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UNIVERSITY OF STAVANGER

Application of water jet cutting for tunnel boring

A Master's Thesis

By

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Department of Industrial Economics, Risk Management and Urban Design

Submitted in partial fulfillment of the requirements

for the degree of
Master of Science,
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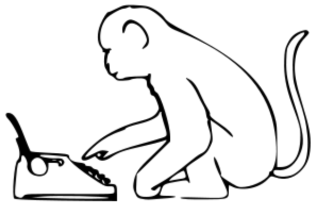

____________, ____________________________
Date, Erik Nygårdsvoll

I dedicate this thesis to my mother Sissel Nygårdsvoll,

thank you for convincing me not to become a truck driver.

ABSTRACT

Water jet cutting has proven to be an effective technology for machining various materials, and providing a distinctive advantage over other cutting methods. Its application in the engineering industry is evolving and improving annually, and is one of the fastest growing machining processes. This thesis addresses the idea of applying water jet cutting technology as a new method for boring through rock in the construction of infrastructural tunnels. So far water jets have only be applied as a supplement to enhance traditional tunneling methods, but with the development of water cutting technology, new applications are increasingly becoming more relevant.

In order to grasp the potential of Water Jet Tunneling, research has be made to further understand how tunnels are constructed, what tunneling methods are currently being used, how they work, and how water jet cutting works.

The most common tunneling method used in Norway today is drilling and blasting (D&B), with an average advance rate about 8 to 10 hour per 5-meter advancement section. An alternative method is via a tunnel-boring machine (TBM), however, despite its fairly low operating cost per kilometer (compared to D&B), the initial cost of installing such a machine is too high relative to the length of the most tunnels constructed in Norway. Making D&B the most relevant competitive method for Norwegian tunneling projects.

The findings of the research suggest that further development need to be devoted to find a new water jet cutting method to increase the cutting depth on harder rock, like granite and meta-sandstone, beyond the conventional limit of approximately 30 cm, in order to at all be competitive for tunneling purposes.

ACKNOWLEDGMENTS

This master's thesis marks the final requirement for a Master of Science at the University of Stavanger. In order to enroll a master's in Industrial Economics, it is required to obtain a Bachelor of Science. I have acquired my bachelor's degree in Mechanical Engineering, and have further specialized my master's degree in Risk Management, and Contract and Project Management.

I would like to extend a gratitude to those who have helped me write this thesis.

Thank you to professor Erik Skaugen at the University of Stavanger, for initiating the idea of applying high-pressure water jet cutting to tunneling mechanics, and for your thoughts and contribution to the subject.

Thank you to Anne-Merete Gilje and Bjørn Dokken at the Norwegian Public Road Administration for listening and providing me with your expertise on the subject of Norwegian tunneling, it was a great help.

Thank you to Jostein Aleksandersen for your comments and helping me structure this thesis, may you have a pleasant read.

Thank you to, whomever it may concern, possibly somewhere in mid 15th century Yemen, for being the fist to figure out that poring hot water over some roasted dry beans is to be considered a good idea. Gratitude to those of my friends whom has spent many hours with me enjoying this particular brew, and kept me motivated.

Thank you security guard for not throwing me out past 11 pm, except that one time.

…Oh, and thank you Marcus Risanger for making that one figure on page 63, trying to make a pie chart in Excel, what was I thinking!

June, 2014

Erik Nygårdsvoll

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LIST OF ACRONYMS

Acronym	*Definition*
AADT	annual average daily traffic
AWC	abrasive water jet cutting
CAGR	compound annual growth rate
CNC	computer numerical control
D/B	design-build
D/B/B	design-bid-build
D&B	drilling and blasting
EMD	electrical discharge machine
HAZ	heat-affected-zone
LED	light emitting diode
NATM	new Austrian tunneling method
NPRA	Norwegian Public Road Administration
ROP	rate of penetration
SEM	sequential excavation method
TBM	tunnel boring machine
UPS	uninterruptible power supply
WJC	water jet cutting
WJT	water jet tunneling

LIST OF SYMBOLS AND UNITS

Symbol	*Unit*	*Definition*
A	m^2	cross sectional area
A_N	m^2	cross sectional area of nozzle
C_N	-	friction coefficient in nozzle
F	N	force
F_N	N	nozzle force
t	h	hour
HP	HP	horse power
l	km	kilometer
E	kW	energy
M	$\times 10^6$	million
mbsl	m	meters below sea level
σ	MPa	uniaxial compressive strength
P_N	bar	nozzle pressure
PSI	lbf/in^2	pound per square inch
P_t	bar	threshold pressure
Q	m^3/s	volumetric flow rate
sec	s	second
v	m/s	velocity
ρ	kg/m^3	density

PART I: Introduction

Chapter 1

Preface

Completing this master's thesis I have learned much about two professions (tunneling and water jet cutting) that I, to begin with, knew only a fraction about. But most importantly I have approached a specific idea and focused on establishing the knowledge base needed in order to better understand its potential. This approach is applicable to any means of innovation, and is therefor a very good skill to develop. We know that it is theoretically possible to apply water jet cutting (WJC) as a method for tunneling, so the question is not '*can it be done?*' but rather '*should it be done?*' This is the main question I wish to address.

1.1 Introduction

The idea of introducing high-pressure water jets for tunnel construction came about as a semester project, for a course in entrepreneurship at the University of Stavanger. The project itself, looked at a scenario in which the students were to present a concept idea for an imaginary group investors, the main goal was to deliver a feasible business model along with a presentation, the reality of the idea was, on the other hand, only limited to what could arguably be possible in the given context. For the project, we assumed that pressurized water jet tunneling was already tested and proven to work efficiently, thus the next step for the 'company' were to acquire enough capital in order to construct the machines needed to perform a tunneling project. I personally grew very keen on taking the idea one step further; in figuring out whether this idea actually had the potential we initially assumed it had. In order to do so I would need to learn more about the current state of tunneling, what methods exists, how efficient they are, and the scope of tunneling activity, more specifically in Norway. I would also need to map the current use of WJC, and investigate the potential of applying it as a new technique for tunnel construction.

The research for this thesis includes literature study, various interviews and personal conversations with professionals in their respected fields, and technical, cost, and process evaluations. The interviews and personal conversations were conducted merely to better understand how methods and theory are applied in Norway, and to see if there are any variations, thus providing a better perspective. Although some difficulties were encountered, as getting contact with some of the key people took more time and effort than anticipated, slowing down the process. This is understandable, and is to be expected as most people have a busy schedule.

1.2 Structure

Key subjects that are important to this thesis are tunneling and water jet cutting mechanics, process evaluation and entrepreneurship. The thesis consists of four parts, dividing the chapters into their area of relevance; this includes introduction (1), background (2), discussion (3) and conclusion (4). The fist part, as this section includes, aims to provide an introduction to the thesis, answering some personal questions (i.e. what has been learned, where did the idea come from, etc.), as well as breaking down the structure of the thesis. The objective of the seconded part is to provide the information that is needed to base the concluding opinion upon, thus substantial effort is taken into covering these chapters. It is important to understand the fundaments of basic tunnel construction and the mechanics high pressure water jets, along with a description of what the Norwegian situation for tunnel construction looks like. In the third part, the evaluation of the methods and theory presented in the previous chapters, will be taken into account for the discussion and evaluation of the initial concept idea, evidently the conclusion (part 4) will finalize the thesis.

1.3 Assumptions and limitations

For this thesis, interviews have been limited to personnel from the Norwegian Public Road Administration, and professor Erik Skaugen at the University of Stavanger. The scope of this thesis have been limited to an extent, practicalities for optimal cutting pattern will not be discussed, support methods beyond the bare essentials are not discussed, this includes grouting and freezing. Geographical limitation as been set to what is practiced in Norway.

PART II: Background

Chapter 2

Introduction to tunneling

The benefit a tunnel contributes to any given society is opening the infrastructural connectivity within a nation. It may also provide a better relation with its surrounding countries. It contributes to a better quality of life, as moving traffic under ground relives its impact on the surrounding environment. Economical advantages are also allied with the construction of tunnels, as it often provides a more convenient means of travel, respectful to both private, public and commercialized use. Tunneling in general is also often used for other reasons than just tunnel construction; there are a great number of examples where tunneling helps make use of underground space for storage, power and water treatment plants, civil defense, safe operation, environmental protection and energy savings to name the most common.

2.1 Tunneling philosophy

Tunnels are very different compared to other structures, mainly concerning civil engineering, in that the building material is not so easily defined, and the properties regarding its foundational structure is vastly dependent on understanding the material, in particular its strength and stability characteristics. As for buildings, bridges and similar structures, materials consists of much more testable properties.

When considering an above ground structure, material properties are managed with less difficulty; quality testing and control are easier accessible during production procedure, and affecting loads for which the structural analyses are carried out are mostly known. Because of this, safety factor relative to failure can be determined, due to a better understanding of the perimeters that are involved in the construction phase.

Whereas for tunneling, the ground compose a lot of uncertainty, and the general inability to influence the material properties, beyond ground improving techniques, limits the ability for quality management. The magnitude of loads affecting the construction is for the most part based on assumptions and past experiences. Due to the number of uncertainties related to material properties and load distortion, it is not possible to determine a quantitative safety factor.

It will in most cases be up to engineering judgment to interpret the site investigation report and come with a recommendation for the best suitable design and construction technique. Only a limited test samples[1] can be taken from the initial site investigation, and its result will only represent a small fraction of the total ground to be affected by the tunneling operation. All though it is arguable that the ground allows three-dimensional stress redistribution around the tunnel, thereby take some if the load, it is a misconception to assume that this will act as a continuous distribution. The real percentage of the grounds load-bearing capacity is therefor very difficult to determine. As a result, most questions related to stress distortion, maximum displacement as a cause for collapse, and the relative danger of a crack in the tunnel lining, rarely have a single answer, with the exception of 'it depends'.

2.2 Notations in tunneling

Some of the following notations will be used in the following chapters, when considering the cross and longitudinal sections of a tunnel. The various locations are denoted by the indicated names shown in Figure 2-1 and Figure 2-2. In addition, the word 'chainage' is used to identify a point along the axis of a tunnel defined by its distance from a fixed reference point.

[1] on the initial site investigation there will be taken several borehole core samples, the number of samples are adjusted for, dependent on the individual site.

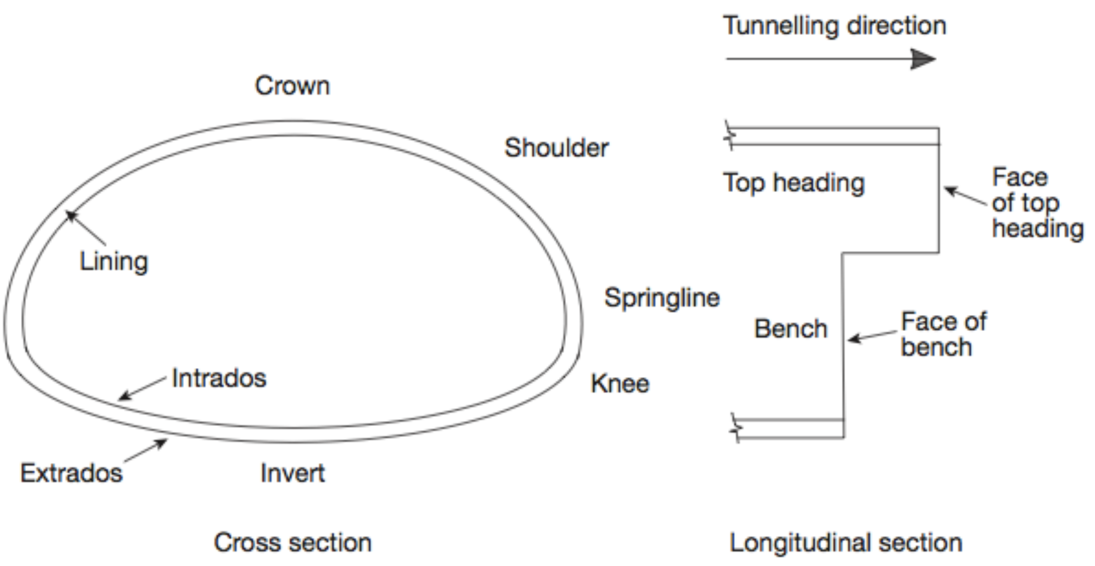

Figure 2-1 Cross section and longitudinal section of tunnel heading

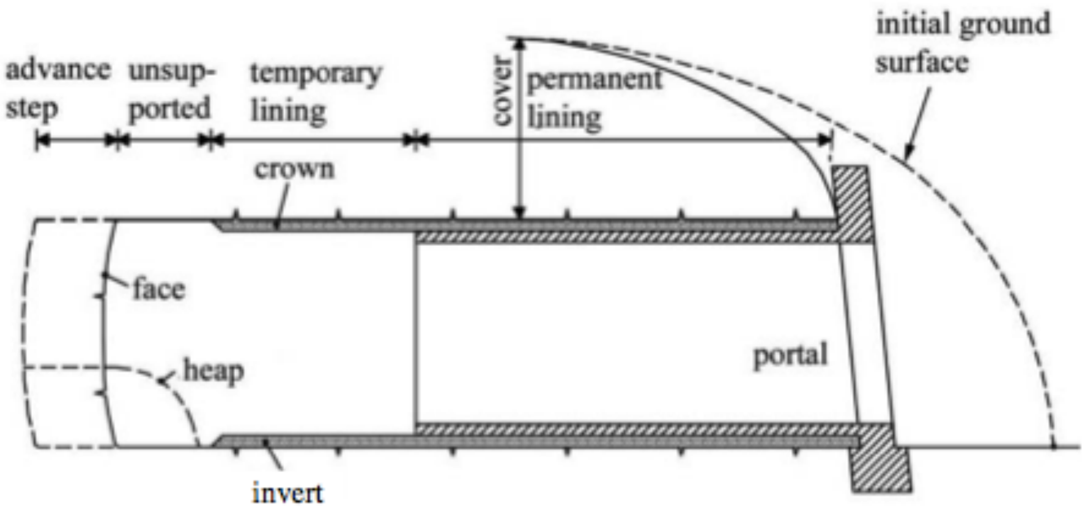

Figure 2-2 Longitudinal section of heading

2.3 Tunnel profile

The cross sectional shape of the tunnel is referred to as a profile. This shape varies with respect to the initial intent for the tunnel, as well as which tunneling method is applied. The most common profiles, on the other hand, are the 'mouth' profile, shown in Figure 2-3 and the circular profile, shown in Figure 2-4. Furthermore, the selection of profile aims to assess different properties with respect to, maintenance, ventilation, risk assessment, avoidance of claustrophobia of end-user, and utilization of space, i.e. circular profiles are better targeted towards single lane traffic, whereas the mouth profile are more useful toward a multi lane traffic.

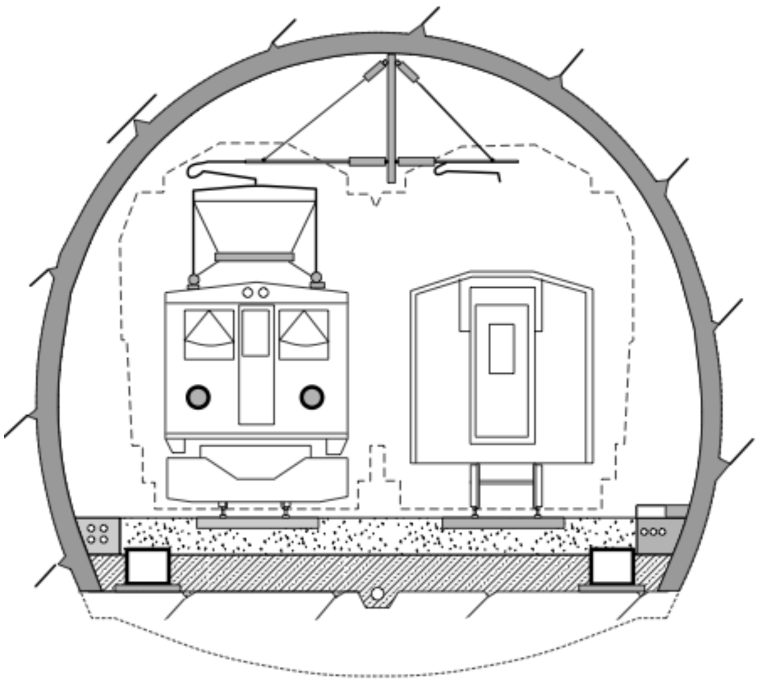

Figure 2-3 Mouth profile

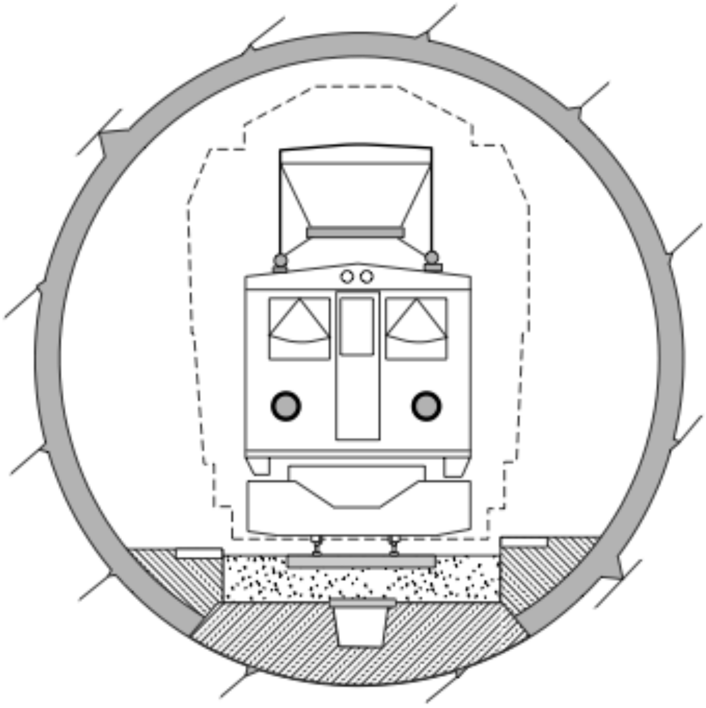

Figure 2-4 Circular profile

When considering the design of a road tunnel, one should, in addition, take into account, expected traffic capacity, safety measures[2], facilities for breakdown[3], horizontal and vertical alignment, as well as widths of several elements that are key to maintain the safety standards required. Such elements can be seen in Figure 2-5[4], although the regulations for their design can vary from country to country. The elements shown in the figure are gathered from PRARC recommendations.

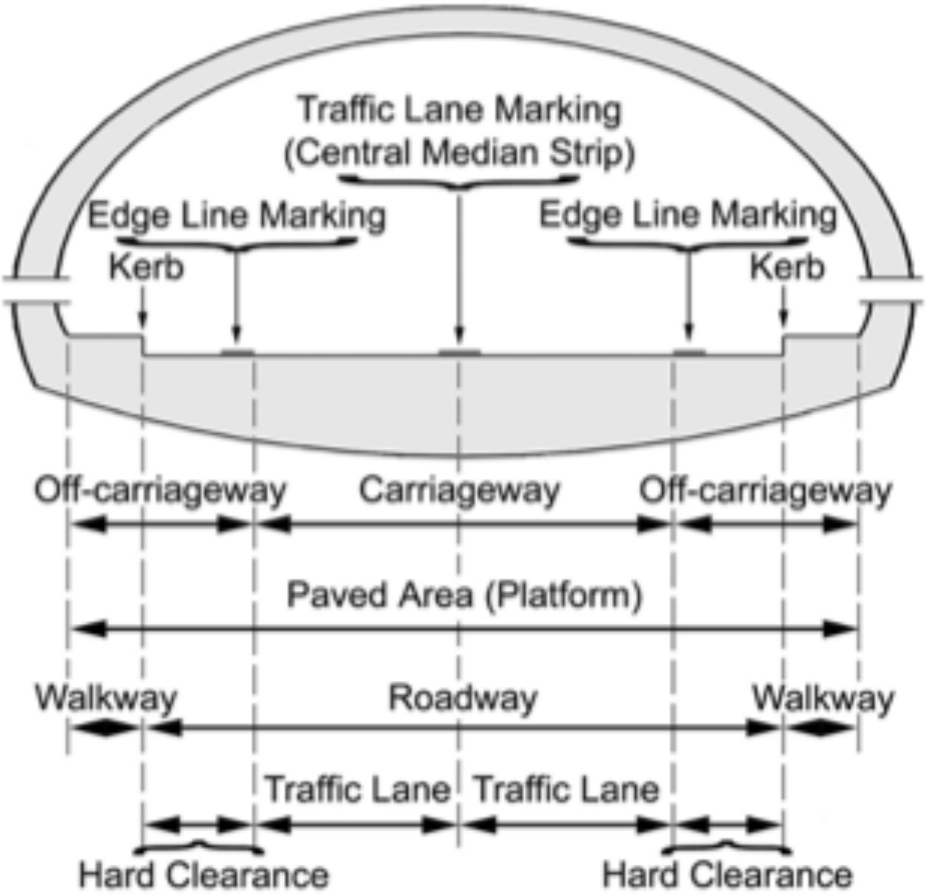

Figure 2-5 Partition of road tunnels according to PIARC

[2] evaluation of safety measures for road tunnels should include emergency exits, evacuation tunnels, lay-by's, vehicle turn around points.
[3] a breakdown is defined as a vehicle stopping inside a tunnel for any reason besides traffic congestion.
[4] World Road Congresses; Technical Committee on Road Tunnels PIARC, Cross Section Design for Bi-Directional Road Tunnels, 2004.

2.4 Statistical review of Norwegian tunnels

It is estimated that in Norway alone there are approximately 1,000 road tunnels, with a total distance of 800 km. Every year new tunnels are constructed adding at a rate of 20 to 30 km/year. As of March 2014, there are a total of 30 underwater tunnels, with more to come, these tunnels can reach depths up to 260 mbsl, and are some of the deepest road tunnels in the world. High traffic density tunnels exist mostly in Oslo, where the daily traffic volume[5] reaches 100,000. Though most other tunnels have an average daily traffic density of 5,000.

A vast majority of Norwegian tunnels are constructed through solid ground, mostly by the use of the drilling and blasting (D&B) technique (see section 3.2). Tunnel boring machines (TBM) are rarely used in Norway, as most of the tunnels constructed are not sufficiently long enough for the method to be economically beneficial.

The total amount of active tunnels in Norway as of April 2009, is give by the Table 2-1:

Table 2-1 Amount of active tunnels in Norway as of 2009[6]

	Single tube	*Twin tube*	*Underwater*	*Underwater twin tube*
< 100 m	118	1	-	-
100 - 499 m	305	16	-	-
500 - 999 m	148	10	-	-
1,000 - 3,000 m	145	12	4	-
> 3,000 m	45	2	16	1

5 daily traffic volume is also called Annual Average Daily Traffic (AADT) = Total traffic flow in one year divided by 365 days. Expressed in vehicles per day. Tunnels exceeding AADT values of 10,000 vehicles per day per lane, are recommended being constructed using twin tube tunnel with bi-directional traffic. As twin tubes provides better safety measures and are also preferable for maintenance.

6 NPRA. "*Tunellteknikk," Statens Vegvesen. March 17, 2014.* http://www.vegvesen.no/Fag/Teknologi/Tunneler

2.4.1 Future development projects

The Norwegian Public Road Administration (NPRA) has at any time more than 500 roads under construction on national and local roadway.

- ~350 contracts under 10 M NOK
- ~100 contracts from 10 to 50 M NOK
- ~50 contracts over 50 M NOK

NPRA does not have its own project/construction department since 2003, all development projects are enlisted on DOFFIN[7], and contractors are then selected by competition. Where the most economically beneficial offer is selected.[8] Contract development is further discussed in section 2.7.

2.5 Installations in tunnels

There is a significant amount of work related installments of modern tunnels, work that may not be fully appreciated by most. The general topics of installations are as following:

- Traffic control
- Telecommunication
- Illumination
- Drainage
- Ventilation (during construction and after)
- Fire protection

More detailed technological equipment might include: power supply (also UPS[9]), illumination computers, CO-sensors, NO-sensors, airflow monitors, manual fire alarms, color monitors, video surveillance, emergency call devices, antennas for radio waves, amplifier stations for mobile phone transposes, etc.

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[7] national database for public procurement (DOFFIN)
[8] NPRA. "*Utbyggingsprosjekter," Statens Vegvesen. November 7, 2012.*
http://www.vegvesen.no/Fag/Veg+og+gate/Prosjektering+og+bygging/Utbyggingsprosjekter
[9] uninterruptible power supply (UPS)

2.5.1 Traffic control

According to a study on road safety in tunnels, performed in 2001, the frequencies of accidents in tunnels are on average 50% lower than on open roads.[10] Another risk management study conducted for Norwegian tunnel safety, states that the accident rating (i.e. number of accidents) per 1,000,000 vehicle kilometer for tunnels are 0.15, compared to 1.05, 0.75 and 0.4 on municipal roads in high-density, semi-density and sparsely populated areas respectfully.[11] The mean reasons why accident ratings are lower in tunnels are because the driver generally respects speed limits in tunnels, the driver also rarely encounters issues with fog, rain, wind, snow or ice. However, even though accident ratings are lower in tunnels than on open roads, one should note that accidents in tunnels are in most cases more severe.

To help manage traffic control, and to endorse traffic safety, certain measures are applied, including:

- Road signs
- Guiding equipment, such as, floor labeling and side reflectors
- Height control, responding to oversized vehicles
- Alarm sensors to notify drivers of emergencies before entering the tunnel
- Video monitoring high density tunnels or tunnels longer that 1,500 m
- Speed sensors, to encourage users to respect the speed limit

2.5.2 Telecommunication

Most tunnels are equipped with communication devices that will allow users to communicate with the authority for health and safety hazardous in the likely event of an emergency. These are normally provided for tunnels greater then 500 m long, and are spaced out through the entire tunnel with a fixed distance (150 m). Other than equipment for emergency calls, service phones and radio communication (for fire-brigade, police and road administration) are also common.

[10] G. Brux, *Safety in road tunnels, Tunnel*, 2001
[11] OECD, *OECD Studies in Risk Management, Norway, Tunnel Safety*, Norway, 2006

2.5.3 Illumination

As a safety measure and a convenience towards end user, tunnels are illuminated to ease the transition from the natural light on open roads relative to that in tunnels. The philosophy in tunnel illumination is to provide sufficient lighting to reduce the risk of accidents, while also reducing the amount of electricity needed to maintain a functional tunnel; this is done by gradually reducing the density of illumination toward the center of the tunnel. With the development of light emitting diodes (or LED), civil contractors are increasingly using this technology to illuminate tunnels, providing a power efficient light source. To achieve maximum illumination, the inner wall of the tunnel is covered by a bright layer, thus reflecting light from the ceiling and vehicle headlight. Gradually over time asphalt dust and exhaust from vehicle pollution will cause the wall to darken; this is regularly cleaned during maintenance.

2.5.4 Drainage

There are three main sources of water that need to be diverted from the tunnel, ground water, service water (e.g. tunnel washing) and day water (e.g. rainwater or melting ice entering the portals). Due to this, tunnels are constructed with a certain incline, for underwater tunnels, the lowest longitudinal point will be located near the middle of the tunnel, in which case pumps are necessary to divert water and prevent flooding.

2.5.5 Ventilation

Ventilation is important in order to maintain a habitable environment, it is important to note that there are different requirements for ventilation during construction (i.e. tunnel heading), and service ventilation during regular use.

Ventilation during construction: The requirement for ventilation during tunnel heading is higher than under normal operation. Oxygen levels should not fall below 20 vol. %[12], as it will cause a hazardous environment for construction workers. Workers expose themselves for a longer duration than otherwise normal, increasing oxygen consumption; combustion engines also increase the need to supply oxygen. Other pollutants also have to be removed, such as: excavation dust, blasting fumes, gas egression form rock, radon

[12] air contains 20 vol % oxygen, this value should be preserved in any work related environment, 15 vol % is the critical minimum.

decay, and dust from shotcreting. Regarding the subject of ventilation requirements, there exist standards and recommendations for fresh air supply given certain tunnel cross sections as well as ratios of fresh air per kW diesel power.[13] The fresh air is usually directed to the face of the excavation, creating a convenient airflow that pushes the polluted air out the portal. It is also important to note that a better airflow will remove moist, causing the shotcrete to harden faster.

Ventilation during normal operation: For the same reason as during construction, ventilation is necessary in order to reduce the concentration of polluted air. It is also an important factor to secure visibility and direct a single directional flow in the event of a fire. The amount of fresh air needed should be calculated with respect to tunnel dimension and estimated daily traffic volume.

2.5.6 Fire protection

Fire hazard are considered to be more dangerous in the confined space of a tunnel, for this reason it is very important to take precautionary steps to guard in the likelihood of a disaster. Over the years there have been a numerous incidents with fires breaking out in metros and tunnels alike, leading to minor and more sever injuries, and even fatal loss of human life. In Norway, August 2013, a trailer started to burn in Gudvangatunnelen hospitalizing 73 people, severely injuring 6 with intoxication, no fatalities. The result of a fire may also damage the concrete walls, as water entrapped in the pores of the concrete transform into vapor, increasing pressure and causing flakes of concrete to fall off. Besides this, thermal expansion is also an issue that needs to be addressed. There are methods to increase the fire resistance of concrete, such as avoiding minerals that disintegrate at higher temperatures.[14]

This can be broken down into three categories:

- Precautionary measures (fire resistant construction material, escape routs, etc.)
- Cautionary measures (heat, gas, smoke, flame detectors)
- Active mitigation (fire extinguisher, fire blanket, fire hose)

[13] The British Standard, BS 6164.2011, stating a fresh air recommendation of $9m^3/(min.m^2)$ tunnel cross sectional area, $1.9m^3/min$ per kW diesel power, $2m^3/(min.kg$ explosives)
[14] "System Hochtief" and "Lightcem"-concrete are examples of such fire resistant concrete. "Lightcem"-concrete can withstand heat up to 1350°C for 2 hours without taking damage

Along with fire protective construction material, safety monitors such as heat, gas, smoke and flame sensors can be used.

2.6 Tunnel safety ratings

EuroTAP (or European Tunnel Assessment Program) is a commission established in 2005, focusing on raising awareness about tunnel safety, by conducting studies on tunnel safety for a portion of European tunnels. Norway was included in the study conducted in 2008 and 2010. The tunnels are tested on the following criteria's:

- Tunnel system (14%)
- Light and power supply (7%)
- Traffic and traffic surveillance (17%)
- Communication (11%)
- Escape and rescue routes (14%)
- Fire protection (18%)
- Ventilation (11%)
- Emergency management (8%)

The result of the study is shown in Table 2-2, rating used to describe safety of road tunnels are: very good, good, acceptable, poor, and very poor in respected order.

Table 2-2 Results of the EuroTAP study on road tunnel safety.[15]

Test year	*Tunnel*	*Length [km]*	*AADT*	*EuroTAP-rating*
2008	Eikefet	4.9	1,970	Very poor
	Jernfjell	2.4	1,438	Very poor
	Matreberg	1.4	1,470	Very poor
2010	Hanekleiv	1.8	21,200	Good
	Botne	1.4	21,200	Acceptable

EuroTAPs studies are an important tribute to map the average tunnel safety; the overall goal is to raise awareness in order to, hopefully, reach a uniform safety standard all over Europe. The effect of the EuroTAP-rating can be demonstrated by a similar test done in 2002, where a Spanish tunnel near Alicante was rated one of the worst tunnels in Europe (very poor), the responsible authority invested 5 million euros, and by 2005 they had improved the tunnels safety level to a much higher standard (good).

2.7 Plan, contract and cost

Tunneling address many aspects throughout the entire project phase. The planning of a tunnel construction, and the stages through the entire project cycle involves a range of different processes, some of them given following:

- Finance
- Site investigation, desk study
- Preface planning (waist disposal and water source)
- Tendering/bid phase
- Design

[15] EuroTAP. "*EuroTAP – The Future of Tunnel Testing," EuroTAP.* Germany. http://w.eurotestmobility.com/eurotappub.php

- Construction
- Operation (traffic logistics, road signs etc.)
- Maintenance
- Casualties' management (accidents)

Even though tunneling has a relative high risk factor due to the difficulties anticipating accurate ground condition, much of the risk is also associated with contamination, third-party impacts (such as unknown utilities, settlement induced damage, delay of property procurement and permit acquisitions) and design flaws. The overall cost of the project is also neither only dependent on technical features, like ground quality nor current rates, but also on other factors, such as:

- Project culture
- Laws and standards
- Legal procedures
- Tendering
- Risk management
- Contract

Table 2-3 will give an impression of cost relations for some recent tunneling projects executed in Norway over the last 10 years.

Table 2-3 Cost of some recent tunnel projects in Norway [16]

Project	*Duration [years]*	*Tunnel length [km]*	*Actual Cost [M NOK]*	*Cost/km [M NOK]*	*Year of completion*
Fv. 107 Jondal	4	10.63	806.6	75.88	2013
Rv. 13 Myrkdal	1.25	1.08	150	138.89	Des. 2008
Rv. 53 Naustbukten	1.33	1.60	100	62.60	Mar. 2009
Rv. 55 Fatland	1.66	2.25	205	91.11	Nov. 2008
Rv. 55 Stedjeberg	2	2.10	160	76.19	Mar. 2007

Due to the geological formation in Norway, many civil engineering projects also need to do extensive work securing against landslide, this will naturally drive up the cost of those projects affected. The Myrdal tunnel (Table 2-3) is an example of a project undergoing such work, in order to secure the area around the construction site. It is also important to note that dividing the total length of the tunnel by the total cost of the project does not provide an accurate measurement, as the general whereabouts of the project inflicts the project method and, consequently, may increase the overall cost, i.e. it is more expensive to build a tunnel in an urban area compared to roads leading between cities. Work might also be associated with additional road construction leading to the tunnel, which will not be justified by this measurement. There are also lump sums associated with rigging equipment, regardless of how long the tunnel is. The purpose of the table is, however, just to give an impression of the situation.

[16] NPRA. *"Vegprojekter," Statens Vegvesen.* Norwegian database for road and tunneling projects http://www.vegvesen.no/Vegprosjekter

2.7.1 Contract

Given the circumstances and the level of risk involved in tunneling projects, good risk allocation needs to be established. Contacts between the two parties, can be designed to address the risk either the owner[17] or the contractor, though this may in both cases cause impracticalities, as laying the risk entirely on the owner may cause considerable cost overruns and promote the contractor to be inefficient, i.e. there is little risk attached to the their deliverance. The same can be said by give the contractor all the risk, the more risk they take the higher it will drive bids, and as the owner is inclined to provide a decent description of the project, it should be in their best interest to do an as thorough field research as possible, in order to give the contractors the necessary information they need to make an offer. So by taking less risk, the owner does not necessarily feel the need to acquire as many borehole core samples as they otherwise should have. Therefor the risk should be shared among the respected parties involved, promoting quality and rewarding efficiency.

As the government of Norway owns the public roads, it will be NPRA whom, through a public forum (according to the law of public procurement), promotes tunnel projects in Norway.

Proper contract design is vital to allocate risk in a healthy manner; two approaches to contract design will be discussed below following the manner of the two scenarios mentioned above:

Design-Bid-Build (or D/B/B): A well-established conventional contract type where the owner is responsible for the overall design. The contract type can be broken down to three sequential phases:

- Design phase
- Bidding (or tender) phase
- Construction phase

[17] related terms are 'client', 'promoter', 'employer'. In Norway this is carried out by The Norwegian Public Road Administration, as all public roads are held by the Norwegian government.

The first, in which the owner will establish a design team, along with consulting engineers, to design and produce bid documents, including drawings and technical specification. This will be the fundament for the various contractors to base their bid to construct the project. This phase usually accounts for 5-10% of total project cost, whereas the construction phase make up the remaining.[18] Once the design phase is complete, contractors whom have interest in the project are invited to bid, where the best suitable offer is selected to carry out the project.

Table 2-4 Pros and cons of design-bid-build contract model

Benefits of design-bid-build	*Potential problems of design-bid-build*
• Design team is impartial and preserves the interest of the owner • All contactors have access to the same documents, ensures fairness and improves decision making • Errors are usually discovered and addressed during bid process • Helps provide a more reasonable price for the project • Enhances efficiency and quality for owner through competition	• Early design errors may cause potential cost overruns and delays • 'Cheaper is better' mentality, may result in increased risk and quality compromise • The contractor has less mobility to inflict the design, as they are brought in after design phase • Conflicting interest, cost versus acceptable quality, between owner and contractor may lead to disputes and potential construction delay

There are growing concern for the efficiency of this contract model, in relation to project cost, schedule and productivity. For this reason, other alternative project delivery methods should be considered.

Design-Build (or D/B): Is the project delivery method most preferred alternative to design-bid-build. It is a contract in which the design and construction is carried out by the contractor. This method is used to minimize the owner's risk and reduce schedule time by

[18] Senate Committee on Local Government. *Faster, Cheaper, Better? A Legislative Oversight Hearing on How Counties Use Design-Build Contracting*. January 20, 2010. Sacramento, California, USA.

overlapping the design phase and the construction phase of the project. The owner's engineers develop a preliminary design that incorporates the essential project requirements; the suitable contractor will then develop this further.

Table 2-5 Pros and cons of design-build contract method

Benefits of design-build	*Potential problems of design-build*
• Increased efficiency of project deliverance • Cost efficient • 'Design as you go', i.e. contractor has more freedom to innovate design solutions, and is more mobile to interact in the construction process	• Owner has less control over the project • Does not make use of competitive bidding, project pricing is subjective • Contractors preparation of proposal is more costly compared to D/B/B • Criteria to select contractor is subjective and difficult to evaluate, contractor may be less interested in long-term performance • Quality controlling barriers are minimized as design and construction phases are unified • May lead to loss of public confidence

All though the contract methods mentioned above are the most common, the following contract types should also be considered:

Admeasurement contracts: The contractor specifies items of work and a fixed rate associated with each item. Payment it paid monthly, with respect to the work that has been completed during that time.

Cost-plus contracts: Contractor is reimbursed for a fixed amount of allowable expenses, plus an additional payment to allow profit.

Lump-sum contracts: Contractor is paid a single price for the completed work section. This may be described as the entire work section or specific key events (or milestones).

Target cost contracts: The contract is based on estimated cost for work, this can however be adjusted accordingly. The contractor's expenses are monitored as a cost-plus contract, and any difference between actual cost and target cost is shared in a specific way. This may apply to time target as well as cost target.

2.7.2 Cost and time

Managing time and cost is a very important aspect of tunneling, as these projects often tend to be, in greater or lesser extent, completed with cost overruns. Reasons for this can, in general, be related to political pressure, optimistic interpretation of geological research results, and lack of cost control. In Norway, many cost overruns can be related to the necessity for extensive safety procedures against landslide and cave-ins. This is often a sign if insufficient geological information. Table 2-6 is an extension of Table 2-3, the new table displays the same projects as previously mentioned, however now comparing budget cost, which is based on the winning contractors offer right before the project is initiated, against the actual cost when the project is complete.

Table 2-6 Comparing budget cost and actual cost of recent tunnel projects in Norway

Project	*Duration [years]*	*Budget cost [M NOK]*	*Actual cost [M NOK]*	*Relative cost increase*	*Year of completion*
Fv. 107 Jondal	4	760	806.6	6%	2013
Rv. 13 Myrkdal	1.25	124	150	20%	Des. 2008
Rv. 53 Naustbukten	1.33	77	100	30%	Mar. 2009
Rv. 55 Fatland	1.66	182	205	13%	Nov. 2008
Rv. 55 Stedjeberg	2	180	160	-11%	Mar. 2007

Project cost estimation can be divided into two stages, pre-project stage, and construction stage. In the pre-project stage, cost is usually determined by presumptuous analysis and past experience, based on expert opinions, providing an estimate with approximately 25% accuracy. During the construction phase, cost can be estimated with better accuracy, as detailed calculations are easier to deduct during each activity, based on current wages, machinery cost and material prices, i.e. excavation, supporting, lining, and installations. Time as well as cost is better monitored using feedback-loops and milestones to recognize variance. These estimations are considered to have accuracy <10%.

The lack of scientific approach still causes tunneling projects to highly rely on expert opinions, and trial and error. Unfortunately, in the school of civil engineering, more specific, tunneling and tunnel construction, experts are often regarded as someone who has gained experience at someone else's expense, or are otherwise about to do so.[19] With technological advances this foothold with gradually loos its ground, and more reliable methods of approach can be used.

[19] Hoek, E. (2001). *The Role of Experts in Tunneling Projects*.

Chapter 3

Tunneling techniques

Tunnels are constructed by various techniques; through the centuries these methods for construction have seen great improvements. The act of heading, in terms of tunneling mechanics, comprises the following actions: excavation, support of the cavity and removal of the excavated earth (also known as mucking, discussed further in section 3.6). The different tunnel construction techniques are distinguished between conventional (also called incremental or cyclic) heading and continuous heading. This chapter introduces the several methods used, and highlights their applications and limitations. In order to choose the most appropriate construction method, one needs to consider attributes such as: geological characteristics, the impact of the construction on the surrounding environment, economic bearing, and health and safety issues. It is also important to note the outcome of different ground hardness, and it's effect on tunneling procedure. If the ground is stable, the tunnel heading can generally be focused around economics and the limits of the tunneling equipment. Whereas for soft ground, which need sufficient supporting straightaway, the construction is mostly focused on attending the necessity to support the advanced step (see Figure 2-2 on page 6) immediately after excavation. As will be further discussed in section 3.1, the total cross sectional area of a tunnel is not necessarily excavated in a single advance, but can also be partly excavated to reduce the risk of cave-in and allow a safer procedure for support structures.

The overall most common tunnel construction techniques used today is either the conventional drilling and blasting (D&B), or continuous heading; tunnel-boring machine (TBM). Drilling and blasting is preferably used when the tunnel is relatively short, thus the high investment cost needed for the TBM is not financially sustainable, or if the ground hardness is relatively high, causing greater wear on the cutting tools. In addition, the B&D allows alternative cross sectional profiles, other than just a circular profile. It is also easier to construct safe passages between twin tube tunnels. However, the drilling and blasting procedures are often conducted sequentially, due to safety hazards when handling explosives, thus the tunneling speed is generally lower compared with TBM tunneling. These methods will be individually discussed further in section 3.2 and 3.3.

Figure 3-1 Example of an emergency cross passage under construction

3.1 Excavation

Excavation is the procedure of removing rock from the tunnel face, creating the tunnel profile that is desired. Since larger excavations generally are less stable than smaller once, partial face excavation are in many cases used, in that the tunnels cross section is not excavated out all at once, but in stead in parts. This method is also often used when constructing tunnels in urban areas, in order to reduce the amount of noise and quake deriving from the explosive charges used in the drilling and blasting method (see section 3.2).

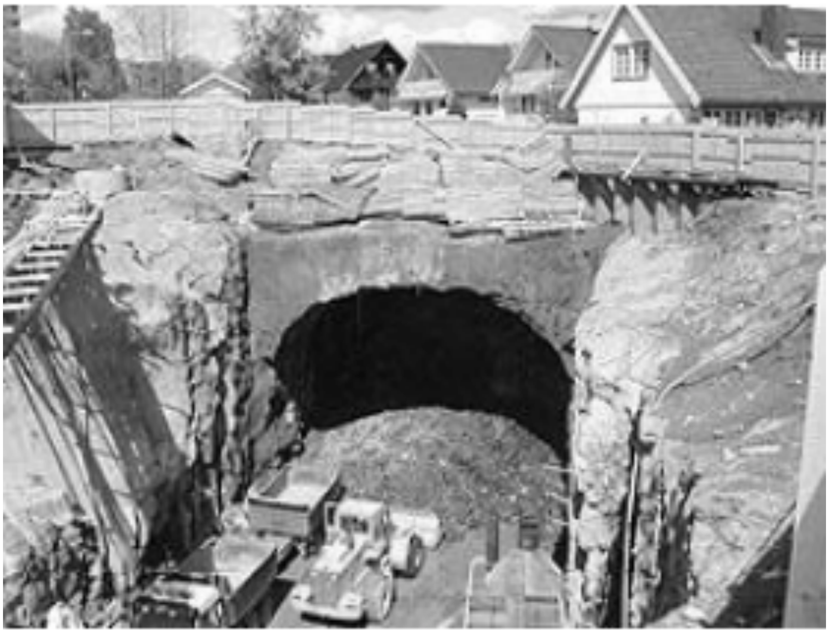

Figure 3-2 Tunneling in an urban area

Throughout the years, tunnel heading has seen a lot of improvement, in earlier years many different techniques of partial face excavation have been developed, thought their terminology was neither particularly systematic nor unique. The Old Austrian Tunneling Method and the core heading (i.e. *Kernbauwise*), are two examples of partial face excavation methods used, they were developed when contemporary support was based on timbering and masonry. Compared to steel and sprayed concrete that is used today.

3.1.1 Old Austrian Tunneling Method

The method is composed by a specific excavation sequence; the tunnel face is segmented into smaller parts, which will allow construction to be performed simultaneously on several excavation faces to allow a faster advance (see Figure 3-4 for illustration). The overall method of sequences is schematically represented in the Figure 3-3.

This method, originally called the 'Austrian Tunneling Method', was first referred to as the 'Old Austrian Tunneling Method' after the technique was further developed, in the 1950s, to the method known today as the New Austrian Tunneling Method (NATM). Although the techniques and knowledge for the method is based on the 'old' method, the new technique took new approach and revolutionized the approach for tunneling, see section 3.1.2 below for a detailed description on NATM.

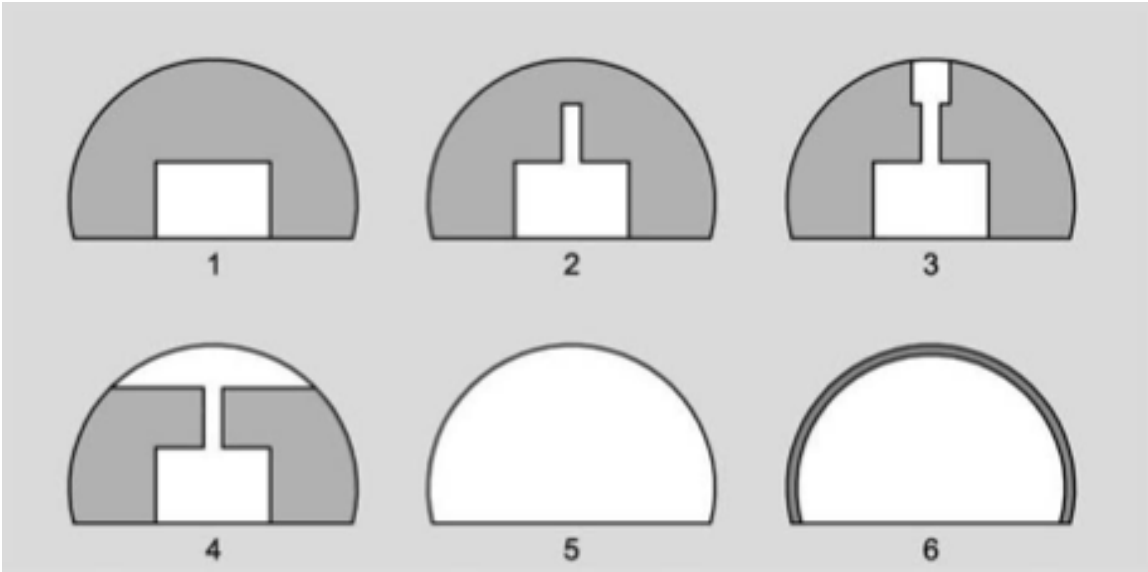

Figure 3-3 Excavation sequence of the Old Austrian Tunneling Method

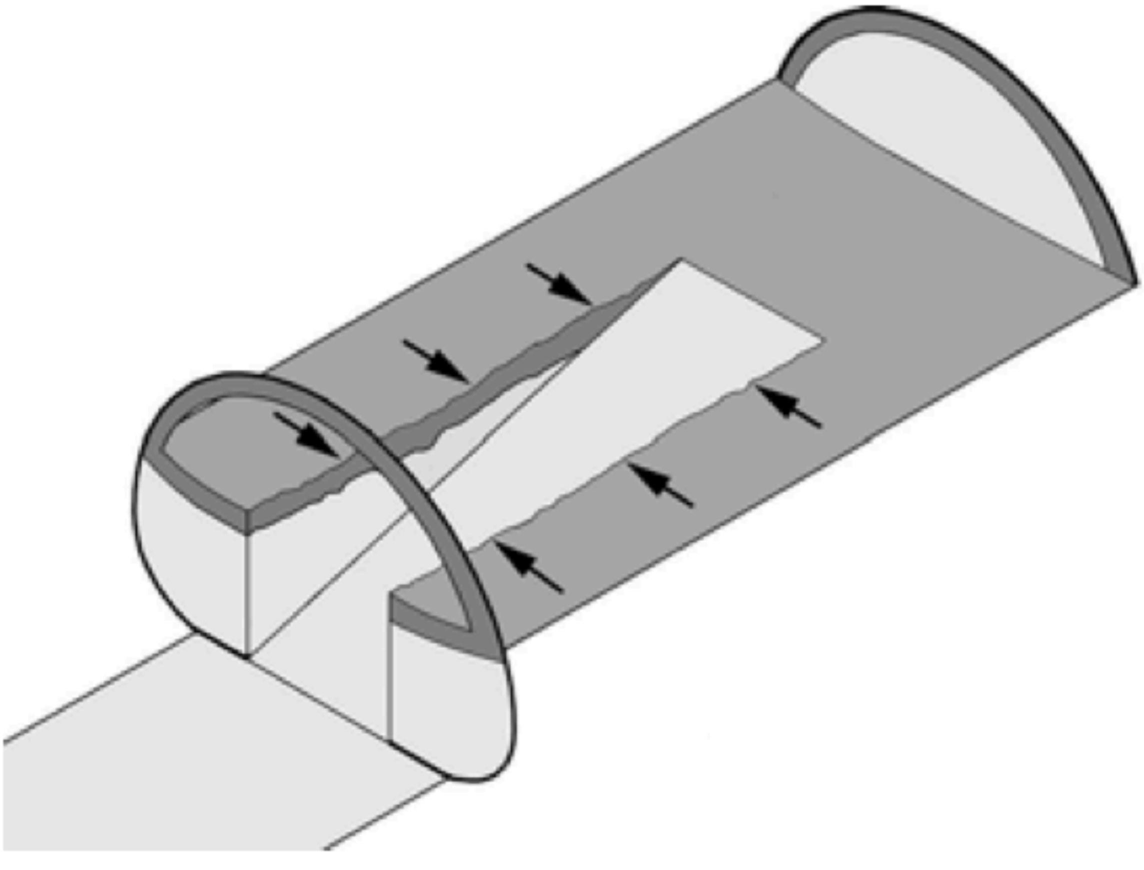

Figure 3-4 Segmented approach for simultaneous face excavation

3.1.2 New Austrian Tunneling Method

The New Austrian Tunneling Method (NATM), also known as Sequential Excavation Method (SEM), was developed in late 1950s, Austria, by Ladislaus von Rabcewicz, Leopold Müller and Franz Pacher. The technique was named NATM in order to distinguish it from the old approach. Although they share similarities, the fundamental difference between the two methods, is the economical advantages to the new method, made available by exploiting the inherent geological strength of the surrounding ground structure, thus stabilizing the tunnel. This means that in order to use the NATM, the ground has to be sufficiently strong enough to support itself over the length of each advance section, i.e. the ground must have a stand-up time. By acknowledging the supporting potential in the existing ground structure, the necessary support lining could be reduced to approximately 20 cm, this was also a consequence of using sprayed concrete (also termed shotcrete) in stead of brick lining which were more common at the time. This change made it possible to construct tunnels where the surrounding formation helped stabilize the tunnel structure, where earlier brick lining left a small gap between the support lining and the formation, making it carry all the weight on its own.

The main elements to NATM can be stated as followed:

- Primary support is directed to enable the ground to support itself; shotcrete has only a secondary supporting function
- Primary function of shotcrete is to minimize loosening and excessive rock deformation and preserve formation strength
- Potential deformation must be carefully monitored. Choice of support and construction sequence is based on displacement monitoring. Subsidies support needs to be installed in the event of a structural glitch
- A thin shotcrete layer allows full contact with exposed rock surface
- Full-face excavation should be used, if not otherwise difficult or unsafe to implement
- Excavation sequence is important to obey in order to achieve optimal stability

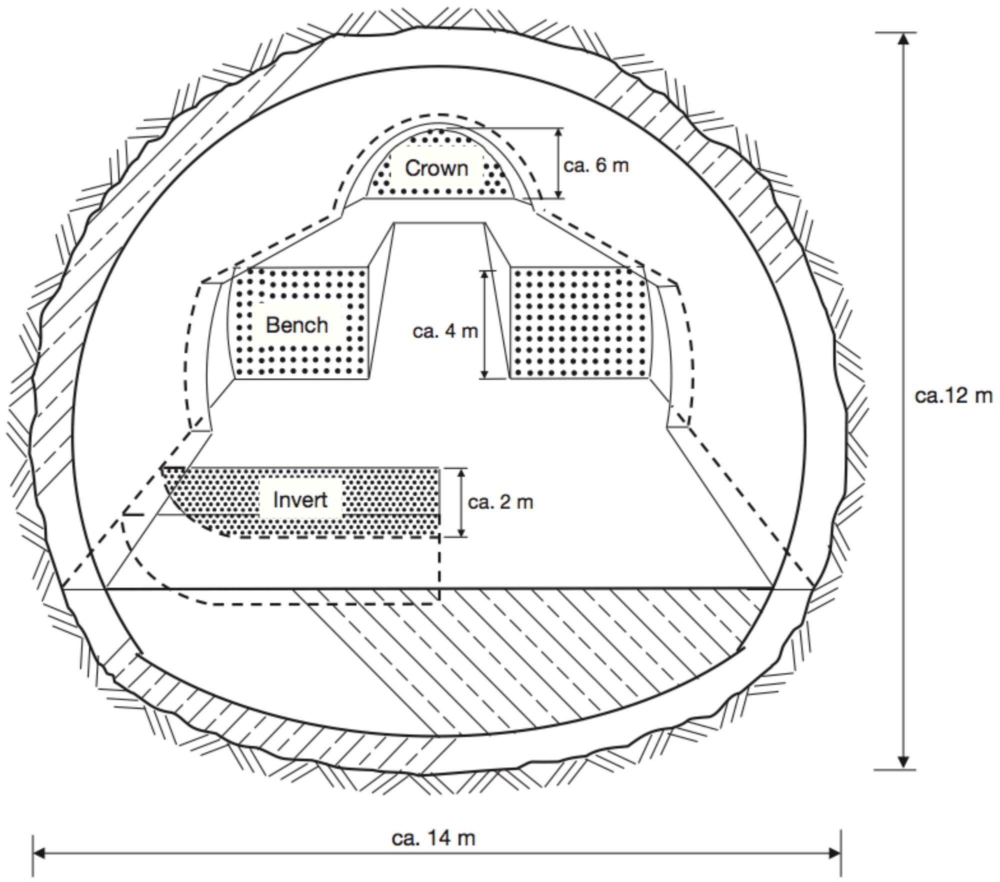

Figure 3-5 Cross sectional illustration of the NATM

The main construction procedure for the NATM is following:

1. Excavation – advancing can be achieved by several methods, either blasting, partial face boring, or even an excavator (as shown in Figure 3-6), depending on the geological conditions
2. Sealing exposed surface (if necessary)
3. Mucking (for more, see section 3.6)
4. First layer installation – installing lattice girders[1] and first layer of reinforcing bars or mesh, supported by spray concrete (Figure 3-7)
5. Potential second layer installation
6. Installing anchors (if required), and, if necessary, tightening of anchors and shotcrete
7. Inner lining construction

[1] a lattice girder is an iron or steel structure consisting of two horizontal beams connected by diagonal struts.

Figure 3-6 Example of using an excavator during a NATM

Figure 3-7 Example of shotcreting mesh reinforcement

3.2 Drilling & blasting

3.2.1 Introduction

Drilling and blasting is one of the most preferred tunneling techniques used today, reason being that it has a large specter of application for different geological formations, e.g. granite, clay, marl, quartz and chalk. It should be noted that the geological formation of Norway mostly consist of hard rock types such as granite and gneiss, though also slate, sandstone and limestone are common. Since most ground conditions are various throughout the tunneling phase, it is desirable to use a method that has a larger range of possible usage. Due to the relative frequency of hard rock formation in Norway, TBM are less preferred as high rock toughness will generate a greater wear on the cutting tools, causing an uneconomic application for the machine. Another benefit to drilling and blasting is the flexibility to shape the tunnel profile and curvature of the tunnel, which is otherwise difficult to achieve using a TBM.

As shown in Table 2-1 on page 9, more than 90% of the tunnels in Norway, by 2009, are less than 3 km long, stating that Norway have, through the years, constructed short tunnels, where drilling and blasting have been the preferred method of tunneling. Nevertheless, TBM have been used in Norway, though in short occasions, and will be further addressed in the oncoming section (3.3).

The downsides to drill and blast is related to cycle dependency, explosive hazard, vibration and noise. The latter three are especially critical when tunneling in a metropolitan area, in which case 'cause and effect' estimations should be conducted. In Norway, it is not unusual for homeowners to dig for self-sufficient wells or geothermal wells, and though it is highly recommended that each homeowner notify government authorities about these independent installments, not many do. This will oppose a safety hazard should an explosive charge be placed awkwardly near the bottom of a well, detonating the explosive will result in total energy loss going up the well, creating a blast wave of air, water and rock that can potentially cause great damage.[2]

[2] as part of the preparation phase, the Norwegian Public Road Administration conducts house-to-house search of every house that is within a fixed perimeter of the affected area for tunneling. Homeowners are instructed to inform about any installations that could be a potential threat.

3.2.2 Process cycle (conventional)

When carrying out drilling and blasting, the process cycle usually consists of the following activities: drilling (i.), charging and stemming (ii.), blasting and ventilation (iii.), mucking (iv.), scaling and cleaning (v.), and supporting, i.e. shotcrete (vi.) and bolting (vii.). These activities are mostly dependent on the prior activity, and thus the method can be more time-consuming. For instance, due to safety standards, charging (ii.) cannot happen until drilling (i.) is complete, in order to avoid the risk of premature detonation. However the entire process would go much faster if two such activities were synergistic. According to the Norwegian Public Road Administration the entire process cycle for a 5 m advance is on average 8 to 10 hours, depending on the necessity for support.[3] Comparing this to the process cycle best- and worst-case scenario in Table 3-1, cycle time can range between 6 to 20 hours per advance.

Table 3-1 Min. / max cycle duration for drilling and blasting[4]

Activety/Time [h]		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
i.	Drilling (1.5-4h)																				
ii.	Charging and stemming(0.5-2h)																				
iii.	Blasting and ventilation (0.1-1h)																				
iv.	Mucking (2-5h)																				
v.	Scaling and cleaning (0.2-1.5h)																				
vi.	Shotcrete (1-3h)																				
vii.	Bolting (0.5 - 3h)																				
Min. / Max.		6 / 19.5 hours																			

Drilling: The drill holes are created, most commonly, by the use of hydraulic drill rigs. These are mobile drilling vehicles, with a decent driving speed allowing the operator to move the vehicle to a safe distance when explosives are detonated, usually equipped with either two or three individual mechanical drill arms. The speed of drilling can range

[3] based on a personall conversation with Anne-Merete Gilje and Bjørn Dokken, Statens Vegvesen, April 10, 2014

[4] according to ENTEA; civil engineering company performing tunneling services, including drilling and blasting, http://entea.ba/o-nama. ENTEA. *"NATM|ENTEA d.o.o," ENTEA. December 27, 2013.* https://www.youtube.com/watch?v=6NX1tdSdAPw

between 1 to 5 m per min, depending on vehicle and conditions. Amount of drill holes required depends on the size of the cross sectional surface and the blast-ability of the rock. E.g. for cross sections ranging between 60 to 70 m^2, depending on conditions, the number of boreholes recommended is 1 to 2 per m^2. Note that drilling into sockets left from previous blasting should be avoided as they may contain explosive residue, and could potentially be very dangerous.

Figure 3-8 Example of a three arm (three-boom) hydraulic drill rig

Charging: The explosive charges are placed in the boreholes after the entire boring sequence is complete; the explosive charge is manually guided to the end of the borehole by a rod. Explosives exist either as emulsion, powder or, most commonly, as a cartridge.

Stemming: Sealing the drill hole to prepare it for detonation. Also prevents any unexploded charges to be discharged and reduces dust. However it has been proven that stemming does not improve the effect of an explosion for long charged column, therefor stemming is often disregarded in order to cut cost and time.

Blasting: Detonation of the explosive matter causes a very rapid chemical reaction with a velocity up to 8 km/s. This creates a high gas pressure, fracturing the mass of the advance section; 1 cm^3 of nitroglycol creates 74×10^6 kW, the largest offshore wind farm (London Array) is designed to produce 1×10^6 kW, though to be fair, the explosive energy only lasts for a fraction of a seconded. Modern explosives are designed to ignite only by a small internal explosion, preventing it to detonate prematurely by damage, friction and heat. The internal ignition can be achieved via an electric detonation or a detonating cord.

Methods for ignition and chemical components make up a good selection for different type of explosives, e.g. gelatin-dynamite, emulsion explosives and powder materials (blasting agents). Figure 3-9 displays an example of how a drill hole pattern can be arranged, detonation will usually be done in sequences milliseconds apart, the central section will go off fist, crating a foundational weakness for the sub sequential explosions. This helps guiding the explosion and secure that it will blow in the manner that is estimated.

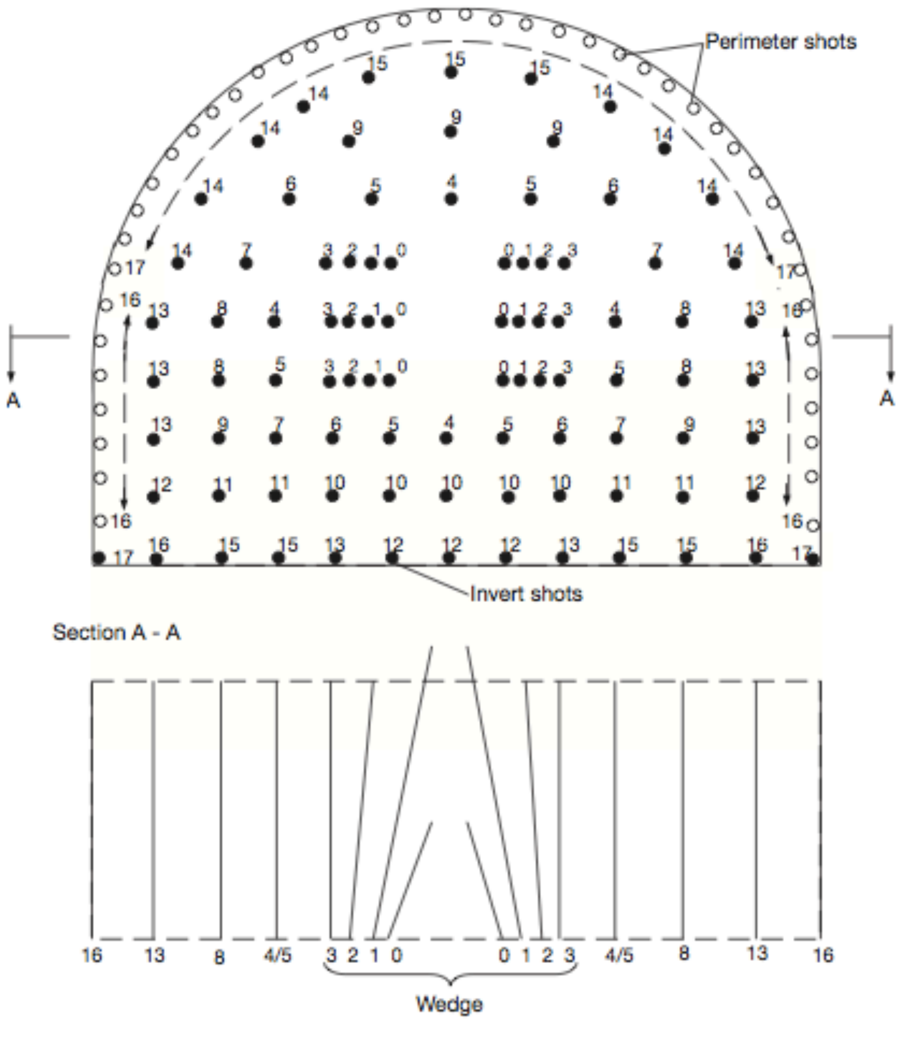

Figure 3-9 Example of a drill hole pattern

Ventilation: After detonation, work should not be resumed until after at least 15 min of sufficient air ventilation. This is due to the amount of toxic gases (i.e. CO_2, CO and nitrogen oxides) and quartz dust generated as a byproduct of the explosion. For this reason it is recommended that all personnel either clear the tunnel, or confine themselves to a secure container before detonating, explosion shock may also cause parts of shotcrete lining to be detached for previous advanced section and fall down.

Mucking: A term used to describe the action of removing excavated mass from the advance section. This action consists of loading, transporting and unloading the spoils. The subject is further described in section 3.6.

Supporting: Depending on the condition of the excavated face, the inner wall should be supported. This is often a combination of shotcrete, bolting, steel mesh and steel arches.[5]

3.2.3 Explosive consumption and cost

The use of explosives has a high impact on overall excavation cost, and varies depending on the cross sectional area of the tunnel, as well as the characteristics of the rock. Explosive consumption can rage between 0.3 to 4.5 kg/m^3.[6] The Norwegian Public Road Administration estimates blasting related costs to be 130 to 140 NOK/m^3.

3.3 Tunnel boring machine

3.3.1 Introduction

A tunnel boring machine (TBM) is a mechanical excavator with a circular cross-section, it consists of a huge rotational cutter head that can mole trough varies soils. The size of these machines can range from a single meter (using a micro-TBM) up to 19.25 m (diameter). TBM is the most relevant option for tunneling to D&B, causing less disturbance to surrounding environment, i.e. vibrations and noise, making it optimal for tunneling in urban areas. Also providing a smooth surface on the inner wall that makes it easier to support. The method is overall more efficient, however it has a very high installation cost, thus the total length of the tunnel affects the decision on whether or not this method is economically beneficial. The machine is expensive to construct, difficult to transport and requires staff with sufficient knowledge. As modern tunnels increasingly

[5] the extent and complexity of supporting tunnel excavations is far greater than is discussed in this thesis.
[6] Kolymbas, D. (2005). *Tunneling and Tunnel Mechanics: A Rational Approach to Tunneling.* Germany. Springer. p. 89

become longer, this method of tunnel construction has a higher advantage to that of drilling and blasting, providing a more efficient option, resulting shorter project duration.

Figure 3-10 Tunnel boring machine (TBM)

3.3.2 Process cycle (continuous)

The advancement of a TBM is achieved using hydraulic jacks to push the cutter head in the appropriate direction, the jacks thrust forward using the inner lining of the tunnel as support, as illustrated in Figure 3-11 below. This means that after each advance step, the jacks retract causing the TBM to halt for the duration of a new support lining. Average advance rated range from 0.5 to 2 m/h. Excavation can be achieved either by full-faced excavation (using rotational cutter heads, Figure 3-10), or partial faced excavation (i.e. roadheaders or thixshield, Figure 3-12).

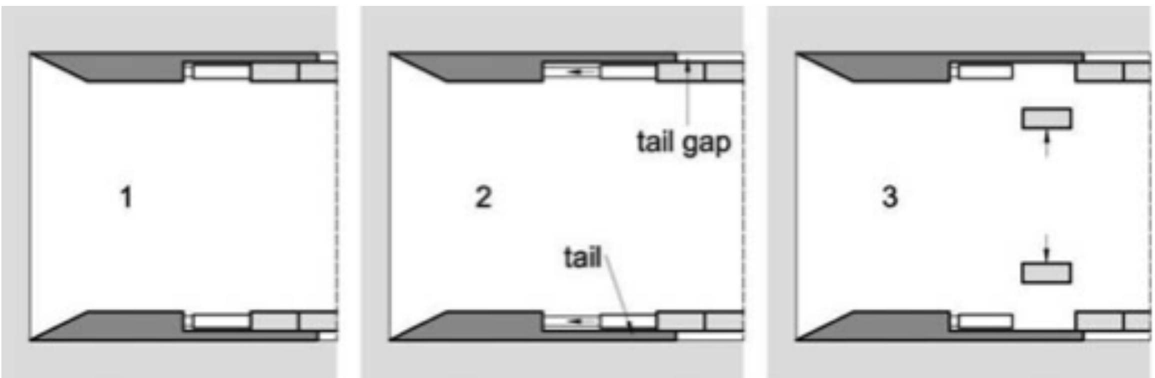

Figure 3-11 TBM process sequence for heading

Figure 3-12 Thixshield excavation header, used for selective excavation

3.3.3 Advance rate

Developing accurate rate of penetration (ROP)[7] estimates is a key factor to determining project schedule and cost, and is vital for the success of tunneling project. It is a difficult and complex task, as it depends on many different factors, such as geological properties (i.e. strength, texture, brittleness) and mechanical specifications; like thrust, torque and component wear. In general TBM advance rate in rock is on average 8 m per day. Field data gathered from excavating Queens Water Tunnel, New York, shows an average ROP equal to 2.5 m/h[8]. Rates can also be estimated by using mathematical equations.

3.4 Urban tunneling

Tunneling in an urban area provide a different environment compared to construction of underground structures in mountains or sparsely inhabited regions. This is because of the larger number of complex constrains imposed by existing infrastructure, settlements and activities nearby. These greatly affect the selection of construction method, alignment of layout, design of excavation and support, as well as for procurement and execution of the project. Environmental and socio-economic factors, e.g. limitations to noise, vibrations

[7] rate of penetration (ROP) is defined as the advance rate, or distance, a machine can achieve at a given time in rock.
[8] Yagiz, S. (2006). *A model for the prediction of tunnel boring machine performance*. Turkey. Pamukkale University.

and other emissions, necessity to maintain operation of existing traffic infrastructure, and restriction on allowable disturbance of surroundings, can have considerable consequences for the implementation of the tunneling project. (e.g. restrictions on cut-and-cover works, avoidance of drilling & blasting tunneling method or schedule restrictions due to site traffic).

The fact of the matter is, that city areas will on average only increase, thus urban tunneling will increase, this will oppose an issue to the extensive use of D&B in Norway, as it is undesirable to use this method in these type of projects. This can be related to the ongoing construction of the new underwater tunnel from Stavanger to Strand, Norway (2012 to 2019). The comprehensive infrastructure of this project involves the construction of an additional tunnel in Stavanger, this tunnel will pass 1.7 meters beneath the already existing 'Byhaugtunnelen' (city tunnel), NPRA has decided to close this tunnel for two months (from June 10, to some time August 2014), as the construction of the new tunnel, due to the selected method of tunneling (D&B), require a road section of the old tunnel to be removed in order to construct a bridge dividing the two tunnels.[9]

3.5 Comparing D&B to TBM

The use of TBM is gradually increasing on an international level, as more tunnels with relative high length are projected. The use of the conventional drilling and blasting is progressively reduced to short tunnels and tunnels requiring varying profiles. Though as the D&B has a low initial cost, it is still economically beneficial for tunnels up to the approximate length of 2 km, as illustrated in Figure 3-13 below. Comparing the two methods, TBM has a beneficial advantage regarding work safety, as the machine will shield the advance area, however there is also loss of well being related to the crammed workspace available. Installment related costs are also high for TBM, thus the method is only beneficial above a certain tunnel length. Table 3-2 notates further comparison of the two methods.

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[9] Nedrebø, R. *"Byhaugtunnelen stenges i to måneder". Stavanger Aftenblad.* February 7, 2014. http://www.aftenbladet.no/nyheter/lokalt/Byhaugtunnelen-stenges-i-to-maneder-3351076.html#.U53VCo2SxuB
Anagnostou, G. (2007). *Basic aspects of underground projects in urban areas.* Switzerland. ETH Zurich

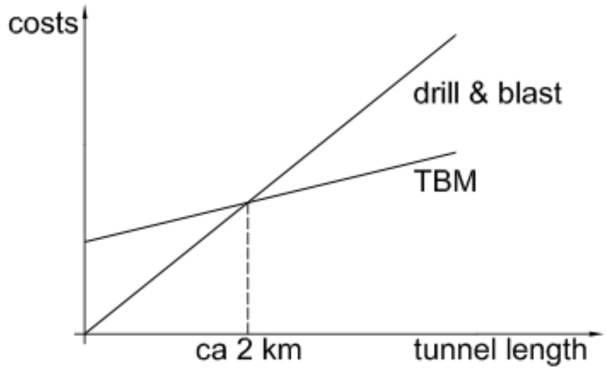

Figure 3-13 Cost comparison D&B - TBM

Table 3-2 Advantages and disadvantages to conventional D&B and TBM

	D&B	*TBM*
Pros	• Enables varying cross sectional profiles • Equipment can be used for other means • Easy to replace • Low installation cost • Adaptable to geologic conditions	• Cost efficient for sufficiently long tunnels • High advance rate • High quality support lining • Relatively safe for personnel • Well suited for soft soil tunneling
Cons	• Personnel are relatively unsecured • Advance rate limited to approximately 8 m per day • Better support is required • Individually dependent processes • Expensive precautions are necessary for tunneling in difficult ground conditions	• Limited to circular cross sectional profile • High installation cost • Jam during tunneling cause high downtime and cost increase • Steep learning curve for staff • Expensive drive-in operations • Difficult to adjust to varying ground conditions

3.6 Mucking

The removal of excavated rock and soil is an integrated procedure of tunneling, which should ideally be done without interrupting other process activities. Mucking consists of following: loading, transporting and unloading excavated mass. Depending on the tunneling technique used, different methods for mucking are implemented, with continuous tunneling mucking is a relative non-interfering, constant process, which uses either a conveyer belt and subsequently a truck or train, or a mixture of water or foam to form a mush that is lifted using a screw conveyer. For the conventional drilling and blasting, it is preferable to use trackless transportation, i.e. loading trucks, this is due to labor intensive costs associated with installment and removal of tracks, compared to the relative small investment related to track-free transport vehicles. Another advantage with rubber-wheeled vehicle transportation is that they are usable for inclines greater than 3% (up to about 7%). However, this does on the other hand increase the total energy used per ton of excavated mass, as diesel engine exhaust increase the need for a more elaborate ventilation system. Whether to use track-free, rail-bound or conveyer aided transportation depends on the specific project, and should be designed with respect to optimize loading capacity relative to the amount of excavated material.

3.6.1 Use of excavated material

Excavated rock, in various sizes, is generally used as a fundamental stabilizer when constructing roads and railways, an as aggregate material for manufacturing concrete.

Sand, gravel and muck are one of the most important raw materials in Norway, after oil and gas. In 2011 the production of sand, gravel and muck was 77 million ton, some of which were a byproduct of the offshore industry. A little over 21 million ton of the total production was in a large proportion exported to Europe, to a value of 1 billion NOK.[10]

[10] NGU. *"Grus og pukk som byggeråstoff," Norges Geologiske Undersøkelse.* June 21, 2012. http://www.ngu.no/no/hm/Georessurser/Sand-grus-og-pukk/Grus-og-pukk-som-byggerastoff/

Chapter 4

Water jet cutting

Water jet cutting (WJC) have gained a vast number of useful applications over the years, and although it can be dated back to the mid-1800s, where it was used in hydraulic mining, one of the first recorded uses of narrow WJC was not until 1933, when the Paper Patents Company in Wisconsin used low pressurized water to cut soft material like paper, on an industrial level. In more recent history, with the development of more accurate and reliable pumps and nozzles, WJC is used to cut a wide variety of materials, including tool steel, titanium, stone and glass. However, the cutting power of WJC is limited to an extent, certain materials like diamonds, tempered glass, advanced ceramics and some composite material either cannot be cut or are otherwise too economically inconvenient or time-consuming to cut.

4.1 Theory

WJC works in that pressurized water is constantly channeled through a reducing cross sectional area of a nozzle, this cause the water particles to rapidly accelerate, upon impact with the respected material, this will cause a 'micro' erosion on a small surface area of the material to be cut. The rapid bombardment of water particles creates minor cracks in the material, which propagates until the material is cut through.

4.1.1 WJC in stone

When using WJC on rock, parameters like compressive strength and fracture toughness, that otherwise would be important for controlling resistance to mechanical destruction of rock, have no relevance in continuous water jet cutting.[1] A rock can be characterized by

[1] Rehbinder, G. (1979). *A Theory About Cutting Rock With a Water Jet*.

its threshold pressure, otherwise interpreted as micro-scale tensile strength, and its erosion resistance, i.e. the ratio of pores in the rock compared to the its relative grain size.[2] When cutting rock, the water jet pressure exceeds the threshold pressure of the rock causing the structure to deteriorate, loosened grains will be washed along with the water stream, further exposing new surface to the water jet (Figure 4-1).

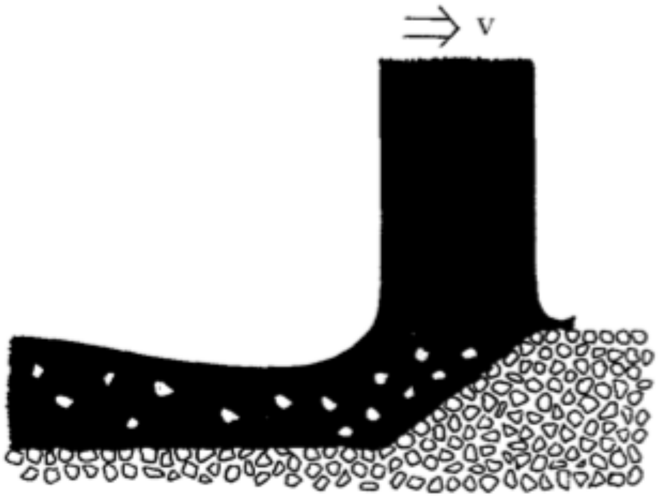

Figure 4-1 WJC where water pressure is larger than the threshold pressure of the rock

Rock erosion is, with respect to its characteristics, i.e. threshold pressure and erosion resistance, proportional to its modified permeability and inversely proportional to its average grain diameter. However, for a given rock and a given jet power, the slot depth of the cut is remarkably unaffected by the jet pressure, should it be more than double the magnitude of the threshold pressure.[3] This means that the slot depth is mainly determined by the power of the jet, given the jet pressure is relatively large (further discussed in 4.2 below).

4.2 Abrasive water jet cutting

The development of abrasive water jet cutting (AWC) made it possible to use WJC to cut harder material, i.e. metals, glass, stone and composites. By mixing abrasive particles to the water jet, materials can be cut more efficiently, as pure water jet cutting is for the most part only efficient for softer material, such as rubber, paper and food products.

[2] erosion resistance in rock can be described as the square of the slenderness ratio of the pores of the rock divided by the diameter of the grains
[3] Rehbinder, G. (1979). *A Theory About Cutting Rock With a Water Jet*. p. 1

Different abrasive materials added to WJC may vary depending on what material is to be cut, although, in most cases garnet abrasives tends to be the preferred choice, more specifically, red garnet.[4] The reason for this is that red garnet is fairly hard, and it forms sharp edges when fractured. Another advantage is the fact that garnet is relatively chemically inert, thus it does not cause any reaction with the material being cut, as well as making it less hazardous to dispose. Even though garnet greatly increases the cutting efficiency of WJC, it also increase the gradual wear of the equipment, especially the nozzle, therefore it is important to justify the use of abrasive material with respect to what material is being cut.

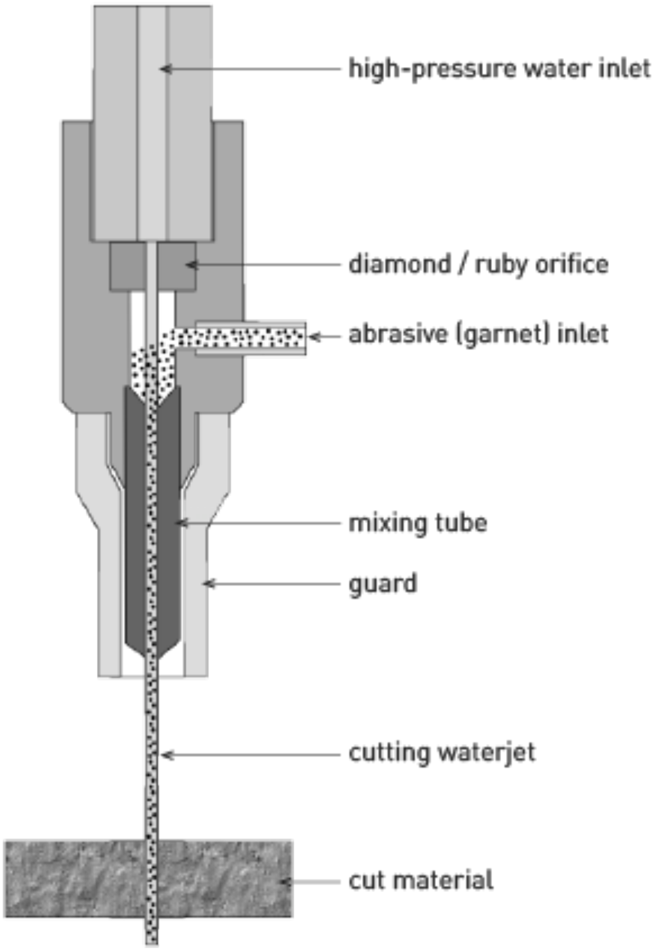

Figure 4-2 Principle of abrasive water jet cutting (AWC)

[4] Waterjets (staff). *"Waterjet Abrasives," Waterjets.* http://waterjets.org/index.php?option=com_content&task=view&id=85&Itemid=55

4.2.1 Pressure efficiency

The slot depth of the cut, is, as mentioned earlier in 4.1, not further determined by the pressure of the water jet, but rather by the power of the jet, provided that the pressure is above the threshold pressure of the rock. This means that when cutting at a given pressure, any additional increase in pressure will not contribute to significantly increase cutting efficiency. This is because, for a given size pump, an increase in pressure would require a reduction in nozzle size, i.e. the power of the pump is proportional to the pressure multiplied by the volume flow rate. Even though a smaller nozzle has a higher power density, which is efficient in many cases using pure water cutting, it is the abrasive material that is performing the cutting. In AWC, the purpose of the water is only to accelerate the abrasive particles; a reduced nozzle orifice is simply not more efficient at accelerating the particles than a regular sized nozzle working at normal pressure.

In addition, there are several downsides to working with higher pressure, than is otherwise necessary, such as:

- Higher cost and maintenance
- Lower reliability
- Lower life expectancy for pump components
- Balance-of-system, i.e. valves, tubing etc.
- Greater wear on mixing tube in nozzle
- More unscheduled downtime due to component fatigue failures

4.2.2 Abrasive material consumption

Abrasives remain the most expensive part of AWC, R&D is looking at ways to reduce or eliminate the use of abrasives. Although the use of abrasive material varies depending on pump and nozzle used, AWC will generally consume 0.1 to 1 kg abrasive material per minute, the normal being 0.45 kg per minute.[5] The abrasive flow rate is usually constant for a given application, and should only vary if there is need for pure water cutting, in which case the abrasive injection is shut off.

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[5] Waterjets (staff). *"Waterjet Abrasives," Waterjets.* http://waterjets.org/index.php?option=com_content&task=view&id=85&Itemid=55

4.3 Applications of WJC

Due to many of the features related to WJC, it has a large range of applications. Pure water cutting is mostly used for low strength material, such as rubber, paper, and food preparations. Where as abrasive cutting (see section 4.2) is used to cut tougher material such as steel, titanium, rock, wood, glass, etc.

In Norway, AWC is used by the offshore industry to perform on-site cutting, as other methods are highly hazardous regarding the strict safety regulations for spark/fire hazards. AWC also eliminates the heat-affected-zone (HAZ), thus causing no heat distortion in the material, which could otherwise potentially damage the material properties.

In addition, WJC is also used in the following industries:

- Architectural – creating custom flooring from stone as well as architectural details from metal, glass, marble and stone
- Automotive and transportation – Used to produce prototypes, parts and tools for manufacturing automobiles, many custom race car parts are made using WJC
- Aerospace – A lot of aluminum parts used for the aerospace industry are created using water jet cutting
- Manufacturing – Used to produce parts that are later sold or used later in machines on assembly lines

4.4 Challenges with WJC

The key to effective WJC is to maintain as much of the pumping power to the nozzle as possible, thus having an efficient pump is critical. It is not just enough to have a large motor, as horsepower of the motor does not equal horsepower of the nozzle. OMAX[6] argues that a crankshaft pump is more efficient than a hydraulic intensifier pump, as the crankshaft pump use only a mechanical system and had less friction loss. The efficiency of the pumping power to a crankshaft pump is 85 to 90%, meaning that 85% or more of

[6] OMAX. American provider of multi-axis water jet systems, founded in 1993.

the motor power can be delivered to the nozzle. Compared to the older, more complex hydraulic intensifier pump that typically delivers 65% pumping power. Hydraulic pumps have had the advantage of longer seal and check-valve life, but with advancing technology, crankshaft pumps are now reliable for higher pumping capacities, up to about 4,100 bar.[7]

Other issues concerning geometry of part, cutting path optimization, programming and software control, and quality management are more related to CNC[8] machining, however motion control, material thickness and component life expectancy are highly interesting in relation to the thesis, and is addressed further. It is important to note that cutting path optimization is very important for repetitive operations, but this thesis will not cover a complex extravasation of how to optimize cutting path to reduce cutting time, and resource use.

4.4.1 Motion control

Motion control is essential to avoid taper, i.e. when the exit angle of the jet stream is different from the angle it enters the cut material. The water jet tends to bend in the direction of cutting motion, illustrated in Figure 4-3; it is crucial to address this issue when using AWC for CNC machining, as accuracy is very important for low tolerance machining. The result of taper is especially noticeable when cutting corners and curves, as the water jet tends to undercut. Using advanced computing models to eliminate this issue, by predicting the motion and shape of the cutting stream, thus compensating for undesired jet motion.

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[7] Veenhuizen, S. *Operating Efficiency of Crankshaft Drive Pumps*. USA. OMAX Corporation.
[8] computer numerical control (CNC) refers to machining using computer guided control

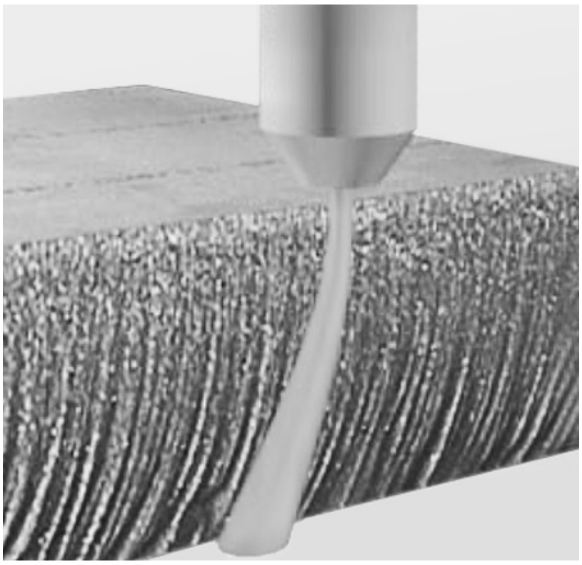

Figure 4-3 Water jet motion control in WJC

4.4.2 Material thickness

When using WJC to machine parts in steel and other hard material, the more common thicknesses tends to range from 2.5 to 10 cm. Maintaining the same level of tolerance, thicker material takes longer to cut, cutting time for thicker material do not follow a linear relation, in that material twice as thick usually takes more than twice the time to cut. So in order to maintain the same relative cutting progression, the overall quality and accuracy of the cut is reduced.

Overall, harder material takes longer time to cut, compared to softer material. Although, it is not always so, in the case of cutting granite, which is a fairly hard rock, the cut-ability of the material, when using WJC, is much swifter than for cutting copper, this is due to the brittleness of the granite, and its grain structure, covered earlier in section 4.1. However, it is a bit more complicated as granite have varied structural composition, resulting in variation of cutting efficiency.

4.4.3 Component life expectancy

Life expectancy is a major factor for all mechanical systems, regardless, as a result of imperfect components (i.e. zero tolerance is practically impossible) and harsh system designs, parts will eventually wear out and need to be replaced. For WJC this includes, pumps, valves, tubing, power supply, and most importantly, gradual wear of cutting nozzle. AWC is designed to accelerate abrasive material to cut relatively hard material;

this will naturally cause an increased wear of the mixing tube in the nozzle. Thus life expectancy of cutting nozzle is a crucial to cost and time efficiency, greater wear results in higher nozzle consumption and higher downtime needed to replace nozzles.

Life expectancy of mixing tube: The majority of wear to the mixing tube happens as the abrasive material mix with the jet stream coming from the orifice, see Figure 4-2. Although the exact duration depends on many factors, the life expectancy of a mixing tube used for conventional WJC typically lasts around 20 to 80 hours, though longer and shorter duration is easily possible, depending on the circumstances in which it is used. It is also difficult to precisely measure when the mixing tube is fully worn, other than its cutting efficiency gradually degrades.

Recycling of mixing tubes: The mixing tube itself is usually made with a hard, but brittle material, and when worn, it is possible to recycle it by drilling it out, e.g. by using an EDM[9], this will of course result in a larger orifice mixing tube with reduce cutting efficiency, but it is a method that can be use to significantly extend life expectancy.

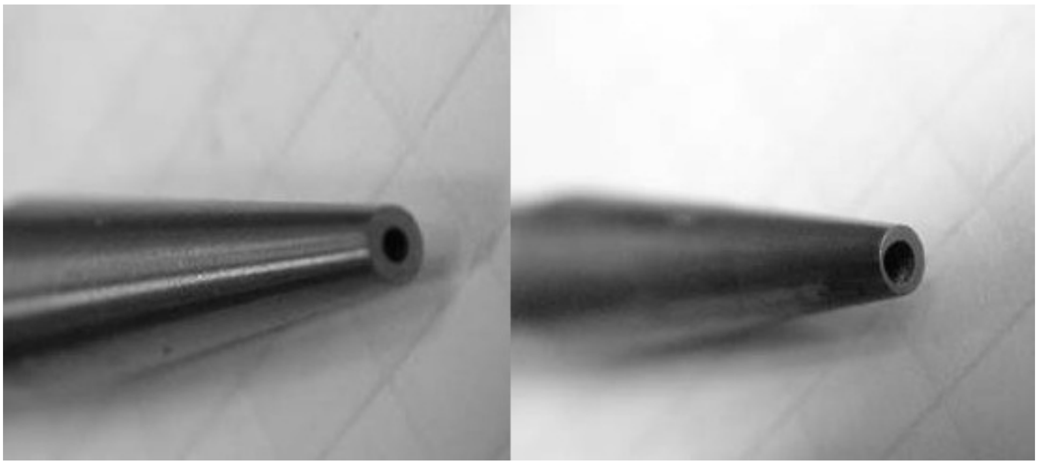

Figure 4-4 New mixing tube (left), used mixing tube (right)

4.5 Summary

WJC is today a well-established cutting method for CNC machining; it has many advantages to the alternative cutting methods available, i.e. plasma, laser, EDM, milling and punch press. The water jet technology is growing annually, technology-research company Technavio stated in a report published December 2013, a forecast CAGR[10] of

[9] electrical discharge machine (EMD)
[10] compound annual growth rate (CAGR)

9.3% for the period 2013-2018.[11] A key factor for this market growth is the need for machining materials. Important advantages and disadvantages with water jet cutting are summarized in Table 4-1 below.

Table 4-1 Advantaged and disadvantages with WJC

Advantages	*Disadvantages*
• No HAZ, very useful for cutting metals where heat can damage material properties • No dust is generated • Very little material is removed in the process • Highly efficient for milling • Water jet cutting can easily be automated • The cut surface is left with a very smooth finish • The equipment needed to carry out the procedure is very light, reducing effort needed to accelerate and decelerate • Less energy is required to operate equipment • Gradual wear can be monitored, occurs most specifically at the nozzle	• Dimensional accuracy is very difficult when cutting very thick material, may cause ruff wave pattern and curved cut face • Water jet cutting is limited to the number of material it can cut economically, while it is possible to cut tool steel and other hard material, the cutting rate needs to be reduced, also causing a disadvantage in cutting time • Taper is a known issue with water jet cutting, causing dimensional inaccuracy. Taper is described as when the exit angle of the jet stream is different from the angle it enters the cut material

[11] Technavio, "*Global Waterjet Machine Market 2014-2018," Technavio. December 3, 2013.* http://www.technavio.com/report/global-waterjet-machine-market-2014-2018

PART III: Discussion

Chapter 5

Water jet tunneling

5.1 Introduction

The purpose of this thesis it to break down the concept of traditional tunneling, and further discuss the possibility of applying what technology already exists for water jet cutting, as a new method of tunneling; water jet tunneling (WJT). By applying high-pressure water to the advance face, the idea is to cut the face surface rock into blocks that can be removed mechanically, these blocks should be easier to transport and have a high potential profitability, as it can be sold as construction material, e.g. facades, pavement, etc. The assumption is that it will allow a less process dependent cycle, e.g. mucking can start even though cutting is still active, and the overall cycle should be less expensive, as energy per ton excavated mass is arguably less than for traditional tunneling methods. The purpose of the thesis in not to propose a concept design or a detailed technical extravasation, but rather propose a thorough evaluation of the system application and it's potential.

For the sake of argument, TBM will not be accounted for in this discussion, this is because D&B, as discussed earlier in section 3.2, is the most common tunneling method used in Norway, and is still the overall, most economically suitable method for most of the current tunneling projects.

In order for a new tunneling method to be validated, it needs to provide a superior improvement to some of the aspects delivered by the available methods used today, such as:

- Faster cutting speed
- Reduced downtime

- Higher advance rate
- Significantly lower operation cost
- Low hazards
- Minor impact on surroundings
- Profitable byproduct(s)

These aspects are not equally important/impactful, but they all contribute to process development.

5.2 Concept

The concept of WJT is based on using a similar mobile, three-boom, hydraulic drill rig that is used in D&B (see Figure 3-8 on page 32), however, in stead of hydraulic drill booms, the rig is equip with a series of WJC nozzles to operate as cutting tools. For this to work the rig needs water supply/source, pumping power, abrasive feeder, water recycling (i.e. draining and rinsing), and a mucking system (power supply is a given).

5.3 Process cycle (hypothetical)

This section aims to provide a hypothetical breakdown of the process cycle of WJT.

With water jet tunneling, many of the traditional activities for D&B can (in theory) be eliminated, such as charging explosives, blasting, ventilation and scaling (see section 3.2 for more detail on D&B). As a result of using explosives, the majority of the activities for D&B depend on the prior activity to be complete before subsequent activities can start.

The four major activities for WJT can be narrowed down to cutting (i.), removing blocks of carved rock (ii.), support (iii.) and recycling (iv.). With the use of mechanical excavation, it will be possible to remove carved rock while the cutting activity still is active, removing any human interaction, allowing mucking to start as soon as a block of rock is carved out. It can also be argued that, the extension of support can be greatly reduced, up to the point where the need for shotcreting and bolting in some areas will be nonexistent. The proposed tunneling method, WJT, will leave the tunnel wall with a much smoother surface, and have little impact on the surrounding environment. Given that water supply is a closed system, it will need to be filtered and recycled for new use. This means that the rate of which the water is filtered and ready to be reused, needs to be equally as efficient as the pumping power of the WJC in addition to expected downtime between cutting, in order to not cause further downtime.

With WJT the main activities are WJC, mucking, support and recycling, while ventilation is only a continuous sub cycles. These activities will be further discussed in section 6.2.

WJC: By using the technology presented in Chapter 4, it is possible to use multiple water jet cutting nozzles to carve out rock formation in the advance step when tunneling. The amount of nozzles used will define the effectiveness of this method. Consequently, pumping power, water supply and recycling capability will limit the number of operating nozzles, as you will want to have enough resources regeneration to support the amount of nozzles used, so that the operation can run as smooth and continuous as possible.

Mucking: A mechanical excavation system mounted on the cutting rig, mucking should be connected via a conveyer belt to allow efficient removal of carved blocks.

Supporting: As the water jet cutting will provide a smooth surface, and the method does not fracture the structure, like D&B does, the need shotcrete should not be relevant, bolting, grouting and freezing on the other hand, is still relevant support measurements, as the surrounding structure may be unstable in some areas and need to be reinforced accordingly.

Recycling: WJT requires vast amounts of water, thus the water supply needs to be in a closed system, where the water is constantly recycled. As mentioned earlier in this section, the recycling process needs to efficiently match the rate of operation in order to not cause unnecessary downtime.

Ventilation (sub-cycle): Regular ventilation is required, depending on the source of the power supply, i.e. should it be generated via diesel motors or similar, ventilation needs to account for extra exhaust.

5.4 Challenges with WJT

Obviously many of the challenges related to WJC (see section 4.4) are also present in WJT, in addition to challenges occurring when applying the method as a tunneling technique.

The biggest challenge is creating a WJC system that can consistently cut through varying rock formation; this is thoroughly covered in the upcoming analyses in Chapter 6.

Other concerns and challenges are:

- Water flow dynamics for multiple nozzles
- When tunneling underwater tunnels, salt seawater may mix in with the operation system, causing potential threat for erosion damage to mechanical systems, tubing, valves, nozzles etc.
- May prove difficult to detect groundwater leakage, making it harder to evaluate support needs
- Bench cutting may be difficult with accumulated water, thus proper drainage needs to be implemented

Chapter 6

Analyses

This chapter is concerned with the market, technical and economical evaluation of WJT, and will take basis on information presented earlier, as well as some interesting research that was found on water jet cutting rates. The economic evaluation is heavily based on costs associated with conventional WJC, in addition to a personal conversation with professor Erik Skaugen, at the University of Stavanger. It is important to evaluate these aspects, as they greatly enhance the conclusion in the upcoming chapter "Conclusion and recommendations".

6.1 Market evaluation

As the thesis implies, introducing a new tunneling method would indicate that the targeted market for operation is tunneling construction. In Norway, these projects are initiated by the NPRA, and follow the law regarding public procurement, so that for a tunneling project, contractors are encouraged to provide their best offer, from which the most economically beneficial offer wins.

6.1.1 Market

As presented earlier in section 2.4, every year new tunnels are constructed adding at a rate of 20 to 30 km/year. NPRA has at any time more than 500 road constructions on national and local roadway.

- ~350 contracts under 10 M NOK
- ~100 contracts from 10 to 50 M NOK
- ~50 contracts over 50 M NOK

The majority of tunneling projects planned for 2014 – 2016 are unit price contracts; this kind of contract is based on estimated quantities of items included in the project and their unit price.

6.1.2 Competition

In Norway alone there are many different civil engineering companies, who perform a varying degree of services involved in tunneling projects, ranging from specific tasks, like D&B, tunnel installations or road construction, to turnkey projects.

6.2 Technical evaluation

Due to lacking research, it is difficult to say something about potential cutting rates of WJT on harder rock types, such as granite. relevant research has been sought, however it proved difficult to find research reports conducting experiments to find water jet cutting rates for material thicker than one meter, as the majority of WJC technology is mostly revolved around machining parts for production, including cutting pipes, tubing, plates, rods, etc. Which is one of the reasons why water jet cutting rates have not been covered earlier, as theory found on cutting rates for WJC have not been particularly relevant for material thicknesses exceeding one meter. One development paper on new water jet technology was however found, and will be covered in the coming section 6.2.1 on cutting rates.

6.2.1 Cutting rates

In order to justify a new method of tunneling, it is desired to achieve cutting depth up to approximately 1 to 4 m. Hence the pure WJC without abrasives is not appropriate for this cause, due to it's very limited cutting depth of about 15 cm. However with the addition of abrasives, research had shown a potential penetration rate in sandstone greater than 1.4 m, with a cutting rate of about 2 to 4 m per minute. This section will address the main results gathered from a 2004 study on water jet cutting (Jeng F., Huang T., Hilmersson S., *New Development of Waterjet Technology for Tunnel Excavation Purpose*). The results of the research referred to in this section is shown in Figure 6-1.

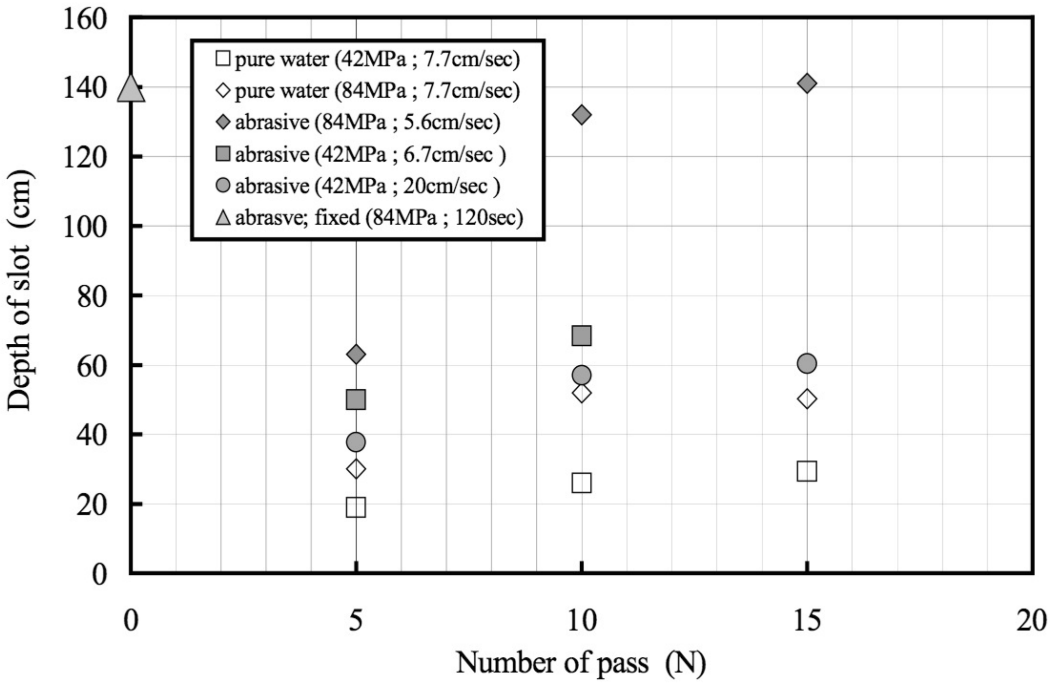

Figure 6-1 Penetration depth with WJC (standoff[1] = 15 cm, interval = 20 sec, sandstone)[2]

In this research, a hydro-demolisher[3] was used to test the cutting depth potential of WJC. This is because a hydro-demolisher allows a longer standoff gap between nozzle orifice and rock surface, as for when using a conventional water jet cutter, the standoff gap is limited to a very short distance of only a few centimeters, making it less practical for a rugged surface environment. The down side to using a hydro-demolisher is its pressure limitations at approximately 800 to 1,000 bar.

The results from this approach on hard rock, in this case granite and meta-sandstone, were that pressure up to 850 bar, was insufficient to effectively cut the respected rock, in any case the only advancement in penetration depth was achieved via chipping of rock fragments (see Figure 6-2).

[1] standoff; gap between nozzle orifis and rock surface
[2] Jeng F. et al. (2004). *New Development of Waterjet Technology for Tunnel Excavation Purpose.* Elsevier. p. 8
[3] high work rate water jet, used for fast removal of concrete, requires a greater energy output

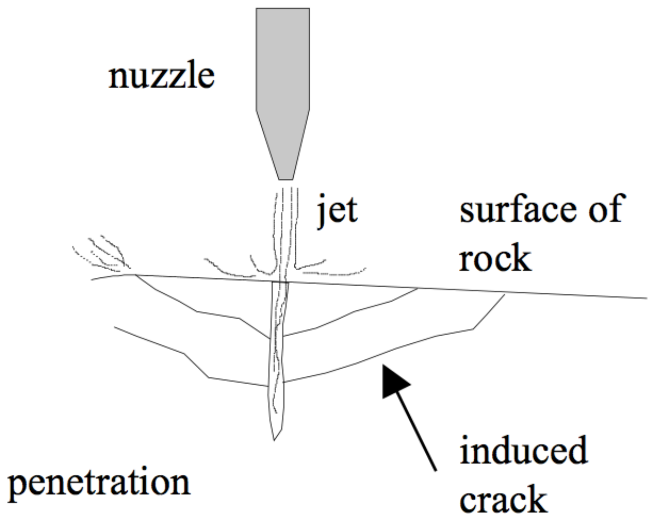

Figure 6-2 Illustration of fracture induced by WJC

As the uniaxial compressive strength (σ) of granite and meta-sandstone is 165 MPa and 148 MPa respectfully, which is almost double the size of the applied hydro-demolisher water jet pressure, resulted in the method not being applicable to cut these rock types. The small advancement in penetration depth achieved, was mainly the cause of chipping rock fragments. This can indicate that the setup used cannot penetrate inside hard rock, at all.

Conflicting parameters:[4] While it is stated in the report (Jeng F., Huang T., Hilmersson S., *New Development of Waterjet Technology for Tunnel Excavation Purpose*) that operating pressure, in order to effectively cut/carve rock, has to be around 2,400 to 4,200 bar, a comment was made by professor Erik Skaugen at the University of Stavanger, that operating pressure would not need to be higher than 1,500 bar in order to successfully penetrate granite. Due to the fact that the field study conducted in the report, concludes that sandstone can be cut efficiently up to 1.5 meters depth by using a 850 bar hydro-demolisher with abrasive quartz sand, suggest that a more thorough research on pressure parameters should be performed. The conflict in parameters may be due to inadequate quality specifications for the rock structure.

Other research suggest that the following characteristics on uniaxial compressive strength in rock:

[4] based on a personall conversation with professor Erik Skaugen at the University of Stavanger, June 13, 2014.

Table 6-1 Field estimate of uniaxial compressive strength of rock[5]

Grade[6]	*Term*	*Uniaxial strength σ [MPa]*	*Point load index [MPa]*	*Fields estimate of strength*	*Examples*
R6	Extremely strong	> 250	> 10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 - 250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 - 50	1 - 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone

[5] Hoek, E. (2007). Practical Rock Engineering, *Rock mass properties*, chapter 11 p. 6 (the entire table is not cited here, grade R2, R1 and R0 are considered to be less interesting for the sake of this thesis)
[6] grade according to Brown (1981)

6.2.2 Nozzle

Nozzle wear: As the use of abrasives greatly increases the wear on the nozzle mixing tube (see Figure 4-2, on page 42), it is highly recommended to manufacture a mixing tube of a more durable material, like ceramic or industrial-grade diamond.

Nozzle force: The potential force acting from the nozzle due to the water pressure can be determined numerically by the following equation:

Let the speed of the water exiting the nozzle be v, and the pressure required to penetrate rock be ΔP_N. To avoid issues with cavitation it is recommended to keep the speed of the water jet lower than the speed of sound in liquid water at 25°C, i.e.

$$v < 1{,}497\ {}^{m}/_{s}$$

The applied pressure from the nozzle, ΔP_N, needs to be high enough to erode hard rock formation, like granite, thus the nozzle pressure (pressure of the water jet stream) needs to be high enough to perform cutting, the range of applicable pressure in relation to the purpose of the WJC is summarized in Table 6-2.

Table 6-2 Corresponding parameters according to purpose of water jet (without the use of abrasives)[7]

Purpose	*Pressure [bar]*	*Flow rate, Q [liter/min]*	*Output energy [kW]*
Cleaning	~500	~80	~70
Cutting	2,400 ~ 4,200	~22	~90
Hydro-demolition	800 ~1,000	~160	~270

Thus according to Table 6-2, the applied pressure, ΔP_N, needs to be at least 2,400 bar.

$$\Delta P_N \geq 2{,}400 \text{ bar}$$

[7] Jeng F. et al. (2004). *New Development of Waterjet Technology for Tunnel Excavation Purpose.* Elsevier. p. 2

Analyses

These are the perimeters, for which the operation can take place; it is ideal to find the optimal speed where penetration rate is prudent to the amount of energy and resources required. This is on the other hand difficult to achieve with various ground conditions. Assuming $\Delta P_N = 2{,}500\ bar$, friction in the nozzle $C_N = 0.95$ and with water density $\rho = 1{,}000\ kg\ /\ m^3$, the rate of water flow is determined by

$$v = C_N \sqrt{\frac{2\Delta P_N}{\rho}} \tag{6.1}$$

$$v = 0.95 \sqrt{\frac{2 * 2{,}500\ bar \times 10^5}{1{,}000\ {kg}/{m^3}}} \approx 670\ {m}/{s}$$

Determining the volumetric flow rate Q of water for a nozzle with cross-sectional surface opening $A_N = 0.1cm^2$,

$$Q = v * A_N = 600\ {m}/{s} * 0.1cm^2 = 0.0067\ {m^3}/{s} \tag{6.2}$$

Mass flow rate is equal to the volumetric flow rate multiplied by density

$$m = Q * \rho = 6.7\ {kg}/{s} \tag{6.3}$$

The effective force F_N from the nozzle is the product of mass flow rate and speed of jet stream. A

$$F_N = m * v \tag{6.4}$$

$$F_N = 6.7\ {kg}/{s} * 670\ {m}/{s}$$

$$F_N = 4{,}489\ N$$

Assuming 50 nozzles is sufficient for an efficient operation, the total force from such a system will be defined as

$$F_{N,50} = 50 * F_N$$

$$F_{N,50} = 50 * 4{,}489\ N$$

$$F_{N,50} = 224.45\ kN$$

Meaning that a system consisting of 50 nozzles working at a rate of 6.7 liter per second, would only apply a reacting force of approximately 225 kN. Thus it should not require too heavy of a vehicle to operate such a mechanical system as described above.

The same equation could be calculated for using 1,500 bar, however the intentions is only to show an approximation of the reaction force from the operating nozzles.

The amount of nozzles needed will depend on how much water is available, and at what rates it can be recycled, i.e. if you consume x liters/min, you will have to at least be able to filter and recycle x liter/min in order to sustain a process cycle with least amount of downtime. Or, you will need to provide enough water, and a rinsing capability good enough to sustain the full duration of operation, as there most likely will be a period where WJC is not operating, this time can be efficiently used to filter and recycle the rest of the water.

6.2.3 Pumps and tanks

In order to provide enough water to sustain the system for an extended period of time, it will require a long ‘train’ of water tanks and pumping units, to maintain operation. This will impose a space issue relative to the size of the constructed tunnel in relation to mobility access for construction vehicles along with the occupied space taken by the mucking system. Depending on how many nozzles are operating at a time, defines the required pumping power, and the water supply. Using the example above in 6.2.2 to set things in perspective, 50 nozzles, each with a flow rate of 6 liters per second will result in a net consumption of 18,000 liters per minute, having 10 containers, each with a volume capacity of 50,000 liters (i.e. 2500 × 10550 mm cylindrical tank), would result in a little under 30 min of full operation, not accounting for water recycling.

6.2.4 Abrasive recycling

Because cost associated with abrasive consumption, usually tend to be a fairly large portion to the total cost of operation, as will be further mentioned in section 6.3, abrasive recycling is a good way to reduce cutting cost.

For WJT it is also highly important to filter out the abrasive consumable, as the water itself should be recycled and reused, thus any abrasive material left in the recycled water will oppose a large additional (unnecessary) fatigue to the entire system should would otherwise only be affected by the high-pressure water.

6.3 Economical evaluation

Evaluating the potential cost of operating a WJT system, as described in Chapter 5, is a tough task, so by analyzing the operation cost of conventional WJC, it is possible to better speculate associated cost for WJT. It is important to understand what major factors drive the cost of WJC; these can be sectioned in to four areas: cost of water, power, abrasives, and cost of maintenance and operation. Garnet abrasive consumption can for instance accumulate up to about 75% of total operating cost for a WJC system, thus it is important to understand what is driving the use.

6.3.1 Operating and maintenance cost

When considering conventional WJC, there are different machine specifications that will affect overall cost of operation and maintenance, other factors that can greatly change the cost to produce a part is labor, overhead and burden rates. Meaning that, while running a 60,000 PSI (4,137 bar), 50 HP pump may be less expensive per part produced, compared to a 60,000 PSI, 100 HP pump, once accounting for labor, overhead and burden rates, this might prove to be the other way around.[8] Even so, labor will not be accounted for, as it is difficult to speculate on labor costs for WJT. This section will mainly focus on highlighting the cost associated with machine specific operation.

Normally conventional WJC operate most economically around 60,000 PSI or less, because of the increased maintenance and unscheduled downtime that occur when working with pressure pumps above 60,000 PSI, due to accelerated component fatigue. Maintenance includes all components that are wetted by the high-pressure water, and all parts through which abrasives flows.[9]

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[8] ESAB. *"How much does waterjet cutting cost?" ESAB Knowledge Center.* August 26, 2013. http://www.esabna.com/us/en/education/blog/how-much-does-waterjet-cutting-cost.cfm
[9] OMAX. *"What to consider before buying," OMAX.* http://www.omax.com/learn/what-to-consider-before-buying

Cost of water: While foremost being one of the main components for operation, it is the least expensive. Water consumption costs will for conventional WJC account for approximately 2 to 3% of total operating cost. This need not necessarily be equally applicable in Norway as water sources are easy to come by, and the water used for excavation will be filtered and could technically be released without opposing a hazardous threat to the environment.

Cost of power: On average, cost of power for conventional WJC can be estimated to around 8 to 11% of total operating cost, depending on the size of the pump used.

Cost of abrasives: The most expensive part of WJC is the cost related to abrasive consumption, depending on feed rate and abrasive quality, the cost of abrasives can range from 45 to 75% of total operation cost. The feed rate of abrasives reflect on what material is being cut, where cutting steel and other hard material would need a higher abrasive consumption in order to cut effectively. There are also different types of abrasives that can be used, though two types in particular are mainly common; garnet (hard rock and alluvial), and quartz sand. The main difference between the abrasives is its structure, where hard rock garnet is basically rock crushed down to a specific mesh size, and with its rougher shape, it cuts better through material faster than the alternative alluvial and quartz sand. Alluvial garnet and quartz sand is mined from riverbeds where the individual grain is naturally worn down to sand, thus cuts a bit slower than hard rock, the benefit is that it is cheaper to acquire. To find an effective way to use the abrasive material better, abrasive recycling need to be effective. For this, the optimum particle size of recycled and recharged abrasives for the maximum cutting performance as well as for the minimum cutting cost and for the maximum profit rate should be determined. In addition, the economics of cutting with recycled and recharged abrasives should be investigated.

Cost of component wear: Due to the rapid wear of parts, including orifice, mixing tube, pump seals and check valves, part replacement represent a large portion of operation costs, that can be calculated as cost-per-hour. On average, replacing miscellaneous parts, constitute about 11 to 44% of total operation cost.

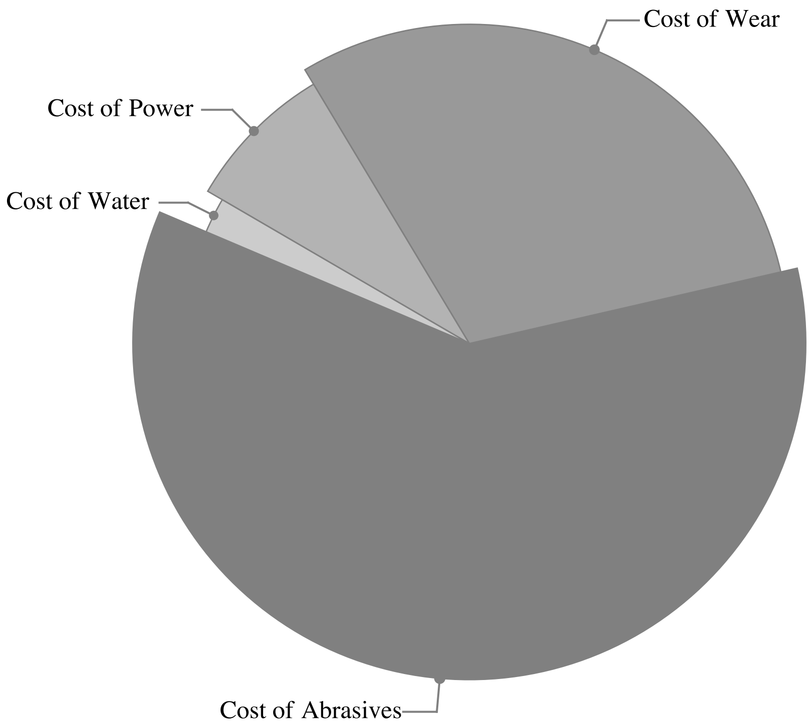

Figure 6-3 Operating and maintenance cost of WJC

The cost of water jet cutting is largely affected by the use of abrasives and the gradual fatigue of specific components, mixing tube in particular. So in order to increase cost control, understanding of how to maximize the use of the selected abrasives will greatly benefit total operation cost. In addition, component design and material selection need to reflect intended application for WJC so to increase wear resistance.

6.3.2 Profit potential for stone blocks[10]

One of the bigger questions that have not been addressed until now is the potential profit in blocks of stone, especially compared to gravel and muck, as that will be the competitive byproduct of D&B and TBM. In many cases, excavated mass can be more of a burden than a profitable product; this is due to the transportation costs followed by moving the masses around. As a result, the excavated muck will ideally be used as filler for further construction phases surrounding the area of the tunnel.

[10] the content of this section is based on a personall conversation with professor Erik Skaugen at the University of Stavanger, June 13, 2014.

When considering a block of stone, if it is made of high quality granite, the potential profit can be very high, up to about 20,000 NOK per cubic meter (2.7 ton). However, this is extremely rare to come by, almost non-existent as far as tunnel excavation goes. Even so, lesser granite compositions are more realistic to encounter, exporting this kind of granite can prove to be less profitable, if not at all. When constructing tunnels near the coast of Norway, where the distance to the nearest port is relatively short, transportation expenses are much lower, making it more likely to gain a positive return. As for constructing tunnels further inland, the transportation expenditures will increase, most likely to the point where profitable return is near zero.

Chapter 7

The bigger picture

Is 'application of WJC as a tunneling method' the right area one should focus on to improve tunneling?

As the purpose of the new application, presented in this thesis, is to provide a more efficient tunneling method, it is an important question to ask whether it is the excavation method that has the largest potential for improvement. This chapter will address an issue that was presented by NPRA, in oppose to finding a new method. It will however not be discussed in any great detail, as the amount of work needed to address this issue thoroughly, would exceed the purpose of this thesis.

7.1 From start to finish

By looking at the entire process from project start to the opening of a functional tunnel, there are many different aspects that play an important part to the overall process of constructing a tunnel, some of which have a bigger impact on time and cost. The entire process can be broken down to three simple project-phases:

- Pre-tunneling
- Tunneling
- Infrastructural construction

Pre-tunneling: Including concept development, tunnel design, desk studies, field research, contract development, and everything else that takes place prior to official start of tunneling. Some of which has been covered in section 2.7.

Tunneling: Including the major areas that have been presented and discussed in this thesis, see Chapter 3. Involving excavation, support of the cavity and removal of the excavated earth (i.e. mucking).

Infrastructural construction: Briefly covered in section 2.5, the infrastructural project-phase consist of the remaining activities that eventually leads to a functional tunnel. This includes, road surface (or pavement), road signs, illumination, drainage and ventilation (see section 2.5).

7.2 Project-phase transitions

In order to increase overall effectiveness of tunneling projects, processes should transition as smooth as possible, meaning that activities need to start as soon as they can, without further delays. Ideally, concerning the use of time, work related to infrastructure and tunnel installments, should start as soon as tunneling advancement is at a safe and practical distance. In the case of constructing the tunnel on Solbakk, Rogaland, Norway, the work related to installments and road construction will be initiated fall 2014, which is 2 years before the tunneling phase will be completed.

Even though it is practically possible to conduct this approach, in order to save time, the entrepreneur, will in many cases not want to start construction of infrastructure until tunneling is complete, as it is then possible to use heavier construction vehicles, among other things, during the infrastructure phase of the project.

Although there are ways to increase efficiency, and there are reasons not to conduct the least time consuming approach, overall proper project planning is vital in order to minimize time and cost overruns.

PART IV: Conclusion

Chapter 8

Conclusion and recommendations

This final chapter deals with the conclusion of the study conducted for this thesis, in addition to recommendations for further development.

8.1 Conclusion

The goal of this thesis is to evaluate the current situation for tunneling in Norway, and further address the concept idea of applying water jet cutting technology as a new tunneling method. To do this, extensive work has been put into breaking down how tunneling works, and its relation, and application in Norway, as well as developing a thorough understanding of costs and mechanics behind water jet cutting and abrasive water jet cutting.

From research it appears that there are no method available today, which can effectively cut through hard rock beyond the 30 cm. Thus, to completely answer the question whether WJT should become a reality, further research need to be directed towards developing and field-testing a method for rapidly cutting hard rock (e.g. granite, meta-sandstone, gneiss, etc.) in thicknesses from 1 to 5 meters. One of the biggest issues with applying WJC as a tunneling method, is the abrasive consumption; it is a critical cost factor for conventional WJC, and will become an even bigger factor in operation cost for WJT.

It is recommended to conduct similar tests, to the one presented in "*New Development of Waterjet Technology for Tunnel Excavation Purpose*", discussed in 6.2, for cutting hard-rock material, in order to confidently draw a conclusion to the application of WJC as a new tunneling method. This new method should prove to either cut faster than previous tunneling methods, or be overall less expensive to perform, or both.

It remains to further develop an efficient application of WJC technology to enable deeper cutting with high cutting rate for hard rock, and at the same time, prevent the chipping issues discovered when using a hydro-demolisher to carve granite and meta-sandstone.

The findings of this thesis also suggest that further research need to be targeted toward defining operating pressure to cut hard rock both with and without the use of abrasives.

8.2 Recommendations for further development

The following recommendations are suggested in order to further develop the potential application of WJC as a new method for tunneling:

- *Field studies on increasing cutting depth for WJC in hard rock.* There are few studies on water jet cutting potential other than for conventional use to cut parts from different material, using CNC technology. WJC has been proven to work for cutting sandstone up to 1.5 m depth with a fairly fast cutting rate of 2 to 4 meters per minute. Thus it would be interesting to see further methods being developed to cut granite with higher advance rate.
- *Develop alternative abrasives.* If abrasives are to be used in WJT, abrasive recycling is strongly recommended to reduce cost of consumables, recycling method need to be swift as to not cause inconvenient downtime. By using magnetic abrasives like steel or iron particles, recycling can prove to be executed quite efficiently, in addition, due to the structure, and high density of steel, it should have a good potential as an abrasive. Higher density would mean higher impact force, and the structure of steel makes it more durable than brittle abrasives, in that steel will deform if exposed to an excessive impact exceeding the yield force of steel. Brittle abrasives on the other hand tend to fracture if the impact force is too great. Another example could be to find a way to induce ice crystals as an abrasive, that way recycling should only be focused on removing excavated rock fragments.
- *Address abrasive feeding rate to maximize cutting depth*. As abrasives are one of the main factors for AWC penetration depth, further study on abrasive feeding rate would be interesting. Increasing abrasive feeding rate increases penetration

depth, however if the feeding rate is to high, it tends to clog nozzle and/or feeding hose (i.e. abrasive inlet). As for the nozzle, the rule of thumb is; the orifice of the nozzle should at least be three times larger than the largest particle to pass through the orifice. Meaning that three particles are more likely to jam the opening than four. One should also keep in mind that stronger abrasives also wear out the equipment much faster, thus more durable parts should be considered.

- *Further investigate the potential difference in profit for rock as a solid block versus gravel/muck.* The question that remains is whether excavated muck is more profitable (or less costly), as a solid block or as gravel/muck.

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