is the minimum for smaller TBM (Maidl, 2008).

With its continuous operation, this system increases the performance and higher transport compared with dumper, which has intermittent transport. The investment is higher for a conveyor system than for a dumper operation, but the overall wage cost is less. About 60% of driving in a tunnel by the trackless system is unnecessary, and the cost of conveyor operation is 25% less than with dumper without including the reduction of ventilation equipment (Maidl, 2008).

The muck removal by conveyor system may also cause some problems as blockage by a large block of stone, and a problem can arise with excessive water inflow at the face of the cutter head and lead to blockage (Maidl, 2008).

2.1.4.5 Support System

After the mucking, the primary support system is installed. This installation of rock support is necessary at the right time to protect the workers and equipment from injury and damage by falling rocks and collapsing.

The support system in TBM tunnelling is different in comparison to D&B tunnelling (Maidl, 2008). The initial support in the TBM method is usually installed concurrently with excavation and support installed as the TBM machine moves forward; hence the initial ground support is like a cyclic process. The initial support may consist of steel ribs, lattice girders, shotcrete, or rock bolts. The function of initial support is to reinforce the rock. By use of this method helped the rock mass to support itself. It is more economical to strengthen the rock mass than support it. By increasing the rock quality, the required initial ground helps decrease (Williams, 1997).

A fault zone in front of the cutter head needed to secure by using advanced support methods as bolts, piles, grouting and even freezing. The support system is contracted to high advance time, i.e. support system takes more of the available time for boring, and the advance rate will fall by increasing the requirement for support (Maidl, 2008).

2.1.5 TBM Limitation

The TBM method is not economical for short and medium-long tunnels due to the time needed to start boring after signing the contract. This long time, which may take from four months to one year, depends on the manufacturing of the TBM and backup and transport to and assembly at the site (Maidl, 2008).

The TBMs diameter is also one parameter that is important for excavation (Maidl, 2008). Tunnelling in small (smaller than 2 m) diameter with TBM is challenging to equip for installing support system and ventilation system (Williams, 1997).

There are limitations to the curve radius for the TBM machine. This limitation depends on the TBM its size and backup, the minimum size of the curve radius is 40-80m and the minimum radius for backup equipment is almost 250-450m but varies depending on TBM type (Holen, 1994). The slope of the tunnel also effects the tunnelling method, the TBM method has little slop and operation at any slope is not possible, the maximum tunnel slope is 5% (2014).

There are different types of TBM machines due to their function in different environments. For example, the gripper TBM machine is sensitive against the large groundwater flow, but the shield TBM can work in most environments (Nygqvist, 2005). The TBM method usually has a lower negative impact on the environment than the drilling and blasting method. The vibration from the TBM method felt in the very immediate area in the form of the noise. The limited space is from 50 to 150 m.

There is no standard form of contract, tendering or awarding for tunnelling operation with TBM. Most of the contracts are adapted with experience (Maidl, 2008).

TBM require low ventilations tools compared to the D&B method; therefore TBM method usually uses electricity, and the dust of the drilling is generally shallow. (Maidl, 2008)

2.2 Drilling and Blasting Method

The D&B is the most usual method in a very long time and is commonly used for industry excavation in hard rock. This method is more economical in hard rock with high abrasive material. The D&B process is a cycle work. This method uses explosives for excavation and is suitable for hard rock with complex outlines and geometry (Zare, 2007). As presented in Figure 2.7, the cycle includes drilling and surveying, charging with explosives, blasting and ventilation, loading and hauling, scaling and cleaning, rock bolting and grouting (Nath, 2014).

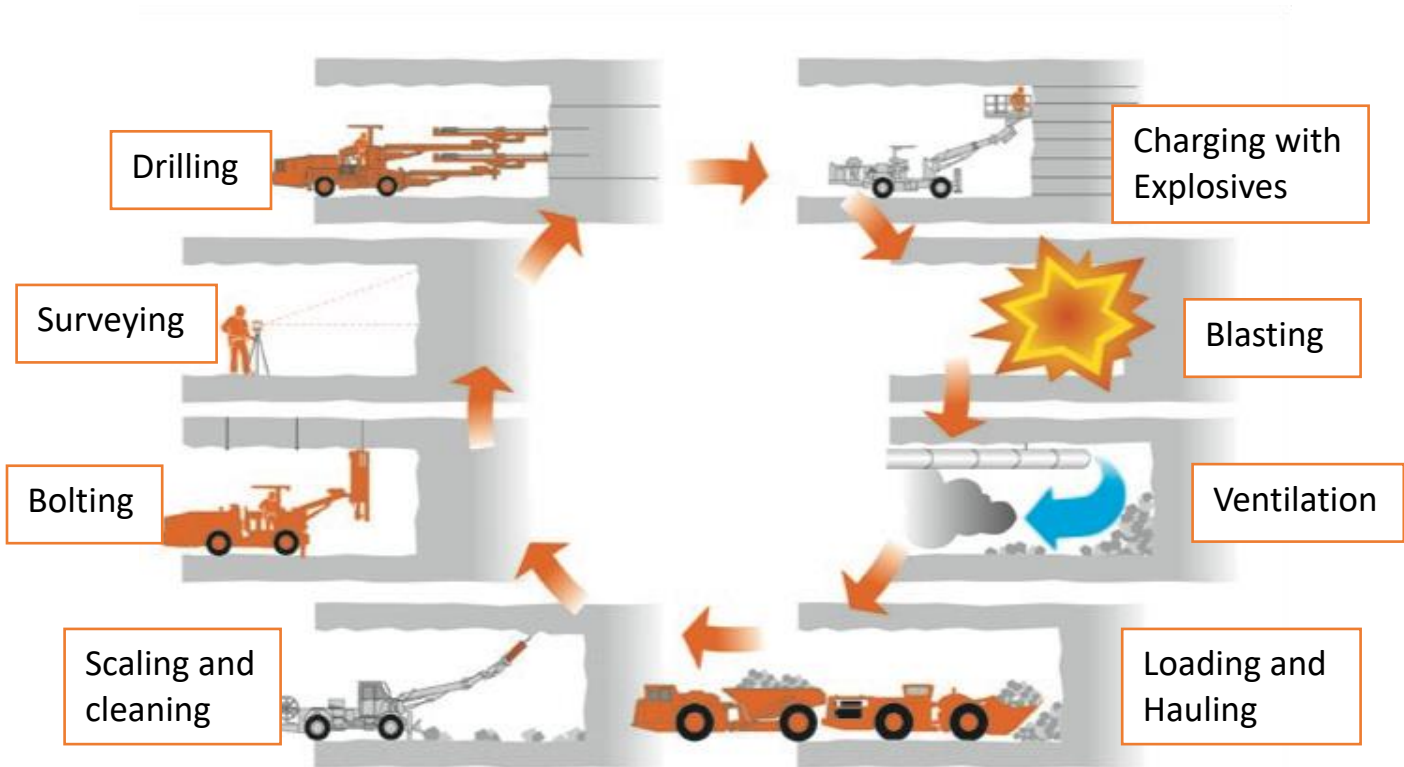


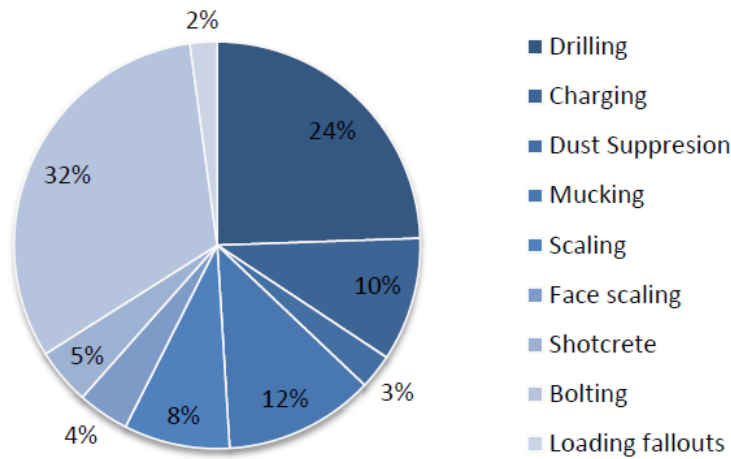
Figure 2.7. Drill and Blast cycle (Nath, 2014)

Some main parameters influence the drill and blast operation, such as rock condition, equipment performance and tunnel crew skill level. The properties of rocks are essential for the blasting process as a structure of fissures, bedding planes, cracks, faults (Persson, 1993).

A drill and blasting method has been investigated to estimate the typical value and percentage for each part in the drill and blast cycle of performance rate (drilling, charging, ventilation, etc.), shown in Figure 2.8. In this investigation, the machine drilled 85 holes per blast with around 30 m² cross-section. The length of the drill holes was 5 m, and the dimensions of the tunnels were 6 x 6 m (Skawina, 2013). As presented in Figure 2.8, process drilling and bolting consume a significant amount of time, leading to a higher tunnel project cost. These processes, drilling and bolting, directly depend on the geological condition. Studying the rock geological condition before excavation is maybe able reduce the time of these processes.

Figure 2.8. Activity cycle (Skawina, 2013)

Activity Cycles



2.2.1 Drilling

Drilling is the first cycle process, and there are different ways of drilling, such as hammer drilling and rotary drilling (Skawina, 2013). Drill and blasting methods have during the past decades developed and mainly in drilling and explosives. This development improved the performance and capacity of tunnelling. The cost of drilling depends on the penetration rate, and rock characterises and depends on the depth and size of the drill hole (Zare, 2007).

Penetration rates vary depending on drilling, and according to Figure 2.8, drilling takes extra time compared to the other processes. Therefore calculation of penetration rate determines the drilling and blasting method (Amund, 1998). In this thesis, the values are limited and are not available to calculate the penetration rate. Therefore estimation of penetration rate is based on values of some old tunnel projects.

Calculating penetration rate depends on different parameters such as impact energy imparted to the bit, frequency of impacts, feed pressure, rotational speed, drill bit type, and rock mass properties (Bruland, 1998). The penetration rate equation comes down:

$$P = (214\ 98 \log_{10}(0,145S_c) WR/(250D)) \quad (2.7)$$

Where:

P = penetration rate (m/hr)

S_c = rock compressive strength (MPa)

W = Pulldown weight of drill (t)

R = drill rotary speed (rpm)

D = hole diameter (mm)

2.2.2 Explosive

The second process in the cycle is charging and blasting. There are two common explosives used in the charging process, such as ammonium nitrate fuel oil and different types of emulsion. The emulsion explosive with a non-electrical initiation system like NONEL has increased and is more safe and effective. The new and modern emulsion explosive produces a minimum of toxic, provides a better operation condition and is water-resistant. This explosive reduces time consumption, improves worker safety, and has adverse effects such as ground vibrations, air shock, fly-rock, and noxious gases (Zare, 2007).

2.2.3 Ventilation

Ventilation takes place next to get rid of toxic gases and harmful particles. The toxic particles and gases created by the drill and blast method in the tunnel call Suspended Particulate Matter (SPM) and have to remove by a ventilation system and by using an intelligent ventilation system to reduce the cost and the impact on the environment (Zare, 2007).

2.2.4 Rock Support

There are two main types of rock support, rock bolts and sprayed concrete. These two types of supports developed towards stronger, high strength and quick installation. The rock support depends on the rock condition.

The typical length of rock bolts is about 2-4 m with a 20-25 m diameter. The dimensions of the bolts are often designed according to the rock mass condition. The following equations can estimate the length of bolts in roof and wall (Palmström, 2010).

$$L_{b,roof} = 1.4 + 0,175 D_t (1 + 0,1/D_b) \quad (2.8)$$

$$L_{b,wall} = 1.4 + 0,1(D_t + W_t) (1 + 0,1/D_b) \quad (2.9)$$

Where

D_t = diameter or span of the tunnel

D_b = block diameter

W_t = tunnel well height

The second method of rock support is shotcrete. This method is obtained by spraying concrete. There are three different types of shotcrete methods; wet or dry mix, net reinforced shotcrete and fibre-reinforced shotcrete, and the fibre creates the most common practice in Scandinavia (Palmström, 2010). The modern equipment for sprayed concrete is the sprayed concrete robot, which applies the poured concrete (Zare, 2007). Table 2.3 presents some bonds measured between shotcrete and different rock types. According to Table 2.3, rock types like sandstone or marble consume great shotcrete, but more challenging rock types like gneiss require less rock support.

Table 2.3. Bond measured between shotcrete and different types of rocks (Norwegian Concrete associate, 1999)

Type of rock	Rough rock surface (Bond: MPa)	Rupture plane (Bond: MPa)
Shale	$0.24 \pm 0,18$	$0.28 \pm 0,11$
Gneiss \perp foliation	1.53 ± 0.28	1.8
Gneiss // foliation	$0,19 \pm 0.05$	$0.51 \pm 0,11$
Sandstone	> 1.8	> 1.8
Marl	1.49	1.84
Limestone	$1.58 \pm 0,12$	1.54 ± 0.30
Marble	1.38 ± 0.30	1.52 ± 0.28
Granite/diorite	1.48 ± 0.45	$1.71 \pm 0,14$
Gabbro, diabase	1.56 ± 0.25	1.7

2.2.5 Grouting

Tunnel construction creates a pressure gradient that impacts the groundwater direction, and the gradient leads the groundwater towards the cavity (Eriksson, 2014). During the tunnelling is vital to reduce the ground water inflow. During tunnelling, there are different parameters affected by groundwater inflow as work environment, pump cost and equipment for backup, and the

maintenance of the tunnel also depends on the water inflow (Svebefo, 2006). There are usually two types of grouting, pre-grouting and post-grouting. Post grouting is not usual in the Scandinavian rock type (Zetterlund, 2014). Post-grouting is used after the construction in case of too high inflow and, compared to pre-grouting, is more challenging to perform (Hernqvist, 2011).

Grouting rock in Sweden is generally more challenging than in other countries to seal the tunnel and the cavern towards water inflow and reduce the ground water reduction (Zetterlund, 2014). The law in the form of an environmental ruling governs these requirements (Svebefo, 2006).

By grouting method is possible to seal even the fractures that are difficult to detect in the site investigation. The grouting method is essential from both an economic and environmental point of view. The grouting is usually cement grouting and consists of different equipment such as a stirring device, colloid mixture and grouting's pump (Svebefo, 2006).

2.2.6 Drill and blast Limitation

The excavation speed is limited, and it's the most significant disadvantage of this method, together with sound and vibration pollution from explosives (Holen, 1994). The use of the blasting method in a small area is limited, and the site should be at least 15 m² (Zetterlund, 2014).

The drilling and blasting method requires more ventilation in comparison to the TBM method. This needed ventilation removes the gas and dust from blasting and work vehicles that use diesel fuel. Maintenance is also required more in the blasting method. According to explosive, the fracturing increase and the uneven surface after blasting process, the demand for tunnel maintenance increase (Zetterlund, 2014).

2.3 Calculation of cost and time for tunnelling project

The capital cost for the tunnelling method varies depending on the excavation method. The capital cost is much higher with TBM than D&B, which may depend on the geology condition. The excavation cost is just a part of the total capital cost, and due to the high price for the TBM method, excavation of short tunnels is not economic (Holen, 1994). The excavation cost for tunnelling is usually depending on the cross-section area and geological condition. The civil and transport engineering department at NTNU has published models for design, advance rate and excavation cost estimation with TBM and D&B methods.

Figures 2.9, 2.10 and 2.11 presented the advance rate and excavation cost for both methods on different rock conditions and portability. The advance rate is 101 working hours per week for tunnels with 3 km length with 3.5, 6 and 9 m TBM. The rock support is not included in the advance rate because the rock support depends on the rock mass and tunnel application (Zare, 2007).

The excavation cost of the D&B method may depend on some other factors such as the holes number, the consumption of explosives and the wear of drilling steel. The excavation cost for the TBM method is usually higher, as presented in Figure 2.9 and varies a lot with the D&B method. Rock quality also affects the cost of the operation. TBM method cost is more dependent on rock quality compared to the D&B process. Therefore, the excavation cost of the D&B method varies little with different rock conditions presented in Figure 2.9 (Zare, 2007).

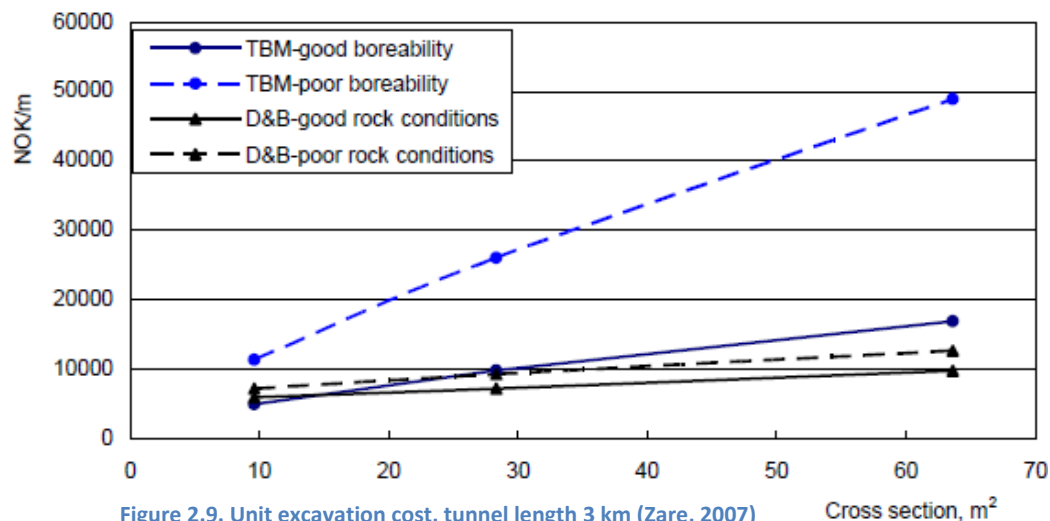


Figure 2.9. Unit excavation cost, tunnel length 3 km (Zare, 2007)

The total cost of the project is estimated in two stages; the pre-project status and the construction phase. The estimation is based on experience in the first stage, and the estimation accuracy is 25%. The cost of different project processes is calculated in detail in the construction phase, as machine cost, support system, installation, lining, material prices. The accuracy of this calculation is only 10% (Holen, 1994).

Estimation of the cost due to wear out of the equipment is needed to calculate the wear cost. Calculation of wear cost depends on the cutter quality, hardness of the rock and how often the cutters have to be changed. The high cutter wear increases the wear cost, which affects the driving price (Nygqvist, 2005).

The lifetime cost of the tunnel varies depending on the excavation method. Usually, the TBM method has a lower lifetime cost. This probably depends on whether the excavation method requires lower tunnel maintenance and a smooth final profile. For the drilling and blasting method, the lifetime cost depends on the water and frost installation in the tunnel. Still, usually the maintenance and final profile lifetime cost is higher (Zetterlund, 2014).

The tunnelling project's total time depends on the excavation method, and different processes and parameters in each method influence the time. The total time with the D&B method is usually longer than the TBM method. This may be because of the high advance rate the TBM method has. According to Figure 2.8, activity cycle, rock support consume great time 32% (Skawina, 2013) in D&B strategy, maybe rock support influences that this method has longer total time. Different parameters influence the drilling time, such as the number of holes, drill hole diameter, drill hole length, type and number of rock drills and the rock type Drilling Rate Index (DRI). Three factors determine Drillability's drilling rate, bit wear and bit life (Persson, 1993).

As presented in Figure 2.10, the advance rate increased by changing portability and rock condition. The advance rate increased 3 - 4 times when the TBM portability changed from poor to good portability. D&B method advance rate also increased, about 20 – 40 %, when the rock condition improved. The cost curve Figure 2.9 also preset the same, therefore with good TBM portability, the excavation cost is less (Zare, 2007).

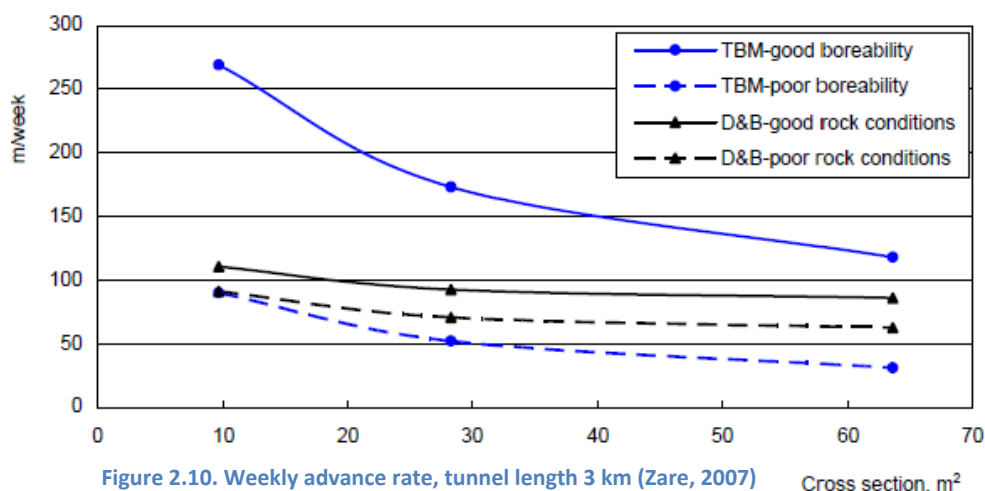


Figure 2.10. Weekly advance rate, tunnel length 3 km (Zare, 2007)

Figure 2.11 also presented a hypothetical comparison between the advance rate of the two tunnelling methods (Drill & blast and TBM). This graph will be used in this thesis for the calculation of the advance rate. These curves show the hypothetical rate which is strongly

affected by rock quality (Isaksson, 2002). The rock quality and Q value are described more in the next chapter and how the rock quality affects the advance rate.

As presented in Figure 2.11 TBM method is more varying regarding utilisation and Q value—the advance rate depending on Q value, changes on a large scale. For example, the advance rate with Q value from 0,1 to 1 increases by about 50 m/week and has the highest advance rate at Q value 1. The advance rate for the D&B method depends on Q value but does not vary on a large scale. The advance rate increase with growing Q value and has the highest advance with Q value 10.

To compare the advance rate of driving methods by the following equation can be used:

$$AR = PR \times U \quad (3.1)$$

Where

AR = Advance rate

PR = Penetration rate

U = Utilisation [%]

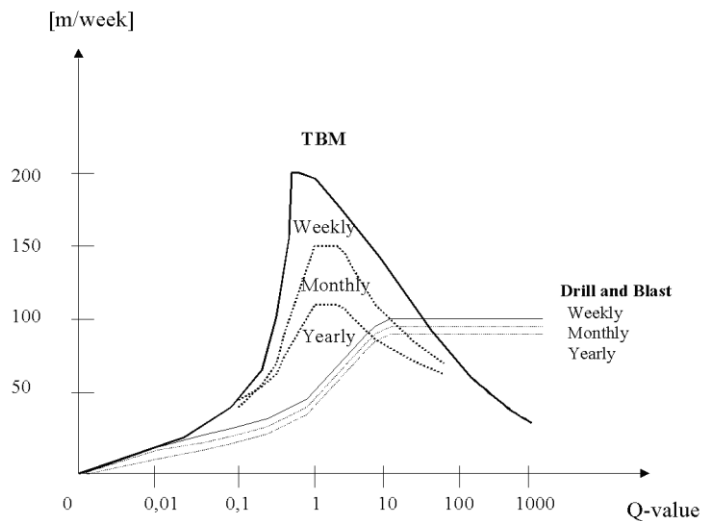


Figure 2.11. Hypothetical comparison of drill-and-blast and TBM advance rates in m/week (solid curves). Dotted curves represent monthly and yearly rates (Isaksson, 2002)

The time needed between the signed contract and start boring with the TBM method is much longer, maybe up to one year, while the D&B method is only 2-6 weeks. This long time for the TBM method means that it is not cost-effective for excavating tunnels in short or medium-long (Bruland, 2000)

2.4 Excavated material from the tunnel

There is a large amount of excavated material after the tunnel project. About several million tons of muck are produced every year in many countries. Suppose muck treated as waste or disposals increased the tunnel cost and reduced the cost for a more sustainable project. Will this material be recycled to substitute gravelly, which can be used in different ways as aggregates for concrete, fill material or subbase in highway construction? (Gertsch, 2000)

Long tunnels produce a large amount of excavated material, and if these materials are considered waste than a possible recourse, the double problem will arise. To decrease this problem, environmental and economical these materials should be reused in the best environmentally friendly way.

The excavation method affects the muck material from the tunnelling project, excavation material from TBM is smaller than material from the D&B method. The excavated material from the D&B method is usually having a larger volume (bellopede, 2011).

3 Geological Parameters

Geological parameters mainly influence the tunnelling performance (Rundsch, 1997). Choice of tunnelling method based on geological parameters may be an effective method. The geological parameters include some information needed to understand what kind of challenge and problems the rock mass will be offering for the tunnelling project. This information is about the joint system, crushed zones and other rock mass properties (Nyqvist, 2005). The investigation of the geological properties is vital for tunnelling since these properties may affect the penetration rate, compressive and tensile strength, design, planning and the choice of tunnelling method. Several geological parameters influence the tunnelling method, but only some seem to impact the excavation method significantly and will be studied in this project. Following come to some geological parameters that are important for hard rock tunnelling (Rundsch, 1997):

- Rock mass strength and elastic properties
- Rock types and rock abrasiveness
- Degree and type of jointing and fissuring of the rock mass
- Rock porosity and permeability
- Dip, strike and direction of drive
- Over burden and in situ stress
- Faults
- Stand up time
- Water inflow

The correlation between the tunnelling method and geological parameters will be studied by studying the geological parameter such as minerals, rock type, and rock mass properties (Rundsch, 1997).

3.1 Mineralogy

The mineralogy of rock mass needs to evaluate the stability and rock support and evaluate portability. The usual rock mineral consists of a chemical compound of silicon and oxygen. The most common form of silicate mineral is quartz, an essential mineral in a rock mass (Lindblom, 2010). Figure 3.1 presented the main minerals in the Scandinavia rock types (only acid rock types). The most common minerals in the Scandinavia rock types are alkali feldspar, quartz and plagioclase.

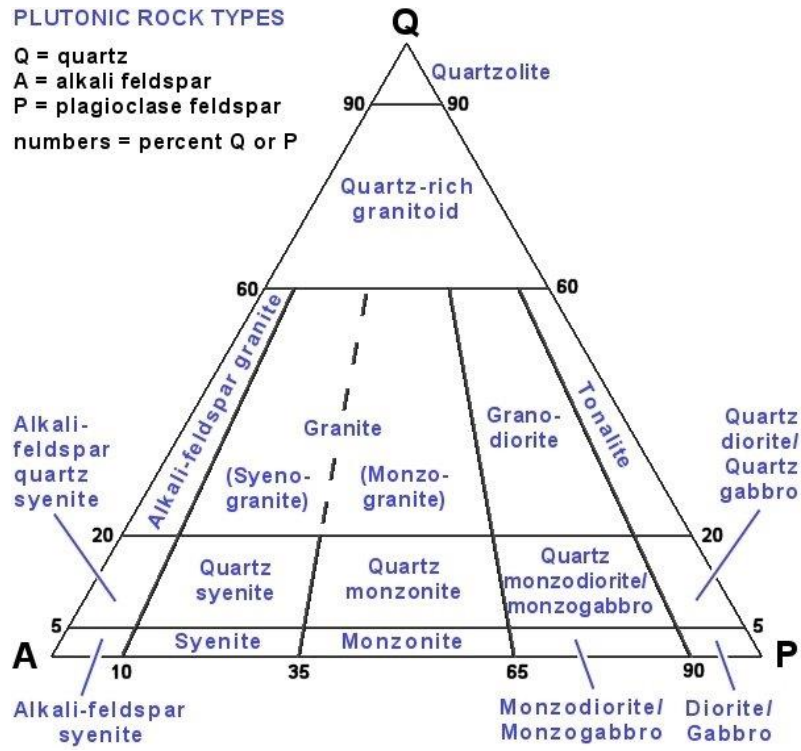


Figure 3.1. Composition of igneous acid rock based on present quartz, feldspar and plagioclase (Iaden, 2008)

Plagioclase and alkali feldspar have grade 6 on the Moh’s scale (Spicar, 1995). These minerals plus quartz constitute the central part of the most magmatic and metamorphic rock types. Quartz grades with grade 7 in the Moh’s scale, sharp and the obtuse angle. Minerals in feldspar series and plagioclase are cleaved easily in two directions by about 90° angle, while quartz has not the same property and gets an irregular fracture surface (Johansson, 2014).

Plagioclase and alkali feldspar have good cleavage and form smooth surfaces. These minerals cause minor drill bit wear and TBM cutter wear than quartz, which has a higher impact on the excavation and a higher disadvantage for the life of drill bit and cutter wear. Plagioclase minerals are not as hard as feldspar, and the richer they are in calcium, the easier crumbling them (Spicar, 1995). The rock type with more plagioclase is more ductile (Zetterlund, 2014).

Soluble minerals like carbonate minerals in limestone and marble, and rock salt can influence the stability and increase the water inflow. Calcite by chemical process dissolved by groundwater and it cause weakness zone and development of cavities in limestone. The holes can cause water problems during the tunnelling.

The swelling minerals by changing moisture from water absorption can lead to reduced instability. The swelling rocks with clay are montmorillonite shale, altered or weathered basalts and other igneous and metamorphic rocks.

3.1.1 Equivalent quartz content

By analysing the equivalent of quartz (Mohs' hardness of 7, harder than steel), the mineral of a rock sample can be determined. The rock types with many minerals of quartz make the rock hard and abrasive (Zetterlund, 2014).

Definition of rock type is a leading parameter for the tunnelling performance, and the tool wear results from minerals. The tool wear like TBM cutter wear and bit wear in drilling and D&B method varies depending on the quartz content. The tools wear increases by drilling in the rock type with high quartz content. Increased range of fine-grained quartz cause high drill bit wear and TBM cutter wear (Palmström, 2010). Usually, mineral with high quartz content has a more negative impact on the TBM method than the D&B method due to the high cost of TBM cutter wear and more delay needed to change the cutters. Mineral with high quartz content is challenging and excavation by blasting method in this case, according to Figure 3-2, has a higher advance rate than the TBM method. Therefore, the TBM method will not be cost-effective with high abrasive because it will lead to high TBM cutter wear and decrease BMI performance (Thuro, 2003).

3.2 Rock Types

The critical part of the ground investigation is to collect information about rock types. The rock type with high silicate minerals called for acid and with low for basic. The rock types with low silicates, such as olivine, pyroxene, and calcium-rich plagioclase, have a high congealing point, making these rock types stronger at rock movement and more ductile than the acid rocks.

The permeability is often higher in the acid rock than the basic, and it depends on that the acid rock is more brittle and make it easier to lead water. Still, it is essential to know that the variation within a stone is always more significant than the differences between the various rock types. The permeability is depth-dependent, and the reason is the rock cracks decrease by growing depth, but the rock stress increases (Gustafson, 2009).

Tensile strength plays a part in the design and excavation method of the tunnel. With low tensile strength, the rock is more brittle, which for example, will not cause high TBM cutter wear. Still, with high tensile strength, the rock is more ductile, and excavation by TBM cause more time and

delay because of the change of the disc cutter (more cutter wear), but the high tensile strength has a negative impact on the D&B method, required more amount of explosive.

The basic rock types such as gabbro and diabase have high tensile strain and low E-module. Minerals in these rock types have insufficient chemical stability, which causes larger cracks because of the chemical weathering (Gustafson, 2009).

The acid rocks types like gneiss, rhyolite, etc., may influence the mechanical properties of the rock mass. Hence these rock types have higher E-module and lower low tensile strain, which makes them more brittle, and the excavation in the rock mass with these rock types is more accessible, and the necessary power to excavation is less compared to the basic rock. The acid rocks are usually more complex rock, and tool wear for these rocks are higher than basic rocks. The acid rock types and can handle the large load from rock movement at excavation because of the higher e-module they have (Gustafson, 2009).

In Table 3.1, the average value of the most common Scandinavia rock type's properties is presented. This can be used to have a primary suggestion of rock mass properties in a project.

Table 3.1. Typical mechanical properties of Norwegian rocks (2012)

Rock type	Uniaxial compressive strength (MPa)	Point load index (tensile strength) (MPa)	Young's modulus (GPa)	Poisson's ratio
Amphibolite	110	12	70	0,20
Diorite	150	14	50	0,15
Gneiss	130	15	45	0,18
Granite	170	15	40	0,15
Greenstone	100	10	55	0,20
Limestone	75	8	70	0,30
Mica schist	70	8	30	0,20
Phyllite	35	6	30	0,10
Quartzite	170	15	55	0,15
Sandstone	150	15	30	0,20

In figure 15 presents how the different rock types affect the drilling rate and bit wear with the drilling and blasting methods. The diagram shows that the most usually, Scandinavia rock types, such as quartzite, cause extremely high bit wear and inferior drilling rate. This diagram is from 25 case studies in 9 tunnel projects in Germany, Austria and overseas (Rundsch, 1997). As presented in Figure 3.2, excavation in the hard rocks require high to highly high bit wear and this influence the drilling rate, the drilling rate for these Scandinavia rock types is poor to extremely poor.

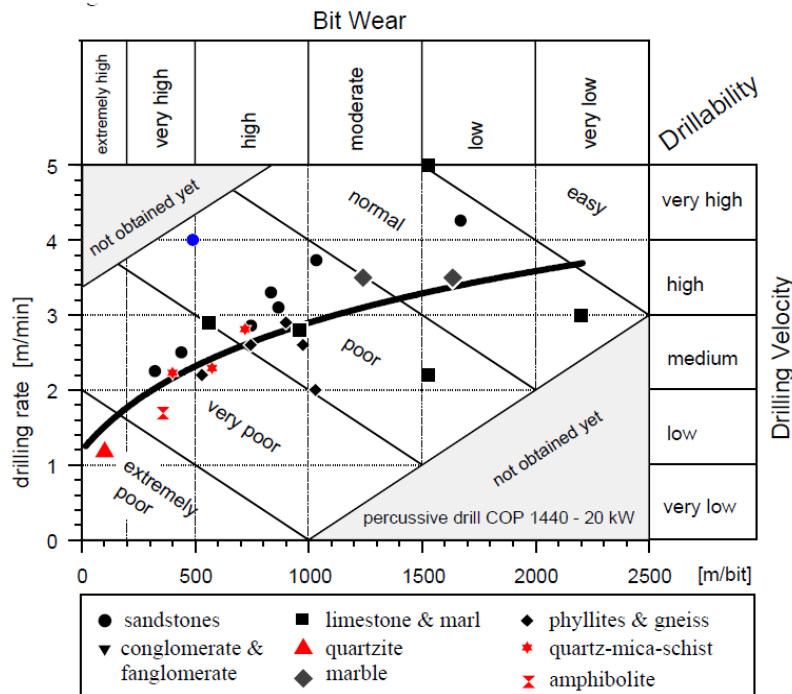


Figure 3.2. Classification diagram enclosing 25 case studies of different rock types from 9 tunnel project (Rundsch, 1997)

3.3 Rock Mass Properties

In tunnel projects, the surrounding rock mass properties are also important and not solely rock type. Rock mass properties that affect the tunnelling method are rock blocks, cracks between blocks, strength, deformation and ground water. This chapter will describe how the rock properties and ground water influence the tunnelling method. For example, the TBM method is more sensitive to rock mass properties and rock type variation than the D&B method (Palmström, 2010). The interpretation of rock properties cause more cutter wear and more delay but with the D&B method is possible to change the excavation class when the rock mass properties or the rock quality changes during the tuunneling.

Calculating rock properties cannot be measured directly because of the large scale of the rock mass. The empirical relations and numerical simulation will estimate these properties, but these methods include some uncertainties (Andersson, 2002).

The interaction between blocks and cracks determines the deformation and strength. The cracks are more significant in larger rock volume, meaning the rock's deformability increases and strength decreases, growing importance (Lindblom, 2010).

There are different rock qualities classes systems based on rock properties, i.e., using empirical relation based on additional rock mass classification system help to determine the mass properties. Over an extended period, the classification systems have been applied to design underground excavations, especially tunnels (Andersson, 2002).

Rock mass classification helps to determine the compressive strength of the rock mass and rock quality. The classification system helps decide the construction and support system for the tunnel and the determination of total time and cost for the tunnelling project (Amund, 1998). The most usual classification systems that are used now are the Rock Mass Rating (RMR) system and the Tunnelling Quality Index (Q) system (Bieniawski, 1998). The abrasiveness of the rock can be estimated by DRI (Drill Rate Index) and the CLI, Figure 2.6.

The Q-system includes six parameters: joint set, joint roughness joint alteration, stress reduction factor, joint water reduction factor, and rock quality designation. Rock Mass Rating (RMR) system includes six parameters: uniaxial compressive strength of rock material, spacing of discontinuities, condition of discontinuities, groundwater condition, the orientation of discontinuities and rock quality designation (RQD). Rock mass classes with very good RMR are usually tough rock, and excavation in this rock usually requires high tool wear, but the support system is low.

The Q classification is a method to calculate the rock quality. For example, poorer rocks reduce the stability with the excavation by TBM and excellent quality and high abrasiveness reduce the advance rate because of the low cutter performance.

With the help of Figure 2.11 and Table, 3.2 is possible to evaluate the tunnelling performance based on the rock mass conditions. Rock mass condition can reduce or improve the tunnelling operation. For example, using the TBM method in right and favourable rock geological conditions with Q values between 0,1 to 10 increases the advance rate. It reduces the required support compared to the drill and blast method, and the D&B method has a high advance rate for rock mass with a Q value higher than 10. (Palmström, 2010). Thus different rock mass properties have other influences on tunnelling operation.

Table 3.2. Q value for different rock quality (Palmström, 2010)

Rock Quality	Q value
For rock masses of good quality	$Q > 10$
For Rock masses of intermediate quality	$0.1 < Q < 10$
For rock masses of poor quality	$Q < 0,1$

3.3.1 Strength

High overburden causes high stress, and if the tensile or compressive strength exceeds in the rock, mass failure will occur. Failures have to be considered for tunnelling projects at more considerable depth in compact rock. There are two main rock failure mechanisms; brittle and ductile failure mechanisms. To support the rock against these failures require the equipment to provide bearing capacity. Determination of these failures information is impossible by direct situ testing. There are some methods for calculating intact rock properties and characteristics of the discontinuities in the rock mass (Hoek, 2007).

The uniaxial compressive strength can also be estimated by point load test, the correlation between the uniaxial compressive strength and point load test is (Amund, 1998):

$$\sigma_c = (14 + 0,175) \times I_s \quad (3.2)$$

$$I_s = F/D_e^2 \quad (3.3)$$

Where:

- σ_c = uniaxial compressive strength
- I_s = point load index
- F = Applied Load
- D_e = Equivalent Core Diameter

Estimation of the uniaxial compressive can be prepared from on the laboratory test, but in this thesis, the laboratory tests are not possible. The rock type's properties value from Table 3-1 can be used. The test from the laboratory should be fulfilling with moisture contents as close as possible with the test in the field (Hoek, 2007).

The TBM method used commonly in rock with uniaxial compressive strength of 60-300 MPa and tensile strength higher than 2 MPa and very high hardness and abrasiveness is not suitable for the TBM method. The TBM method is usually not ideal at low compressive strength of 20 MPa (Isaksson, 2002).

The ground's compressive strength and abrasiveness determine the possibility of the D&B method (Isaksson, 2002). The rock with very high hardness and high compressive strength will not be cost-effective with TBM, which means the use of the D&B method may be more economical.

3.3.2 Deformation

The support systems of the tunnelling project have to be flexible in the case of squeezing rock and, at the same time, with sufficient support, have to hold the deformation in an allowed range. The deformation of a tunnel is estimated by deformation modulus (Young's modulus) (Hoek, 2007), which is defined by the axial stress change to axial strain in the rock mass. The deformation (both elastic and inelastic) of the intact rock and fractures makes the rock mass strain (Andersson, 2002). The rock mass strength and the stress are needed to estimate formation (Hoek, 2007).

The stress around the tunnel causes different types of instability for the tunnel. Therefore the estimation of pressure is essential. By analysing and calculating the effect of stress, the right and suitable support system can be used. The shape of the tunnel may have an adverse effect on these stresses, especially when the virgin stress has an anisotropic situation. For example, stress around the tunnel with a circular opening depends on the tunnel radius (Palmström, 2010). A layered rock is an anisotropy that controls the mechanical and hydrogeological properties of the rock mass (Gustafson, 2009).

The tangential stress around the opening will vary, and the tangential stresses depend on the degree of the stress anisotropy. The shape of the tunnel's entrance influences the magnitude of maximum tangential stress. For example, using TBM, the tunnel will be circular and tangential stress will be lower wall due to lower A coefficient according to table 3.3 and equation 3.5.

The tangential stress around different types of tunnel opening can be estimated by Hoek and Brown (Palmström, 2010).

- Tangential stress in the roof:

$$\sigma_{\theta r} = (A \cdot k - 1)\sigma_z \quad (3.5)$$

- Tangential stress in the wall:

$$\sigma_{\theta w} = (B - k)\sigma_z \quad (3.6)$$





Where:

A, B = roof and wall coefficient for various excavation shapes (see table below)

K = ratio horizontal/vertical stress

σ_z = vertical, virgin stress

Table 3.3. The Value of A and B coefficient. (Lindblom, 2010)

Tunnel shape				
A	3.1	3.0	3.2	1.9
B	2.7	3.0	2.3	1.9

With Equations 3.5 and 3.6, the stress in the wall of the roof of the tunnel for different shapes of the tunnel is estimated and plotted in Figures 3.3 and 3.4. These figures present how the shape of the tunnel influences the stress, and usually, the stress of the wall affects the tunnel stability and stress in the roof is almost the same for both methods, but stress is higher in the walls for the circular tunnel. Higher stress can lead to the rock being compressed, and the risk of block breakout decrease.

The use of TBM provides a circular shape, and the tunnel with a circular shape has lower tangential stress in the roof, and the horseshoe shape has lower stress in the wall of the tunnel. The horizontal or vertical stress ratio is assessed to be 2 (Lindblom, 2010), and the vertical virgin stress is 0,027 MPa of the depth below the surface. In this calculation, the depth is up to 150 meters.

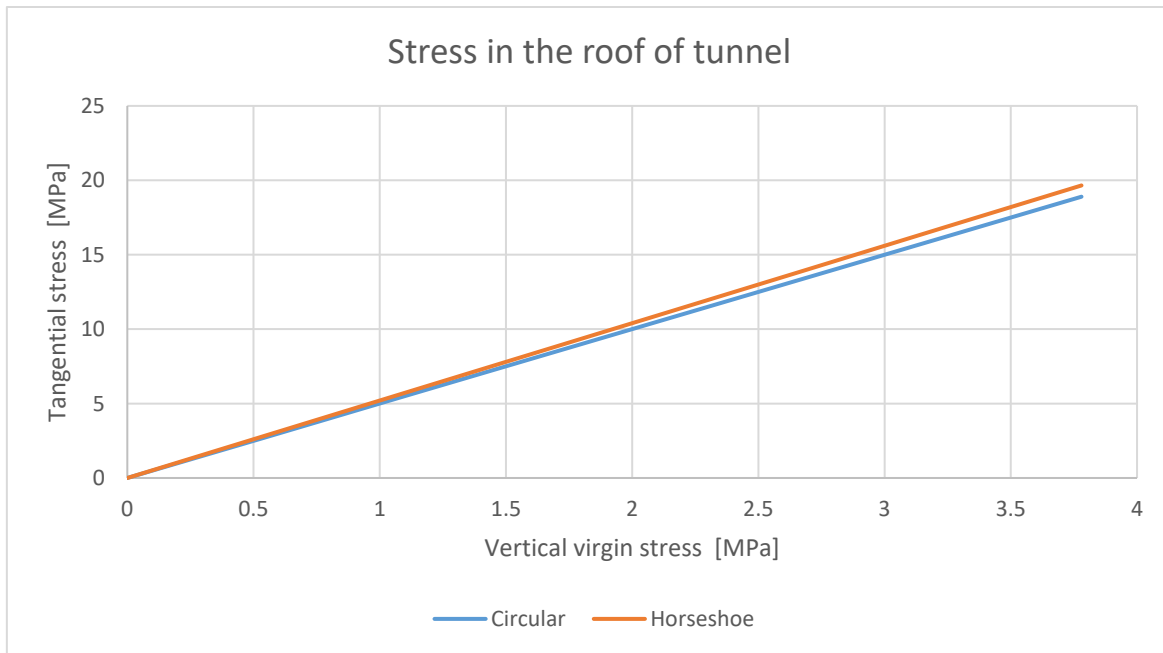


Figure 3.3. Tangential stress in the roof of tunnel

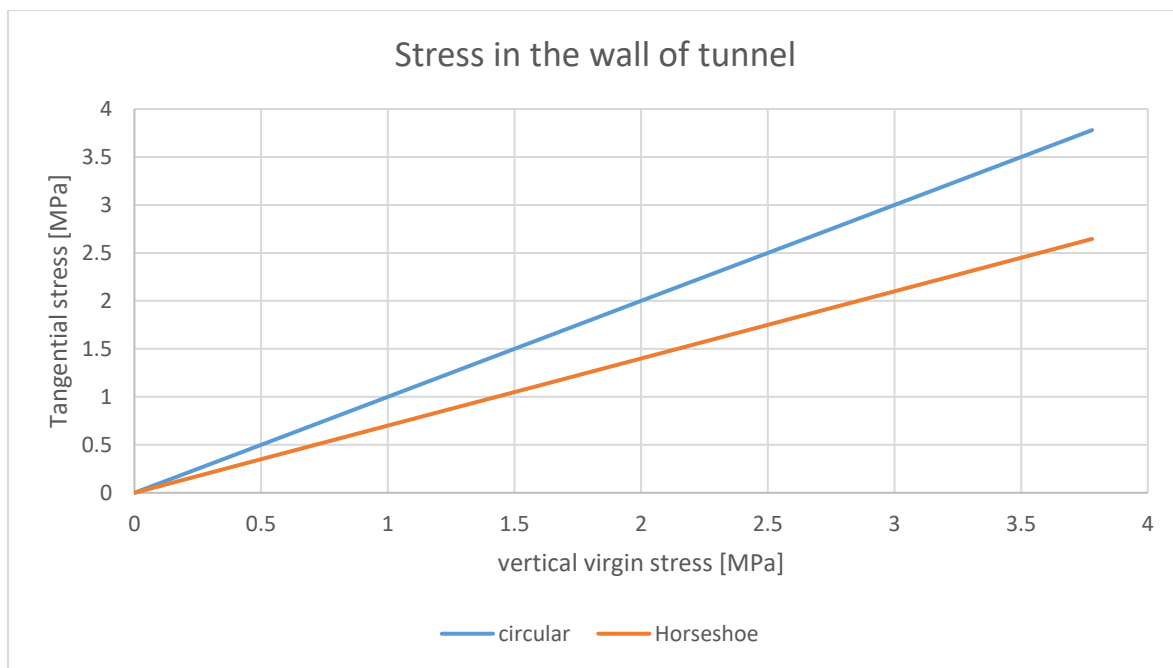


Figure 3.4. Tangential stress in the wall of tunnel

Estimation of the tangential stress determines the risk of the slabbing, and the slabbing is expected to occur when the magnitude of tangential stress exceeds about half of the uniaxial compression strength (Palmström, 2010).

3.3.3 Discontinues

Studying orientation and spacing of discontinues and the influence of groundwater can determine the type of behaviour expected for rock mass around the tunnel. Discontinues are as fault and weakness plane in the rock mass, but sometimes it is hard to determine the boundary between the fault zone and the quiet zones in stable hard rock (Nyqvist, 2005). Minerals in the fault zones affect the zones. For example, mineral quartz causes durable and high strength, which improve stability (Thuro, 2003).

The high degrees of rock cracks provide different problems, such as stability and groundwater influenhydrogeological properties (Nyqvist, 2005). In the excavation, the degree, orientation and spacing of rock cracks influence the choice of the method because the degrees of cracks decide and lead the water into the tunnel.

The favourable joint spacing for the TBM method is 0.2-6.0 m due to the cutter wear. This limitation for joint spacing for the TBM method will lower delay and lower TBM cutter wear (Delision, 2012). The drilling rate depends on the spacing of discontinues in the rock mass. The drilling velocity increases when the joint gets closer (Runds, 1997), but drilling accuracy decreases and the risk of drilling obliquely increase, leading the excavation of too much rock and the increasing costs of the project (Zetterlund, 2014).

Hard rock in Scandinavia with slapping and rockburst influence the tunnelling method. These rocks have a negative effect on the TBM method. The TBM machines have some drawbacks due to increase of cutter wear and cutter head, and also the irregular size and shape of the muck cause stoppage and waste of time, therefore the high maintenance and time of TBM operation in these rocks may seriously slow down the TBM machine performance (Delision, 2012).

3.3.4 Groundwater

If the tunnel is not drained, the groundwater influences the life cycle cost and the maintenance, but generally, it is difficult to predict the quantities and location of water inflow to the tunnel. The inflow of water into the tunnel cause different problems such as reduced excavation capacity, negative impact on the environment and rock stability problem (Gustafson, 2009). Another negative impact of groundwater on the tunnel is a reduction in the strength of the rock material and discontinued shear strength decreased (Palmström, 2010).

Groundwater is often close to the land surface and affects most minerals like calcite and increases rock cracks (Palmström, 2010). The groundwater also consists of some minerals that, in contact with oxygen, may crystallize and lead to frost in a cold climate. This increase the load and

breakdown in fracture. By growing depth, the inflow of groundwater into the tunnel decreased due decreasing in permeability. (Palmström, 2010).

The drill and blast method application is limited where their ground is flowing, and in the area the rock is weak, and overburden is thin (Isaksson, 2002), in this case, using the correct type of TBM method may be more suitable. To prevent the large inflow of groundwater, pre-grouting is performed. In TBM, grouting can be done from behind the head, but demands stop an advance rate. Conclusion This means that the TBM method needs extensive grouting to decrease the method's performance, but with the D&B method, the grouting is generally included in the excavation cycle (Zetterlund, 2014).

4 Summary of literature review

The main parameters that affect the Follo line's excavation method are the rock types and quality, portability CLI, the length and the advance rate. The Follo Line is a 22 km long double-track railway between Oslo and Ski that runs through a 19,5 km single tunnel (see figure 4.1).

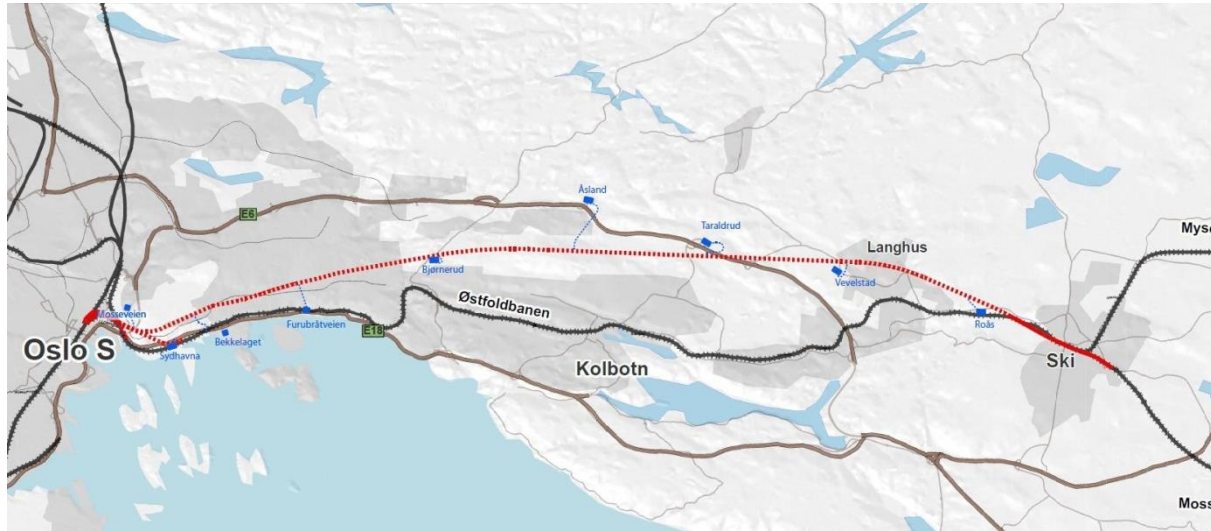


Figure 4.1. Tunnel line between Oslo and Ski (Follobanen, 2013)

These two tracks are connected with a cross-section at every 500 meters, which will be used as escape routes (see figure 4.2. This method is an inter-European safety requirement for long tunnels that will comply with the Follo Line Tunnel. This is the first time a twin-tube railway tunnel is to be built in Norway, and this is also the first time a railway tunnel will be excavated by the TBM method in Norway.

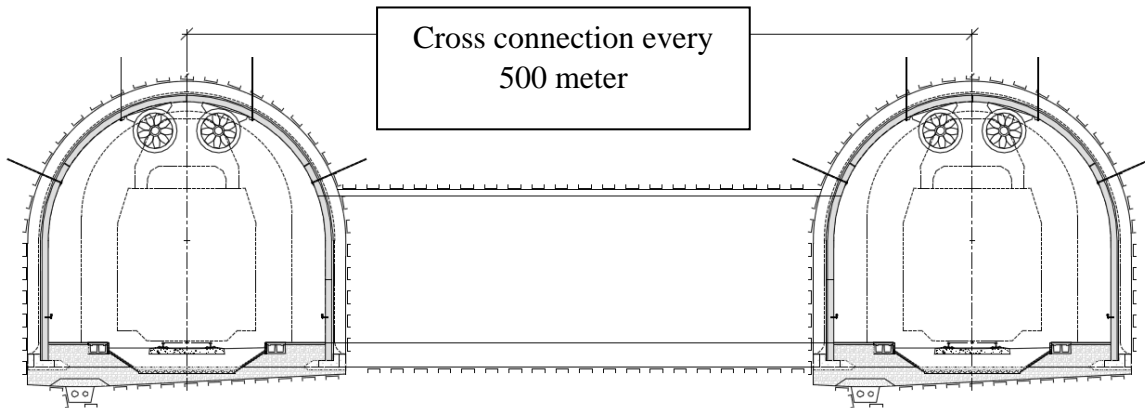


Figure 4-2. Double tracks with cross-connection every 500 meters (Follobanen, 2013)

The rock type is ductile and has a low tensile strength, which leads to easier excavation by TBM, the variation of rock type seems to be low, which will not negatively affect the TBM. From a previous report from the CLI value for the Follo line is low, about 4-14%, and according to figure 2.6, the rock type with this CLI value is estimated to be rock-like quartz, mica or schist, and as it is described in chapter 3 and according to figure 3.2 these rock types will be more suitable to be excavated by TBM. This may be why the TBM method was chosen due to the higher advance rate of 90m/week, about 3 times quicker than the D&B method.

The Norwegian National Rail Administration (NNRA) on this project and decided to excavate the central part of the project by four shield TBM, two machines will drill southwards and the two other northwards and one-third of the project with drill and blast excavation.

Results from the literature review will help to determine the basis for deciding on the tunnelling method.

Realistic estimation of the tunnelling's performance is needed as a basis for project planning, method of tunnelling and scheduling. Comparison of two tunnelling methods (TBM and D&B) focusing on geometrical and geological, economic and environmental may find a basis for deciding which tunnelling method should be selected.

4.1 Comparison of two tunnelling methods

The main reason for the comparison is to excavate the tunnel with the most cost-effective method. Some factors should be considered to make this decision more accessible, but a definitive answer to which method should be chosen is very hard and in this project will find a primary method that may help choose the best method for tunnelling. These factors are advance rates, labour cost, equipment cost and supplies and indirect cost.

Comparison of these two tunnelling methods, TBM and D&B method will be presented in tables 4.1-4.4 in each table presented different are. Some parameters are the same in different areas, but for a general analysis have been divided into four main areas. Tables 4.1 present the geometry factors, table 4.2 presents the rock properties, table 4.3 presents the cost and time factors, and table 4.4 presents the environmental factors.

4.1.1 The Geometry factors

The discussion of geometry factors is based on chapter 2 and is presented in table 4.1. Here will describe how the geometry factors affect the tunnelling method. According to figure 11, tunnels with short lengths should not use the excavation method by TBM as it will require a very high investment cost. It is suggested that the TBM is used for tunnels with a minimum length of two kilometres (Maidl, 2008). However, D&B will allow flexibility and will not be limited to the length of the tunnel.

The area of the tunnel is one parameter that is important for deciding the tunnelling method. TBM method has a limited excavation area, and usually, it is possible to excavate a tunnel with a diameter between 1,5 and 14 meters (Maidl, 2008). The excavation by the D&B method is also limited, and the excavation by the D&B method at the minimal area is not possible due to the place that is needed for equipment, ventilation and working environment. The cross-section area for excavation by the D&B method must be at least 15 m² (Zetterlund, 2014).

The TBM method can only excavate circular tunnels, while the drill and blast method can excavate asymmetrical cross-sections, sharp curves, and crosscuts.

The curve radius is also an important parameter when comparing these two methods. The TBM method has a limitation on curve radius, but the conventional method has typically no practical limitation. The demand curve radius for TBM is between 150 and 450 meters (Holen, 1994).

The slope of the tunnel is also one parameter that may affect the tunnelling method, may use of the TBM method is possible at a slope higher than 5% (2014), but there is no limitation for the use of the D&B method. This is mainly affecting the choice of tunnelling method for construction tunnels.

The final profile of the tunnel is generally smooth by the TBM method and uneven tunnel profile by the D&B method. The required additional concrete or other installation to repair the profile and water or frost protection is less by TBM method than D&B method.

As presented in table 4.1, the parameters that can be important and may affect more the tunnelling method are judged to be area and length.

Table 4.1. The geometry factors

Parameter	TBM method	D&B method
Length	Not usual for short length	Well suited for any length
Tunnel depth	increasing depth has negligible effect on TBM	Well suitable at any depth
Large area/diameter	Not usual for tunnel with diameter larger than 14 meter (Maidl, 2008)	Well suited
Small area/diameter	Not usual at small due to TBM machines diameter(not smaller than 1,5m) (Maidl, 2008)	Not suitable for very small tunnel due to required space for equipment, ventilation and working environment(not smaller than 15 m ²) (Zetterlund, 2014)
Curve radius	Demand (150-450m) (Holen, 1994)	No demand
Slope	Limited max 5% (2014)	No demand
Form of Cross section	Only circular	Well suited to any form
Final profile	Smooth, less demand for additional concrete or other installations in order to place water and frost protection	Uneven

4.1.2 The Geological factors

The discussion of rock properties such as rock mass quality, rock type, deformation, strength, discontinuities, etcetera is based on chapter 3 and will be compared for these two tunnelling methods in table 4.2.

The critical support system is generally more in the D&B method, the explosive and excavation class influence the support system, and TBM usually has less required support system in ideal rock quality. As presented in chapter 3 and figure 3.4, a tunnel with a circular shape has higher stress, and the risk of breakout is less, which means the tunnel needs a minor support system with a circular shape.

Variation of rock quality cause high cutter wears which effect more delay and decrease of advance rate but with D&B method is easier to adopt excavation performance with different variation of rock quality.

By suitable grouting, the leakage of water into the tunnel can be stopped or at least reduced. Usually, grouting is included in the D&B method, but in the case of the enormous inflowing of water into the tunnel, the use of the D&B method is limited. Water leakage into the tunnel limited the choice of borehole orientation by using TBM and needed extensive grouting to decrease the advance rate.

As described in chapter 3, the rock types with high silicate minerals call for acid rocks. Acid rocks like quartzite have low tensile strength and high E-module, which make them brittle. The low tensile strength causes the required power to be low in TBM and low blasting power in the D&B method, but the high hardness of rock increases TBM cutter wear and bit wear in the D&B method. Usually, the Scandinavian rock type is acid rock, and according to figure 2.6, the CLI for these rock types is low, and according to figure 3.2, these rock types require moderate to high tool wear. The rock type with a low amount of silicate mineral and high mineral-like plagioclase calls for basic rock. Basic rocks have high tensile strength and low E-module and are more ductile because of high tensile strength. The required power is higher in basic rock with both TBM and D&B methods. These rock types usually have lower hardness, and the TBM cutter wear and drilling bit wear is lower than acid rocks. The rock with a high E-module has minor stability problems, and these rocks can take the load from rock movement during the excavation.

The classification of rock is essential in determining of tunnelling method. The very good RMR or very high Q value is calculated as a rock with excellent quality, which means these rocks reduce the TBM cutter performance, but these rock types are usually more suitable for the D&B method due to less needed support. According to figure 3.1 and table, 3.2 the TBM method has a high advance rate for rock type with intermediate quality, i.e., a value between 0,1 and 10 and the D&B method has a high advance rate for rock type with a Q value higher than 10 (Palmström, 2010).

The compressive strength affects the rock support. Low reinforcement in the rock makes the TBM performance higher, i.e. the intact compressive strength of the rock affects the choice of tunnelling method. TBM method has the higher advance rate for rock with a compressive strength between 60 to 300 MPa (Isaksson, 2002), but the use of TBM in the highly abrasive and challenging rock led to delay and cost, the drilling process is more difficult in these rocks, and the cost is high, the delay is because of some parameter such as changing of the cutter and also from structural failures. In this case use of the D&B method can be more suitable. The use of D&B usually is possible in all types of rock, but the needed reinforcement varies.

Discontinuities influence the tunnelling method, the spacing of discontinuities affect the drilling velocity. When the joint is closer, the drilling rate is higher, but the drilling accuracy is reduced. The favourable spacing of discontinuities for the TBM method is between 0.2 to 6.0 meters due to lower cutter wear and lower delay (Delision, 2012). Length of discontinuities also affects the D&B method. The long cracks may cause water leakage into the tunnel. The length of cracks has a lower impact on the TBM method, but rock with high slapping and rockburst negatively impacts TBM.

The parameters presented in table 4.2 from rock properties area, some of them are judged to affect more the tunnelling method, these parameters are judged to be the rock hardness and the variation of rock mass quality.

Table 4.1. The rock properties factors

Parameter	TBM method	D&B method
Rock support	The support system is easier and required support is less due the rock quality	Usually Required more support system due the explosive and excavation class
Variation in rock mass quality	Demands more maintenance of cutters, risk of large delays if rock quality is much poorer than stipulated	Can be handled by excavation method
Water leakage	Has to be prepared for grouting, limited chose of borehole orientation	Grouting is general included in the excavation cycle
Acid rocks Rock type with high silicate mineral	Required less power but more TBM cutter wear due to high hardness	Required less powerful blast but more bit wear and due to high hardness the drilling rate is low
Basic rocks Rock with low silicate and more plagioclase mineral is basic rock	Required more power but less TBM cutter wear compared to acid rock	Required more powerful blast but less bit wear compared to acid rock
Rock mass class	Very good rock RMR negative impact due to the rock is ductile and reduce the cutter performance	Very good rock RMR required generally no support and suited well with this method
Deformation	With High E-module lower stability problem	With high E-module lower stability problem
Parameter	TBM method	D&B method
Rock Strength	Is used normally in rock with uniaxial compressive strength of 60-300 MPa (Isaksson, 2002)	Is used in all rock from weak rock to very hard rock but the required reinforcement volume varied
Spacing of Discontinuities	The favourable spacing of joint Lower impact is 0.2 – 6 meter (Delision, 2012)	Closing of joint decrease the drilling accuracy
Length of discontinuities	Lower impact	The rock with long racks has negative impact due to inflow of water into tunnel

4.1.3 The Economic factors

The discussion of cost and time factors is based on chapters 2 and 3 that will be presented in table 4.3. Here will present how the cost and time factors affect the tunnelling method.

The advance rate is a crucial parameter for comparing the tunnelling method, and according to Figures 2.10 and 2.11 TBM method has a higher advance rate.

TBM excavates a tunnel generally has a lower lifetime cost but is assumed to have a longer lifetime. The excavation by D&B usually has a higher lifetime cost but vary depending on the water and frost condition (Zare, 2007). According to figure 2.9, the excavation cost is generally higher with TBM than D&B. The excavation by the TBM method in good portability will not cost much higher than the D&B method. Thus the rock quality and cross-section affects more TBM method than the D&B method.

The start-up time is longer for the TBM method between the signed contract and the excavation rate. According to chapter 3.3, the total time depends on the geological condition and excavation length.

Generally, the tunnel maintenance is less by TBM due to undisturbed rock, but fracturing from the D&B method increase demand for maintenance. Maintenance is a part that influences the performance rate due to downtime. The TBM method is ideal rock condition and good rock quality requires minor cutter wear and less delay that will be needed to change the cutter. The D&B method generally is critical to ensure that all equipment is in good, safe and reliable working order and this means with D&B method required normally more maintenance such as preventive-, corrective- and reliability maintenance.

From the parameters presented in table 4.3, the advance rate and excavation cost are estimated to be important parameters that may affect the tunnelling method more.

Table 4.2. Time and Cost factors

Parameter	TBM method	D&B method
Advance rate for Scandinavian rock types (Q between 0,1-10)	high	low
Lifetime Cost	Low after excavation	Depend on water and frost system, general higher than for TBM
Start-up Time	Up to one year between the signed contact and start boring	General 2-6 weeks between the signed contact and start boring (Bruland, 2000)
Excavation cost	High	General lower than TBM
Tunnel maintenance	Generally less due to undisturbed rock	Fracturing due to blasting can increase demand for maintenance

4.1.4 The environmental factors

In table 4.4 compared the environmental factors for these two tunnelling methods. The discussion about the environment is based on chapter 2.

TBM method machines drive on electricity, and the need for ventilation is lower than the D&B method. The machines used in D&B drive on diesel fuel, and the toxic particles and gases created by this method have to ventilate out of the tunnel. Therefore, the needed ventilation for the D&B method is higher.

TBM usually has less impact on the environment, less noise impact and blast vibration (Maidl, 2008). The D&B method usually impacts the immediate environment in damage, noise, and blast vibration. The TBM method at the very immediate area has considerable vibration experienced as noise in areas between 50 and 150 meters (Maidl, 2008), and the TBM method generally has less explosion vibration at the surrounding area than the D&B method.

The excavated rock volume varies and depends on the excavation method, and usually, the excavated rock from TBM is smaller but depends on the bore profile in TBM and excavation class in the D&B method. The TBM excavated according to profile, but D&B always has to excavate more rock than the theoretical profile. This leads to that more rock being continuously excavated by D&B.

The damage zone after excavation varies by different methods, the damage zone after excavation by TBM is usually limited compared to the D&B method, but the damage zone after excavation by the D&B method varies depending on the excavation class.

Table 4.3. Environmental and environmental impact factors

Parameter	TBM method	D&B method
ventilation	Less demand due to is operating on electricity and required less ventilation	Is operating on diesel fuel and required more ventilation and Excavation gases has to be ventilated
Vibration	Considerable vibration at very near area (50-150 m) which lead to noise in the near area but no blast vibration (Maidl, 2008)	Blast vibration at surrounding area
Excavated rock volume	According to bore profile	Depending on excavation class but larger than the type profile
Excavation damage zone	Very limited	Depending on excavation class

4.2 Effect on operation's cost and time

Based on the literature survey and gained knowledge, estimation of the impact of the essential parameters regarding time and cost has been performed. The result is presented in table 4.5. This will help to understand how these parameters affect the cost and time of tunnelling. In table 4.5 presents the stated parameters from chapter 4.5

This table illustrates how different parameters affect the choice of excavation method, TBM and D&B. Single plus means the parameter increases the project's time or cost, double plus means significant increase, and mines means has no effect on the time or cost the project. This table presents only the parameters that, in my opinion, seem to affect the time or cost of the tunnelling project for the respective excavation method.

After study table 4.5, the parameters estimated to be more critical and should be studied are the diameter, length, variation of rock quality and rock hardness. These parameters are estimated to affect more tunnelling by increasing the time and cost of the project. The and need to be

Table 4.4. Estimated of different factors on Time and cost

Parameter	TBM	D&B	+=
Depth	+	+	
Diameter>12 m	++	+	
Diameter<5 m	+	++	
Short length	-	+	
Long length	+	++	
Rock support	+	++	
Variation of rock quality	++	+	
Water leakage	++	+	
High amount of quartz	++	++	
Very hard rock	++	+	
Weak rock	++	++	
Low tensile strength	+	+	
High tensile strength	++	++	
Long length of discontinues	++	++	
Very close spacing of discontinues	+	++	
High E-module	+	+	
Q value > 10	++	+	
Q value < 10	+	++	

Increase in total time or cost

++ = Large increases in total time or cost

- = Method not applicable/ not affect in time or cost

5 Oslo - Skien Railway tunnel

This chapter will sort out the different factors that affected the choice of the tunnelling method for the Oslo - Skien tunnel using chapters 2 and 3. This chapter's information, data, and figures are taken from the Norwegian Jernbaneverket rapport (2013).

5.1 Factors affecting the choice of tunnelling method for Follo Line Project

This chapter aims to determine which parameter influenced the TBM method chosen for Follo line Project. The Follo project is divided into pre-work and the central tunnel work. In the pre-work, the tunnel adits will excavate by drill and blast method, and the main work consists of two methods; TBMs machines and drill and blast. The drill and blast method will be used in the Oslo centre, and the rest with the TBM method.

As described in chapter 2 and 3, the main factors that influenced the choice of TBM are such as the tunnel length, the rock properties, generally adequate overburden, less impact on the external environment in a populated area, access to a large rig area and the choice of TBM method will guarantee a high quality work.

The drill and blast method will be used for two central adits tunnels, each up to 1000m long, and about 1 km section of the innermost tunnel in Oslo central station will also be excavated by the D&B method. The D&B method is chosen for these adits, and in the Oslo central may be the short length of cross passages and the curve radius in the central adit. According to chapter 2, using the TBM method for a tunnel with a short length cannot be profitable, and there is a limit for curve radius for TBM.

The TBM system consists of a concrete enclosed ring that is impermeable and protects the tunnel from rockfall, water and frost and the entire lining. These properties may be more suitable for a railway tunnel with high speed and heavy traffic. The gap behind the concrete segment and tunnel wall will be filled by grout. This protection method requires less maintenance and provides a longer lifetime of a tunnel than the traditional method; rock bolt and sprayed concrete.

The TBM machine chosen for this project is a double shield TBM. This machine has good performance and is independent of the ground condition with permanent rock support through segment lining. The pre-grouting and water and frost protection are needed for the open TBM machine, but the double shield machine is limited. The recommended protection against water and frost used in this project is single shell lining, a concrete segment with gaskets (is watertight).

5.1.1 The geometrical factors

As described in chapters 2 and 3, the geometrical factors influence the choice tunnelling method, and the main geometrical parameters for the Follo Line project that affect the choice of the tunnelling method are the shape and length of the tunnel. The Follo line tunnel will have a width

of about 9m, and excavation of the cross-section with drill and blast will be about 7,9 m wide and 7,6 m high and by TBM method will be 8,7 m diameter, which means with the TBM method, the tunnel area will be about 59 m² and 60 m² with D&B method. Using the TBM method, the shape of the tunnel will be circular, and the circular shape, as mentioned in chapter 3, has lower roof tangential stress, but the difference is minimal. The long length of the Follo line tunnel can be a good factor and economic benefit that the TBM method may be a suitable choice.

5.1.2 The geological factors

Knowledge of geological conditions and experience from similar rock conditions are essential for choosing the tunnelling method. The Follo line tunnel passes mainly through tonalities to granitic gneiss. As described in chapter 3, these rock types are brittle due to low tensile strength and cause less CLI, which means the cutter wear will be high, and the cost of the excavation by TBM will be lower than the D&B method. These rock types have high E-module and can handle the load from rock movement at excavation, which means the rockfall will be low due to the high E-module. According to figure 14, these rock types consist of more mineral plagioclase, making the rock type more ductile and TBM excavating requires lower tool wear. The large rigging area southward of Oslo provides a significant construction site that makes TBM machines possible.

The study of the geological condition for the Follo Line tunnel will be analysed with the aid of a literature study from chapter 2 and 3. The information about the geological condition for the Follo Line tunnel is taken from the Norwegian Jernbaneverket rapport.

The Follo Line tunnel passes through metamorphic rocks, mainly Precambrian gneiss, with 1-2 degrees of fractured zones. This area has a varied topography, from an urban area to agricultural land and forest. There are some weakness zones in this area with thick width (> 10 m).

The portability value for the Oslo tunnel was calculated according to the rock mass properties. The rock mass parameters such as the DRI (Drilling Rate Index) in this area is between 27 -52% and CLI (Cutter Life Index) in the range 4 -14 %. The stability of the rock mass in this area is considered to be good, except for some weak zones. The inflow of water is expected in the area with fractured zones.

5.1.3 The economic factors

The significant part of the tunnel cost depends on geological conditions, and when the tunnel passes some existing road tunnels and floods, the excavation cost will be higher.

The advance rate is considered to be the main parameter that influences the economy. The advance rate for TBM in this project is 90 m/ week (15 m/day) and for the drill & blast method is 15-28 m/week (4-5 m/day). The working time for the TBM method is app. 300 days a year (144

h/week), and drill and blast is 101 h/week and 46 weeks/years. . The TBM method provides about 100 years of service life for this tunnel project and minimum maintenance cost.

5.1.4 The environmental factors

The Follo Line is assessed to be a sustainable project. The material and construction methods are chosen with considering the environment. The tunnelling method influences the environment, and if this tunnel excavated by the D&B method required about nine adits to bore this twin tub tunnel but with TBM is only two adits. TBM method was chosen for this project to reduce noise and nuisance.

6 Vättern water tunnel

This chapter will suggest a primary and suitable excavation method for the Vättern water tunnel regarding the geological condition.

Most of the municipalities around the Örebro country lack replacement water-source. The water tunnel aims to transfer water from lake Vättern in a rock tunnel. Vättern water is to be the ordinary and the present spare water. The length of the rock tunnel will be between 35 and 36 km, and the area of the tunnel should be at least 10 m². For a tunnel with an area of about 11 m², the cost for the tunnel will be about 30,000 to 40,000 Kr/m (Israelsson, 2011).

According to figure 5.1 and appendix, 5 tunnels will be excavated from about +80 meter height level from lake to Hallsberg in level +50 meter. The tunnel will have a slope with a 40-meter height difference. Different colours in the topography map present different rock types that the tunnel will pass through, see appendix 1 and 5. These rock types and rock properties will be presented in this chapter.

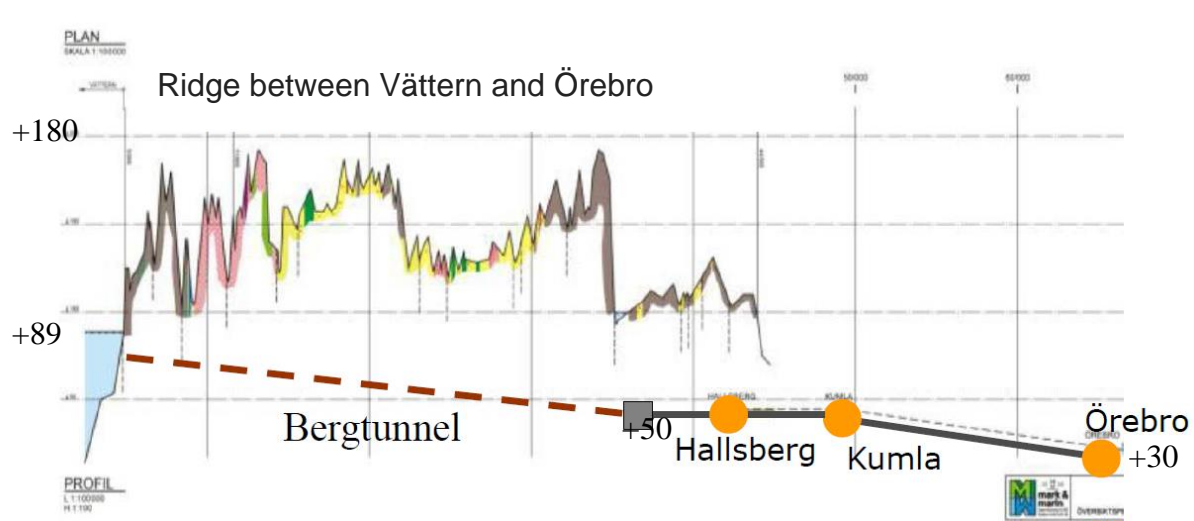


Figure 6.1. Topography of rock tunnel from Vättern lake to south of Hallberg (Ferbe, 2013)

6.1 Geological condition

Based on made field inspection, the geological condition for the Vättern tunnel is generally good for excavation. The water tunnel will pass through three main rock types; gneissic granite, vulcanite and coarse-grained granite. The width of the rock section with highly fractured and weathered is minimal, but there are some deformation zones. The crack distance is from any

centimetres to 1 meter, but the rock quality between the crack zones is good and will not have any unique problem for the excavation of the tunnel.

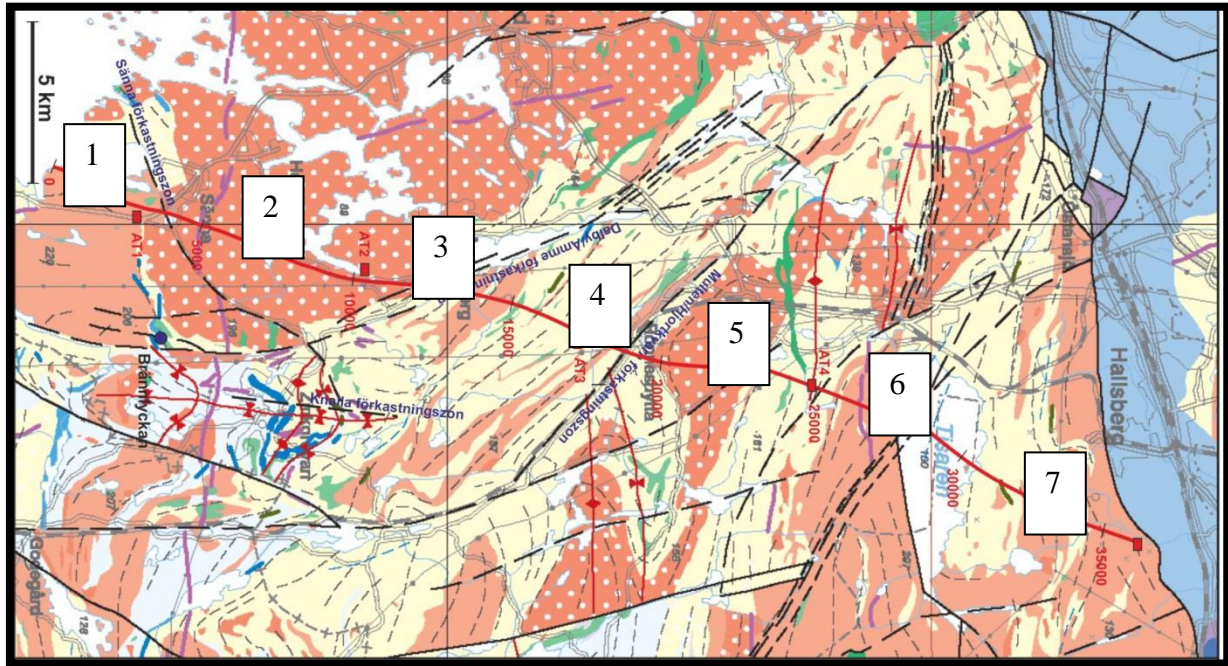


Figure 6.2. Geological map for the rock tunnel (Wallroth, 2012)

The tunnelled line between Vättern Lake and Hallsberg has been divided into 7 sections to describe each section's geological condition in detail (see figure 5.2).

According to table 3.2, the rock with good quality has a Q value higher than 10, with intermediate quality between 0,1 and 10, and the poor rock quality is lower than 0,1. The assessment for rock quality for Vättern tunnel is based on the rock type assessed from geological maps and the deformations zones; the section with deformation zone has a Q value lower than 0,1, the section that has dike rock has Q value between 0,1 and 10 and the section with good quality which means there are no deformation zones and complex rock types has Q value higher than 10. The estimated distribution of Q value for each section is presented in table 5.6. This Q value assessment is made to obtain a first estimate of drive times based on the assumed rock quality.

Section 1,

The area near Vättern lake, Hagerland, has rock type gneissic granite. The other rock types in this section are granite, tonalite, sandstone, and diabase (see appendix 1. In this section, the crack distance on the rock is between 5 -15cm. This fracture direction underlines along Verkaviken (~ N/S) (Wallroth, 2012). From SGU (Sveriges Geologiska Undersökning) rapport, as shown in

appendix 1 and 5, there is a fault zone here, Sänna fault zone. Vättern lake is at a high level, about +89 m, according to figure 5.1 and appendix 5 (Israelsson, 2011).

Section 2.

The rock type around Långviken constitutes coarse-grained granite, and a natural steep runs north of Långviken. According to appendix 1, this section consists of rock types: veined gneiss, granodiorite gneiss, and younger granite.

From SGU rapport, a fault zone fracture extends along the Långviken and then continues to the southwest (Wallroth, 2012).

Section 3.

This area has different rock types, such as volcanic rock rhyolite, gneissic granite, younger granite, veined gneiss, and granodiorite gneiss (see appendix 1. According to SGU, there is some fault zone here and Dalby Åmme fault zone at Åmmelången lake. The rock is fractured with a crack distance from some centimetre to about 1 meter (Wallroth, 2012).

Section 4.

According to appendix 1, the rock type is volcanic rock rhyolite, quartz, and gneissic granite. There is also a fault zone Multan/Hjortkvarn. The tunnel will, in this section, pass through a small lake (Wallroth, 2012).

Section 5.

In this section, the rock types are Augen gneiss, granitic gneiss and granodiorite gneiss, and there is a deformation zone in this section. See appendix 1.

Section 6.

According to appendix 1, the area around the lake Tisaren consists of most rock type granite, gneissic granite, quartz and diabas. The tunnel passes through the Tisaren lake. According to the figure, the Tisaren lake is on level +100 meters. The south strand of Tisaren constitutes soil and loose blocks. There are also some fault and fracture zones in this area.

Section 7.

The most rock type in this area is volcanic rock rhyolite, with a small part of gneissic granite and granite (see appendix 1).

Table 6.1. The Q value of each section

Section	Q >10 [%]	0,1 < Q < 10 [%]	Q < 0,1 [%]
1	50	25	25
2	100	0	0
3	71	0	29
4	64	0	36
5	75	0	25
6	25	46	29
7	100	0	0

6.2 Comparison of tunnelling method for Vättern water tunnel

This chapter suggests a primary excavation method for rock tunnels from Vättern lake to south of Hallsberg based on the identified parameter in chapter 5.1. This chapter will estimate which excavation method is more suitable for the Vättern water tunnel by studying the geological condition, but a definitive answer to which tunnelling method should be chosen is very difficult and will include geological and non-geological parameters (due to many unknown parameters and value). The Vättern water tunnel's geometry data and the geological condition is compared with tables from chapter 5.1 to see how the geometry of the water tunnel and geological condition influences the tunnelling method.

6.2.1 The geometry factors

The tunnel length is about 35 km which is accounted as a long tunnel and is more suitable to excavate by TBM when tunnel calculated as a long tunnel takes more time and cost with the D&B method. The critical area of this tunnel will be a little about 11m² which is possible with TBM, but this area is generally too small for the D&B method. The tunnel's cross-section is not decided yet, but the circular tunnel shape may be a more suitable shape for a water tunnel. According to a pre-study from Norconsult Company for a tunnel with 10m² the pressure loss is 0.453m with and 0,131m with the TBM method. The shape of the tunnel will be circular with TBM, loss of pressure will be much less with circular shape (Israelsson, 2011).

6.2.2 The Geological factors

Based on made field inspection, the geological condition for the Vättern tunnel is generally good for excavation. The water tunnel will pass through three main rock types; gneissic granite, vulcanite and coarse-grained granite. The width of the rock section with highly fractured and

weathered is minimal, but there are some deformation zones. The crack distance is from any centimetres to 1 meter, but the rock quality between the crack zones is good and will not have any particular problem for the excavation of the tunnel.

The rock tunnel will be excavated at a max 100-meter depth below the surface. The excavation in very deep depth has a negative impact on TBM machine skin due to ground pressure, but excavation at 100 meters deep is suitable for using the TBM method and D&B method. The rock tunnel is 35 km long with 40-meter slopes, which means the tunnel is almost straight. Using the TBM method in high slope is not possible, but for this rock, the tunnel will be no problem and excavation by both methods is possible. Access tunnel that will have a high slope is assumed to be excavated by the D&B method. The excavation of the water tunnel will not have any sharp angle that will affect the choice of the tunnelling method.

The favourable crack distance for TBM is between 20 cm to 6 m; therefore, the TBM method in this tunnel will not be any problem due to the properties of the fractures. Generally, the crack distance in the tunnel line is almost between some centimetres to about 1 meter. The close spacing of discontinuities reduces the drilling accuracy in the D&B method more time and cost. According to figure 2.6, the rock types in this tunnel the CLI value is about 20%, these rock types should cause minor tool wear due to figure 3.2. This means excavation by the TBM method will not have high cutter wear.

6.2.3 The time and cost factors

Calculation of time and cost for this tunnel project currently is complicated and requires more investigation for every parameter that influences the project's time or cost. Generally, the total time with TBM is shorter, but the starting time between the signed contract and start boring is more than the D&B method.

The tunnelled line between Vättern Lake and Hallsberg has been divided into 7 sections to describe each section's geological condition in detail (see figure 5.2).

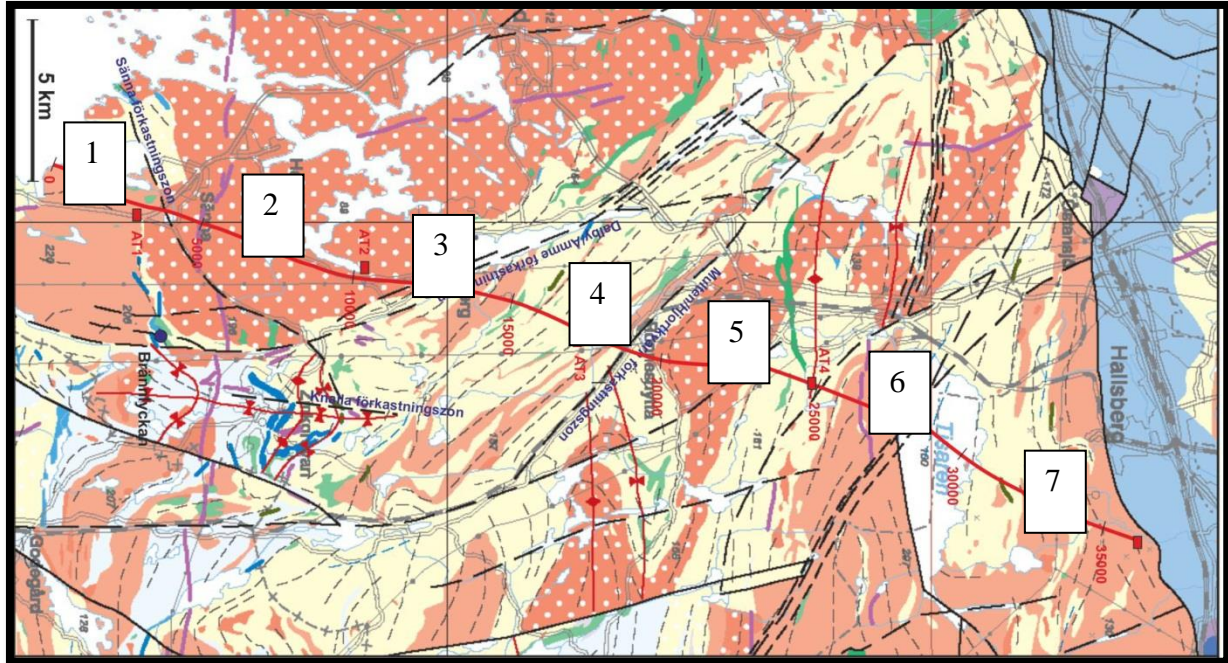


Figure 6.3. Geological map for the rock tunnel (Wallroth, 2012)

The excavation cost of the water tunnel for these two different tunnelling methods are calculated by the NTNU-model, which is presented in chapter 2.3. The excavation cost for TBM varies depending on good and poor portability for TBM and good and poor rock conditions for the D&B method. The excavation cost for the respective method is taken from figure 2.9 to suggest an excavation cost for the Vättern tunnel.

Since the cross-section area is limited for using the D&B method, the excavation cost for the D&B method is taken with areas 15 m² and 10 m² for TBM. The distribution of poor and good portability for the TBM method is based on estimates Q values. Good portability is when the Q value is between 0,1 and 10, while poor portability is when the Q value is higher than 10 and lower 0,1. The distribution for the D&B method is also based on the Q value. The good rock condition has a Q value higher than 10, and the poor rock condition has a lower than 10. This suggestion about the excavation cost of the Vättern tunnel is excluded from grouting, support system and access tunnels. It is just the excavation cost. Thus the total excavation cost of the Vättern tunnel presented in table 5.7 by TBM is about 427 million SEK and about 270 million SEK by D&B method. The high excavation cost of TBM may depend on the geological condition, the variation of rock type, the Q value that most are not suitable for TBM (higher than 10 or lower 0,1).

The tunnelled line between Vättern Lake and Hallsberg has been divided into 7 sections to describe each section's geological condition in detail (see figure 5.2).

According to table 3.2, the rock with good quality has a Q value higher than 10, with intermediate quality between 0,1 and 10, and the poor rock quality is lower than 0,1. The assessment for rock quality for Vättern tunnel is based on the rock type assessed from geological maps and the deformations zones;

The estimated distribution of Q value for each section is presented in table 5.6. This Q value assessment is made to obtain a first estimate of drive times based on the assumed rock quality.

Tabell 5.7. Estimated excavation cost for TBM and D&B on general cost from Zare (2007)

	TBM good boreability	TBM poor boreability	D&B good rock condition	D&B poor rock condition
Excavation Cost [SEK/m]	5525	13260	7182	8840
Total (m)	4800	30200	24250	10750
Excavation cost for Water tunnel	26520000	400452000	174163500	95030000
Total excavation cost [MSEK]		427		270

The estimated costs are based on the same cost for $Q > 10$ and $Q < 0,1$. Rock with poorer quality generally increases the risks of high support, slow advance rate. For high Q value, only the cost wear and tear is affecting, but reinforcement costs will be marginal.

It may be easier to predict which method is more suitable by comparing the advance rate of these two tunnelling methods. Calculating the advance rate of these two excavation methods for the Vättern tunnel measured by the rock quality of this tunnel in sections will help to predict which method will have a higher advance rate on this rock mass. The data for advance rate is taken from figure 2.11, this figure shows the advance rate depending on Q value, and the support system is also included. The use of figure 2.11 and not figure 2.10 is because the support system is not included in figure 2.10. Table 5.7 presents the percentage of each section for different Q values.

Figure 5.3 and Table 5.9 present the calculated advance rate for both excavation methods with the help of the Q value assessed from the geological map (Appendix 1-5). The assumption advance rate for the D&B method and TBM is estimated for every section presented in table 5.8, and each section is about 5000 meters. As shown in figure 5.3, the operation time by TBM is faster compared to the D&B method. The average advance rate by the TBM method is about 56 m/week and 39 m/week by the D&B method. Compared to the Oslo-Skien tunnel advance rate with TBM is also higher, and the length of the Vättern water tunnel is another parameter that can

be compared to the Oslo-Skien tunnel, the extended length tunnel is more suitable to excavated by TBM.

Table 6.2. The operation time for each section by use of TBM and D&B based on Q value

Sections	TBM [Week]	D&B [Week]
1	106	174
2	62,5	56
3	117	184
4	58	61
5	109	167
6	111	197
7	62,5	56

Table 6.3. The average advance rate for TBM and D&B

	TBM	D&B
Total Week	627	894
Total Length [m]	35000	35000
Average Advance rate [m/week]	56	39



Figure 6.4. Advance rate of two tunnelling methods for Vättern tunnel

6.2.4 The environmental factors

According to pre-study from Norconsult, the water leakage to tunnel without grouting is about 10 l/min·100 m, and the reasonable estimate of the water leakage for the current tunnel is about 2 – 5 l/min·100 m (Israelsson, 2011), this means the required grouting will take more time and cost by TBM method because with D&B method grouting is generally included.

6.2.5 Suggestion to primary excavation method

It assumed the main parameters that affect the tunnelling method are the parameters that affect the time and cost of the tunnelling operation, and according to chapter 5.2, the parameters that affect more the time and cost are the hardness, area, length, etc. rock quality and variation of rock quality. To estimate a primary exaction method for the Vättern water tunnel studied the parameters by table 5.5.

The diameter of the tunnel is about 4 m which is less suitable to be excavated by D&B. The length of the tunnel is long and will cause more cost and time with the D&B method.

The rock type and rock quality vary in this tunnel. The variation of rock quality and the cracks in the tunnel affect more cost and time for the TBM method.

The rock is almost hard, and the Q value in most of the tunnels is higher than 10, and the cost and time with the TBM method will increase.

Regarding these parameters, the calculated advance rate, and a suggestion about excavation cost, the TBM method has a higher advance rate but costs more than the D&B method.

According to chapter 4, the advance rate for Oslo tunnel with TBM is about 90 m/week and with the D&B method is 15-28 m/week. Comparison of Vättern water tunnel with Oslo tunnel, the advance rate for TBM is lower, but D&B is higher. These two tunnels are long, the Oslo tunnel is about 20 km, and the Vättern tunnel is 35 km long. According to the Vättern tunnel length, area, geological condition, and advance rate suggest that TBM method may also be a suitable excavation method for the Vättern tunnel.

7 Conclusion and Recommendation

Several different factors affect the choice of a tunnelling method. Having more sources and data makes it easier to make a well-founded decision about the excavation method, but it is essential to understand that it is challenging to find a definitive answer to which tunnelling method should be chosen.

The comparison of the two tunnelling methods, TBM and D&B, has concluded that the geological condition plays a key role in determining the tunnelling method by affecting the time and cost of the tunnelling project. According to table 5.5, the main parameters that may influence the time or cost of the tunnel project are rock hardness, area, length, rock quality and variation of rock quality.

In this project, the Oslo - Skien railway tunnel was studied as a case study to sort out which parameters influenced the choice of excavation method and why TBM was chosen. By studying the geological condition and report from Norwegian Jernbaneverket, the advance rate, CLI and DRI, and length are essential in determining the excavation method. The rock quality is good with low variation of rock type, which can be more suitable for TBM. According to Norwegian Jernbaneverket, the advance rate for TBM due to geological conditions is higher than the D&B method, and as mentioned in chapter 5.1, excavation of a long tunnel is more cost-effective with the TBM method.

Comparing the Vättern water tunnel with Oslo - Skien tunnel, both tunnels have almost the same geological condition and geometry and rock type. The dominating rock type in Oslo – Skien tunnel is gneissic rock, and the tunnel is about 20 km long. The water tunnel from lake Vättern to Hallsberg also passes through the same rock type, about 35 km. This means the excavation of a water tunnel with TBM can also be a suitable option.

The deeper study and investigation on the water tunnel's geological condition can increase the reliability of the choice of excavation method for the water tunnel. A suggestion about the estimated advance rate based on values from Zare (2007) for the Vättern water tunnel is based on Q value estimation from geological maps along the tunnel. The estimated average advance rate for the TBM method is about 56 m/week and 39 m/week for the D&B method. Comparing this to the Oslo tunnel, the advance rate with the TBM is lower, but with the D&B, this was found to be higher. The diameter and the length of the Vättern water tunnel are parameters that affect, and according to table 5.5, the excavation by TBM for this tunnel can cause less cost and time. In this tunnel, there is a variation of rock quality, which will affect the TBM cost and time, but the advance rate as mentioned is higher with TBM, but the cost will also be higher. Thus the suggestion about the primary excavation method for the Vättern water tunnel may be more suitable with TBM.

This study shows that it is difficult to determine a definitive tunnelling method based on the technical parameter. The great advantage of the TBM method usually has a higher advance rate in ideal rock conditions and its limited impact on the surrounding rock environment. The advantage of the D&B method is its flexibility in cross-sectional and short start-up time. The

significant disadvantage with TBM is the high cost of this method, whereas for the D&B method is the low advance rate.

The tables in chapter 5.1 illustrate the main geological parameters that can influence the tunnelling method, which can be a basis for further and deeper study in various parts.

As pointed out before, this choice is not a definitive answer and to be more sure which method has the highest performance rate required more study on other parameters that also influence the tunnelling method.

To increase the probability of determining the tunnelling method and confirm which is more suitable, it even includes parameters such as total operation time, the accessible area for tunnelling, contract form.

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