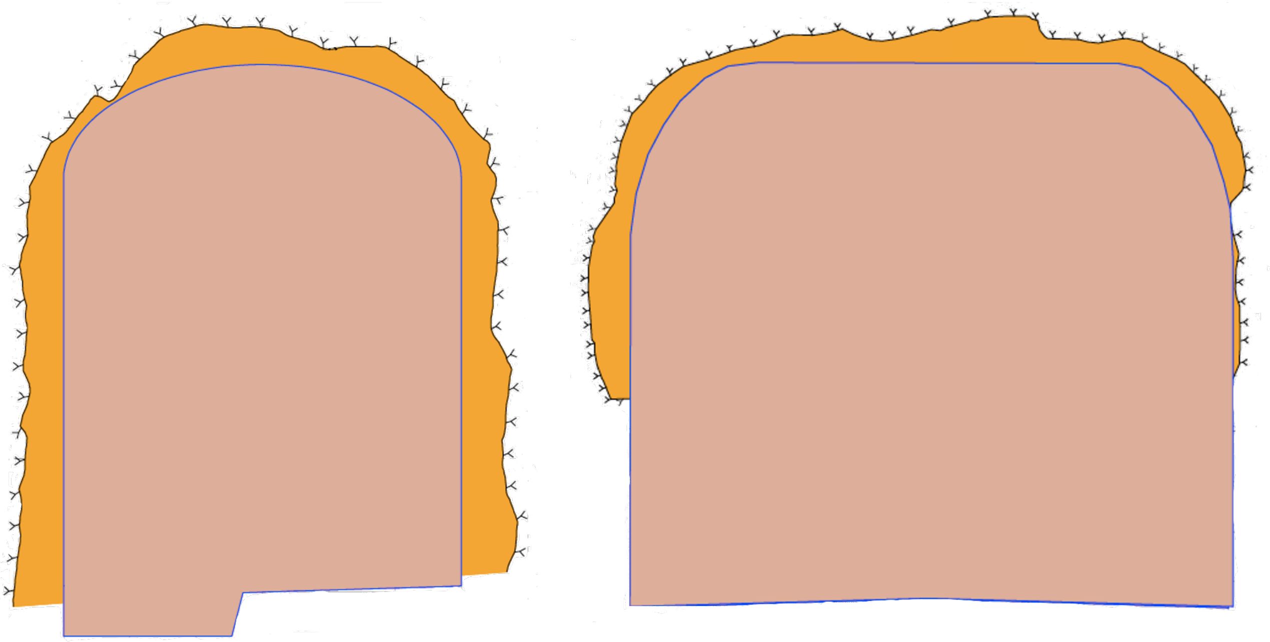

Optimising Productivity and Climate Impact in Complex Tunnelling Projects

A case study of how rock excavation classes impact the amount of overbreak in E05 Contract Korsvägen, Project Västlänken

Master's thesis in Design and Construction Project Management

AMANDA BERGSTRÖM

ELIN NILSSON INSTITORIS

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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Master's thesis ACEX30

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Supervisor: Rasmus Rempling, Department of Architecture and Civil Engineering
Examiner: Rasmus Rempling, Department of Architecture and Civil Engineering

Department of Architecture and Civil Engineering
Division of Construction Management
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 10 00

Cover: Illustration of two of the different tunnel profiles in the contract Korsvägen, with different amount of overbreak. Source: Created by the authors.

Department of Architecture and Civil Engineering
Gothenburg, Sweden 2022

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ELIN NILSSON INSTITORIS
Department of Architecture and Civil Engineering
Division of Design and Construction Project Management
Chalmers University of Technology

Abstract

The city of Gothenburg is going through a big urban development of the city's transport infrastructure to increase the capacity and to find more sustainable ways of travelling. Dominant in this development is the underground tunnelling project Västlänken. The project will contribute to regional growth and expansion of the labour market by shorter commuter times to satellite communities. The tunnels will be constructed beneath the city of Gothenburg, trough drill-and- blast tunnelling, in both rock and soil which involves complex challenges regarding the rock excavation. These challenges are an opportunity for both the contractor and the client to innovate and optimise the drill-and-blast tunnelling process. Furthermore, the production efficiency and optimisation of resources play an important role in reaching the future sustainable requirements and in preventing large cost overruns due to poor overbreak optimisation.

The purpose of the thesis is to evaluate how the choice of rock excavation class affects the production efficiency of the tunnelling process. This by investigating opportunities and challenges of optimising the overbreak in terms of cost, time and sustainability. This to contribute to the industry's data-driven working methods of today. To fulfil the purpose, a qualitative research methodology was developed together with a case study at project Korsvägen, Västlänken. To comprehensively analyse cost, time and sustainability in the tunnelling process, three methods were chosen. The three methods conducted are an interview study, a cost calculation, and a climate impact estimation. The study showed that Rock Excavation Class 3, in acceptable rock quality, generates a larger amount of overbreak compared to Rock Excavation Class 1. Thus, Class 3 causes larger CO2 emissions. Despite this, Class 1 was found to be the most expensive choice of excavation method. This since it disturbs the sensitive tunnelling process and thus is less production effective. Compared to Rock Excavation Class 3, Class 1 may also have a larger negative influence on social and economic sustainability. This due to the health- safety aspects and the longer production time required, which in this large and complex tunnelling project may affect the whole city of Gothenburg.

Keywords: Climate Impact, Drill and Blast Tunnelling, Production Efficiency, Rock Excavation Class, Urban Development, Tunnelling process, Overbreak, Intrusion, Rock Quality, Cost-and-Time Overruns

Optimering av produktivitet och klimatpåverkan i komplexa tunnelprojekt
En fallstudie av hur bergschaktningsklasser påverkar mängden överberg i E05 Entreprenad Korsvägen, Projekt Västlänken
AMANDA BERGSTRÖM
ELIN NILSSON INSTITORIS
Institutionen för Arkitektur och Samhällsbyggnadsteknik
Avdelningen för byggledning
Chalmers Tekniska Högskola

Sammanfattning

Göteborgs stad genomgår en stor utveckling av stadens infrastruktur för att öka kapaciteten och hitta mer hållbara sätt att resa. Tunnelprojektet Västlänken är dominerande i utvecklingen och ska bidra till en regional tillväxt och expandera arbetsmarknaden genom att koppla samman regionen med kortare pendlingstider. Tunnlarna kommer att byggas under Göteborgs stad, genom metoden borr- och sprängning, i både berg och lera, vilket innebär komplexa utmaningar vid bergutschaktning. Dessa utmaningar är en möjlighet för både entreprenören och beställaren att hitta nya sätt att optimera bergschaktningsmetoderna i tunnelprocessen. Produktionseffektivitet och optimering av resurser är också viktiga för att nå framtida hållbarhetskrav och förhindra stora kostnadsöverskridanden. Dessutom spelar produktionseffektivitet och optimering av resurser en viktig roll för att nå de framtida hållbara kraven och för att förhindra stora kostnadsöverskridanden på grund av problem med optimering av överberg.

Syftet med examensarbetet är att utvärdera hur valet av bergschaktningsklass påverkar produktionseffektiviteten i tunneldrivningsprocessen. Detta genom att undersöka möjligheter och utmaningar med att optimera överberg och dess påverkan på kostnad, tid och hållbarhet samt för att bidra till dagens datadrivna arbetssätt i branschen. För att uppfylla syftet, utvecklades en kvalitativ forskningsmetodik tillsammans med en fallstudie. För att heltäckande analysera kostnad, tid och hållbarhet i tunneldrivningsprocessen valdes tre metoder, en intervjustudie, kostnadsberäkning och en klimatkalkyl. Resultaten visade att bergschaktningsklass 3, i acceptabel bergkvalité, genererar en större mängd överberg jämfört med bergschaktningsklass 1. Klass 3 orsakar således också större CO_2-utsläpp. Trots detta var klass 1 det dyraste valet av bergschaktningsmetod. Detta eftersom klass 1 stör den känsliga tunneldrivningsprocessen och därmed är mindre produktionseffektiv. Jämfört med bergschaktningsklass 3 kan klass 1 också ha en större negativ inverkan på social och ekonomisk hållbarhet. Detta på grund av hälso- och säkerhetsaspekterna samt den längre produktionstiden som krävs, vilket i detta stora och komplexa tunnelprojekt kan komma att påverka hela Göteborgs stad.

Nyckelord: Klimatpåverkan, Borr- och Spräng-metod, Produktionseffektivitet, Bergschaktningsklass, Stadsutveckling, Tunneldrivningsprocess, Överberg, Intrång, Bergkvalité, Kostnads- och Tids-överskridanden

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We would like to express our greatest appreciation to our supervisor at NCC, Sofia Lander, for your dedication, feedback, and guidance in this new field of ours. Thank you for your time and knowledge you have given us. We would also like to thank all the colleagues at NCC for your support and participations in our research and for making us feel like one in the team "Bergtunnel". We also want to thank Tomas Öhrling for allowing us to use his well described and helpful illustrations of the activities involved in the tunnelling process. We would also like to give a special thanks to our supervisor and examiner at Chalmers, Rasmus Rempling, for your commitment, endless positivity and for pushing us in the right direction. Without all of you, this thesis would not have been possible to accomplish.

Looking back at these five years at Chalmers, we are grateful for all the relationships we have created and for all the fun and challenging moments. Therefore, we want to thank all our friends, family, and professors for supporting us along the way. Without you, these five years would not have been the same.

Amanda Bergström & Elin Nilsson Institoris, Gothenburg, June 2022

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Nomenclature

Blasting Round	A sequence of detonated charging in order to excavate rock mass
Boxplot	A method to graphically summarise the normal distribution of data in five numbers as the median, the upper and lower limits as well as the maximum and the minimum
Contour-holes	Closely spaced drilled holes along the final excavation surface, timed to detonate last
Control drilling	Drilling performed to determine if the grout screen is sealed correctly
Grouting	Injecting materials into fractures and cavities for sealing the rock
Intrusion	Rock remaining within the theoretical tunnel profile that should have been removed by the blast
Mucking	The removal of blasted rocks
Overbreak	The distance from theoretical tunnel contour to actual tunnel contour
Pre-Grouting	First phase in the tunnelling process, with the purpose of pre-injection of rock mass surrounding the rock section which will be blasted, containing the activities: Drilling, Grouting and Control drilling
Rock Excavation Classes	Regulate the maximum allowed distance between the drilled holes, allowed amount of explosives and maximum allowed damage zone. These regulations are divided in rock excavation classes 1, 2 and 3.
Scaling	The removal of the remaining loose rock from tunnel roof & walls
Structure-borne sound	Vibrations that spread from machines through the rock to buildings
Tunnel face	The working face in an excavation or tunnel from which the tunnelling process is carried out

1 | Introduction

This chapter introduces the challenges of performing tunnelling in urban dense areas and its association to rock excavation and sustainability, which forms the basis for the purpose of this thesis. First, this chapter presents a background to the research topic and further the problem formulation is presented. Then, the purpose of this thesis is introduced with the associated research questions. Lastly, the limitations and the structure of the thesis are presented.

1.1 Background

Ever since Brundlandts Report was published in 1987, sustainability concerns have been an alarming topic on agendas world-wide. In 2015, the United Nations implemented the “Agenda 2030 for Sustainability and Sustainable development” including the 17 Sustainable Development Goals (United Nations, n.d.). Following the concept of sustainability by its three perspectives, economic, environmental, and social, have been established in companies of every industry all over the world (Pero, Moretto, Bottani, & Bigliardi, 2017). Therefore, sustainability is today a crucial issue to consider. Hence, every company needs to participate in reaching sustainable change and drive the sustainable development forward (Pero et al., 2017).

It is well known that the construction industry has an major impact on our environment, influencing all three perspectives of sustainability (Ofori, 2000; Pero et al., 2017). This since the construction industry creates infrastructure, roads, railway, facilities, job opportunities, integrate communities, and thus contributes to the global economy. In Sweden, the construction industry is of great importance for the entire Swedish economy and contributes to the development and growth with an annual revenue of 1,100 BSEK and around 550,000 employees at the year of 2018 (Fossilfritt Sverige, 2018). At the same time, the construction industry is one of the largest users of natural resources, one of the biggest contributors to CO_2 emissions, and stands for one third of the total energy usage in Europe (Pero et al., 2017). Accordingly, the construction industry in Sweden stands for approximately 20% of the total Swedish climate impact due to the manufacture of materials, transports as well as energy usage in the construction phase. (Fossilfritt Sverige, 2018).

There is a big challenge to combine the requirement for urban development with the need for new sustainable solutions and the increased demand for public transportation in cities (Fossilfritt Sverige, 2018). Today, the demand for construction works have increase to a level that have not been seen in Sweden since 1970 (Naturvårdsverket, n.d.-b). To meet this demand there is an accelerating need for capacity in cities regarding their road and railway systems. Accordingly, tunnelling is often the most suitable solution to meet the capacity demands in cities since the space for new road and railway systems above ground is limited (Broere, 2016; Olofsson, 2017). Similar to this, the city of Gothenburg is going through a big urban development of the city's transport infrastructure. Prior to this development has the railway system of Gothenburg reached its maximum capacity (Sweden Underground, n.d.-b). Project Västlänken, with the direct translation The West Link, is the dominant development in increasing the capacity and find more sustainable ways of travelling. Project Västlänken consists of a railway constructed beneath the city of Gothenburg with three new underground stations at Gothenburg Central Station, Haga, and Korsvägen (Sweden Underground, n.d.-b; Swedish Transport Administration, 2021c). An map of the project Västlänken is shown in Figure 1.1.

Figure 1.1: Map of the project Västlänken. Conducted from the project.

Underground tunnelling generates big risks and many challenges for all involved parties as well as affected third parties (Eskesen, Tengborg, Kampmann, & Holst Veicherts, 2004). Accordingly, the project Västlänken involves many challenges regarding the rock excavation. This since the tunnels will be constructed in both rock and soil underneath the city. Moreover, rock excavation could be performed by different methods and the contractor decides which of the methods that is the best suitable. This with respect to the Swedish Transport Administrations restrictions on the surrounding areas (Swedish Transport Administration, 2021a). Since, the surrounding dense urban area is sensitive to noise, vibrations, working hours, deformations and impact on ground water levels, the method used is a traditional drilling- and blasting technique (Swedish Transport Administration, 2021b). The method consists of a tunnelling process which may be divided in three main phases: Pre-grouting, Blasting Cycle, and Reinforcement. These three phases consist of different activities which are repeated to move the tunnelling forward (Swedish Transport Administration, 2020b). This process can be practised differently depending on different techniques and requirements which in this study will be referred to as *rock excavation classes.*

Moreover, the tunnelling process takes time and is costly for both the contractor as well as the client, and involves risks for unforeseen outcomes. This means that a need for accurate and thoroughly planning and investigations beforehand are of high importance to succeed with complex tunnelling project and minimise the risk for additional costs. Furthermore, the production efficiency, meaning the optimisation of resources, also play an important role in both reaching the future sustainable requirements but also in preventing large cost overruns (Flyvbjerg, 2014; Fossilfritt Sverige, 2018).

1.2 Problem Formulation

It is both in the client's and the contractor's interest to account for the consequences and impact of cost and time when performing rock excavation in tunnelling. This due to the big risks arising in complex tunnelling projects, where the contractor has a limited budget and strict time frames which are sensitive to disturbances. At the same time, the contractor desire to deliver according to the clients demands with high quality. Furthermore, the client also faces big risk with tunnelling projects due to the high amount of uncertainties and complexity in underground works which often leads to cost overruns.

The challenges with rock excavation in dense urban areas can be used as an opportunity for both the contractor and the client. An opportunity to find new ways to optimise the tunnelling process, the rock excavation method, and thereby lower the costs and become more sustainable. Accordingly, an interest is emerging to investigate the possibilities of optimising the amount of overbreak in the tunnelling process for infrastructure projects. This to obtain an overall higher production efficiency and a better final quality of the tunnel profile. It is a balancing act for the contractor to be able to optimise the overbreak without increasing the risk for failure in production efficiency. Therefore, the relationship between overbreak and intrusion is important to follow up and its effect on the tunnelling process. At the same time, it is important to consider the need for contractors to take greater responsibility for their climate impact caused by their operations. This since cost, time, and sustainability are key aspects for the construction industry's future development.

1.3 Purpose

The purpose of the thesis is to evaluate how the choice of rock excavation methods affects the production efficiency of the tunnelling process. This will be performed with focus on cost, time and sustainability in complex drill-and-blast tunnelling infrastructure projects located in dense urban areas. The thesis will identify how the choice of rock excavation class affect the production efficiency of a tunnelling project. This will be performed through analysing the opportunities and challenges of focusing on optimising the overbreak and how the rock excavation classes affect the cost, time and sustainability.

1.3.1 Research Questions

To fulfil and support the purpose of this thesis, three research questions were established:

RQ1: *How does the choice of rock excavation class affect the outcome of overbreak when performing rock excavation in contract Korsvägen?*

RQ2: *How does the two studied rock excavation classes affect the outcome of cost and sustainability when performing rock excavation in contract Korsvägen?*

RQ3: *What are the risks with regard to cost and sustainability for the two studied rock excavation classes when performing rock excavation in contract Korsvägen?*

1.4 Delimitation

This study includes a case study of four tunnels in the E05 contract Korsvägen, project Västlänken. Based on the studied four tunnels,a reference case is determined to compare and analyse the differences in cost, time and sustainability between the two studied rock excavation classes. Therefore, all data used is collected from the project and based on experience existing in the industry. However, the numbers presented in the results are modified by the authors in consultation with the contractor to respect company secrecy. Hence, the numbers shall not be viewed as explicit but instead as an indication of the differences. Furthermore, a motivation for the case chosen and the development of the reference case can be found in Section 4.4.

This thesis is performed through a Swedish requirements of the tunnelling process and does not consider the directives or operations of tunnelling projects in other countries. The thesis also involves a perspective of performing rock excavation in a tunnelling project located in Swedish dense urban areas. Moreover, the phases in the tunnelling process that are focus of this study is the Blasting Cycle and Reinforcement, with exception of the activity ventilation. Further, groundwater conditions and groundwater leakage will not be included in this study. The definition for sustainability considered in this thesis is as described in Brundlandts Report "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*" (Commission on Environment, 1987, p. 41). Additionally, it important to highlight that 'Sustainability' is a complex topic which is hard to fully cover, where the impacts of the two rock excavation classes have been the main focus in this thesis.

1.5 Structure of the Thesis

The thesis is based on eight chapters and is structured as stated below:

- *Chapter 1 - 'Introduction'*, presents the background to the subject of this thesis, the problem formulation, and the purpose followed by research questions and delimitation.
- *Chapter 2 - 'Frame of reference'*, provides the relevant literature regarding tunnelling and the management of cost, time, risks, and sustainability.
- *Chapter 3 - 'E05 Contract Korsvägen'*, describes more specific information about the project and provides a background to the case study.
- *Chapter 4 - 'Methodology'*, describes the research approach and method used to perform the thesis. The chapter also compose the ethical considerations and reflections about validation.
- *Chapter 5 - 'Results Case Study'*, provides the results conducted from the case study.
- *Chapter 6 - 'Results Interview Study'*, provides the results conducted from the interview study.
- *Chapter 7 - 'Analysis'*, examine and analyse the findings from the case study, interview study, and with the support from the frame of reference.
- *Chapter 8 - 'Conclusion'*, answers the research questions and purpose of the thesis, followed by recommendations and suggestions for future research.

2 | Frame of Reference

This chapter presents the existing theory related to drill-and-blast tunnelling in complex infrastructure projects. First, the chapter present the tunnelling process and its involved phases and activities. Then, the theory of tunnel profile blasting is explained with a description of the rock excavation classes. Moreover, the concepts of cost, time, and risks in tunnelling are presented. Lastly, the environmental management in tunnelling projects is introduced with an elaboration of the Life Cycle Assessment and the Climate Impact Estimation.

2.1 Drill-and-Blast Tunnelling

Drill-and-blast is the most common way of tunnelling in Sweden and is both flexible and cost-effective (Maidl, Thewes, & Maidl, 2013). To construct a tunnel through drill-and-blast is in this thesis referred to as *'tunnelling'*. Tunnelling is performed in cycles, i.e the tunnelling process, which is divided in three main phases: *Pre-Grouting, Blasting Cycle and Reinforcement*. These three phases consists of different activities repetitively performed to move the tunnelling forward. Accordingly, the tunnel is driven forward by repeating these steps (Swedish Transport Administration, 2020b). The three phases in the tunnelling process are illustrated in Figure 2.1. The steps and activities involved in each phase are further described in this section.

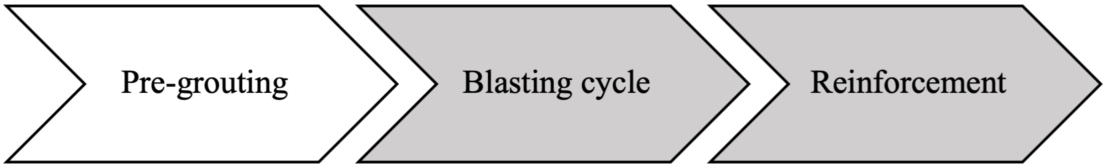


Figure 2.1: Illustration of the tunnelling process. The phases that are the focus of this study are marked in grey. Source: Created by the authors.

2.1.1 Rock Quality & the Q-value

Prior to the start of the tunnelling process, engineering geological mapping is performed by the client, which can be explained as a soil mechanic investigation to forecast the rock quality and its weakness zones in the given project area (Lindfors et al., 2019). Strand and Lexén (2016) explains that a weakness zone is a zone in the rock with lower rock quality, involving areas with crushed rock or high amount of fractures. Weakness zones have a big impact on the strength of the rock, the outcome of overbreak and the required reinforcement (Strand & Lexén, 2016). Hence, it is important that the client has identified these weakness zones before the projects starts to reduce the number of uncertainties. Nevertheless, it is important to highlight that both the determination of the rock quality and the weakness zones, does not provide full information about the actual rock quality. Instead they are used to complement the mapping of the reasonably conditions for the project before the tendering process. Therefore, engineering geological mappings are done repeatedly during the ongoing project, to determine the actual rock quality after each blasting. This information is then used to decide the required pre-grouting- and reinforcement classes (Strand & Lexén, 2016).

According to Lindfors et al. (2019) there exists several international systems to describe, map and categorise the geological conditions of the rock and thereby classify the quality of the rock mass in the engineering geological mapping. The Swedish Transport Administration recommend three of these systems to be used in their projects, these systems are: Rock Mass Rating (RMR), The Quality Index system (Q-system), and the Geological Strength Index (GSI) (Lindfors et al., 2019; Strand & Lexén, 2016). In the contract Korsvägen, the Q-system is mainly used in the engineering geological mapping. The Q-system provides a Q-value which indicates on the stability of the surrounding rock mass where an underground opening has been performed (NGI, 2015). The Q-system is arranged by different parameters measuring the rocks fractures, the solidity and the block size, which together forms the Q-value (Lindfors et al., 2019). The Q-system can be used with or without taking external factors into account. Taking the external parameters into account is referred to as Q, while not taking external parameters into account is referred to as Q_{bas} (Lindfors et al., 2019). Accordingly, the Q-system together with an investigation of the weakness zones provides a good connection between the engineering geological mapping and the follow-ups during the tunnelling process (Strand & Lexén, 2016).

2.1.2 Tunnelling process

Pre-grouting is not the main focus of this thesis, which is why only a generalised explanation is provided. Pre-grouting is the first phase in the tunnelling process and involves activities to reduce the intrusion of groundwater and seal the tunnel (Strømsvik & Gammelsæter, 2020). The activities in pre-grouting are determined by the local geological- and hydro-geological conditions of the rock (Andersson & Sellner, 2000). Detailed knowledge of the rock conditions is gained by the engineering geological mapping. As mentioned, based on this knowledge, the client sets demands on which pre-grouting class to use, in order to obtain a successful grouting result in the project. Accordingly, pre-grouting depends on several uncertain factors and is therefore unique to each tunnel section and the local rock conditions (Andersson & Sellner, 2000). Pre-grouting involves drilling several 20-25 meters long grout holes that are filled with cement mass or a similar liquid with a solidifying effect to seal the rock's fractures, and is illustrated in Figure 2.2 (Andersson & Sellner, 2000; Strømsvik & Gammelsæter, 2020).

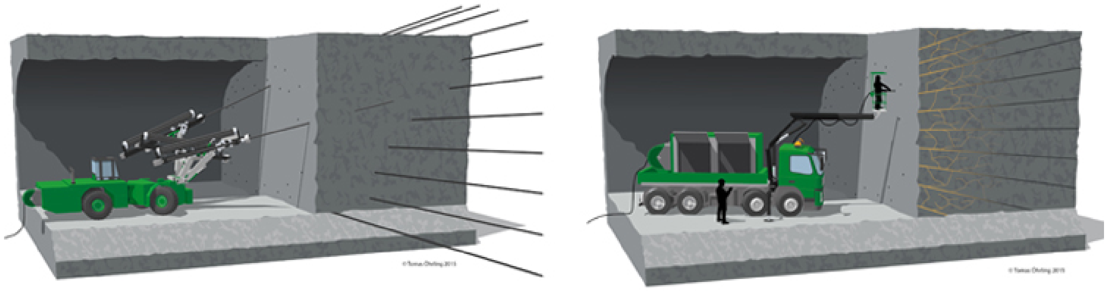


Figure 2.2: Illustration of the first phase in the tunnelling process, pre-grounting. Source: Copyright 2015 by Tomas Öhrling with permission.

The second phase in the tunnelling process is the *Blasting Cycle*, which is also performed in several repetitive steps (Sweden Underground, n.d.-a). Figure 2.3 illustrates the basic theory of the blasting cycle and the activities involved.

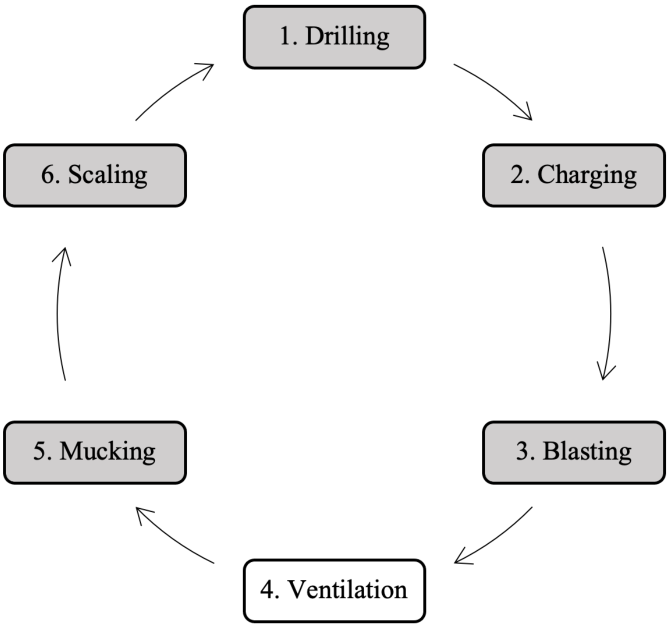


Figure 2.3: Illustration of the Blasting Cycle. The activity steps that in this study are in a special focus are marked in gray. Source: Created by the authors.

The first step in the Blasting Cycle is *Drilling*, which includes the activity of drilling several holes, with different requirements, into the rock in order to control the blasting. The drilled holes are drilled in a pre-calculated pattern and filled with explosive materials (Olofsson, 2017). It is crucial that the drilling holes are done with precision and in the right angle since they are vital for the final rock excavation quality. The drilling holes close to the tunnel profile are called contour-holes, and needs to be drilled in a look-out angle from the theoretical tunnel profile to make space for the drilling rig. Therefore, the drilling is regulated through a drilling plan which is crucial for the final quality of the blasting (Olofsson, 2017). This since a bad performed drilling has a direct effect on the final blasting result, the tunnel profile quality, and effects the fracturing and weakness zone of the surrounding rock area (Karlzén & Johansson, 2011). Olofsson (2017) explains that tunnel blasting is more fixed than above-ground blasting, as it is performed against only one free surface. Thus, the other available surfaces when blasting in tunnels, are created by the drilling holes, which the rock can deform towards (Olofsson, 2017). Accordingly, the drilled holes develop space for the rock mass to fall into after blasting. This created space becomes available since the blasting occurs in intervals (Swedish Transport Administration, 2020b). The drilling is illustrated in Figure 2.4.

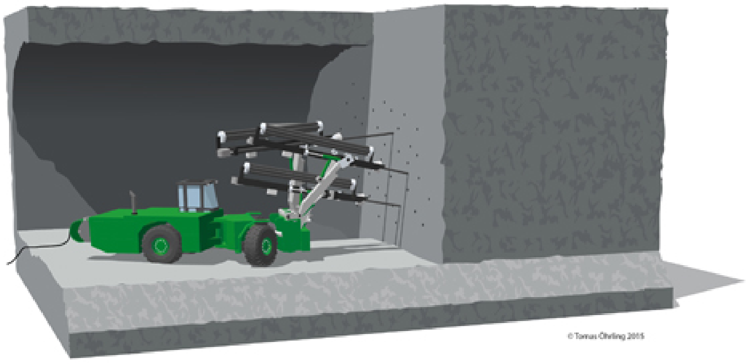


Figure 2.4: Illustration of the first step in the Blasting Cycle - *Drilling*. Source: Copyright 2015 by Tomas Öhrling with permission.

The second activity in the Blasting Cycle is *Charging* (Sweden Underground, n.d.-a). Charging implies the step of charging the drilling holes with explosives and has a big impact on the final result of the tunnel profile. The amount and choice of explosives varies depending on the desired strength of the blasting, the rock quality and the chosen rock excavation class (Olofsson, 2017). This since the power of the explosives affect the amount of overbreak, fracture and weakness zones of the surrounding rock area. The charging of the drilled holes are connected together in a charging-scheme in order for the detonation to occur in the right blast-interval. This is regulated through a charging plan to control, visualize, and plan the process of the rock blasting depending on the surroundings (Olofsson, 2017; Swedish Transport Administration, 2020b). There exist many different kinds of explosives and detonation systems. Performing tunnelling in urban areas, require a smoother and more gentle blasting in order to not harm the surroundings. The charging is illustrated in Figure 2.5.

Figure 2.5: Illustration of the second activity in the Blasting Cycle - *Charging*. Source: Copyright 2015 by Tomas Öhrling with permission.

The third step in the Blasting Cycle is the *Blasting* (Sweden Underground, n.d.-a). The purpose of blasting is to remove the volume of rock. The blasting is illustrated in Figure 2.6. The gases created by the blast must be ventilated out of the tunnel in order to continue the blasting cycle, which is the fourth step in the blasting cycle.

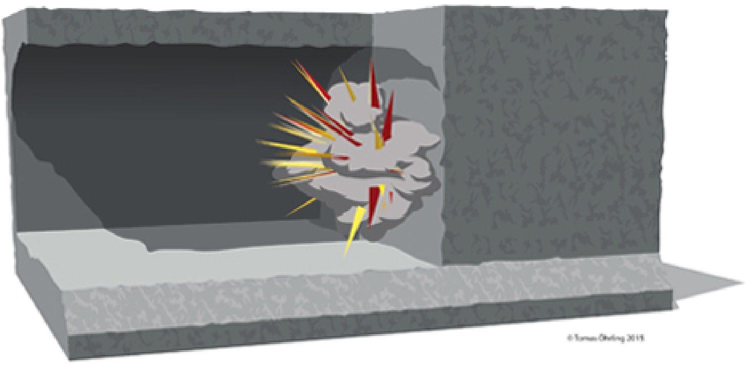


Figure 2.6: Illustration of the third activity in the Blasting Cycle - *Blasting*. Source: Copyright 2015 by Tomas Öhrling with permission.

The fifth step is *Mucking*, which involves the removal of the rock mass (Sweden Underground, n.d.-a). This is transported from the tunnel and is usually reused as material in other parts of the project, or in other projects within the region. Otherwise, the rock mass is transported to a crush-center (Swedish Transport Administration, 2020b). The mucking is illustrated in Figure 2.7.

Figure 2.7: Illustration of the fifth activity in the Blasting Cycle -*Mucking*, removal of rock mass. Source: Copyright 2015 by Tomas Öhrling with permission.

The sixth step is *Scaling* (Sweden Underground, n.d.-a). This involves removing all the loose rock, from both the tunnel's roof and walls, that may remain from the blasting. The purpose of this step is to secure the tunnel from falling rocks and dust. This is done first with a mechanized scaling machine and after that, if needed, the final scaling is done manually (Swedish Transport Administration, 2020b). The scaling is illustrated in Figure 2.8.

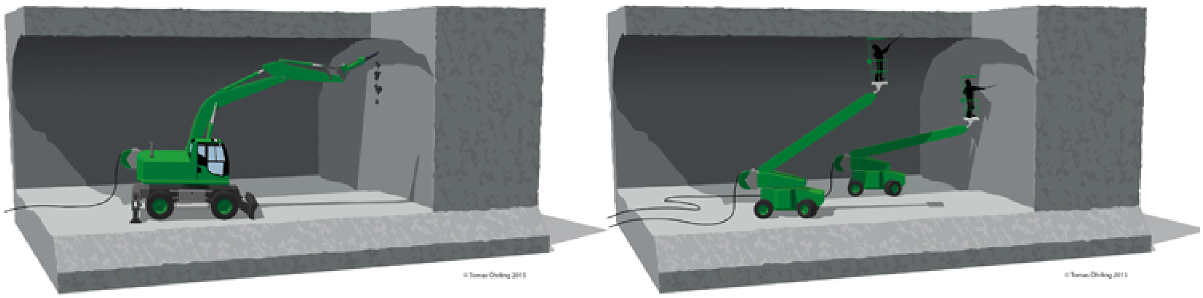


Figure 2.8: Illustration of the sixth step in the Blasting Cycle- *Scaling*, removal of loose rock. Source: Copyright 2015 by Tomas Öhrling with permission.

The third phase of the Tunnelling Process is the *Reinforcement* (Sweden Underground, n.d.-a). This method involves bolting and shot-concrete lining and is done to seal the rock, make the tunnel secure, and maintain a dry environment. Shot-concrete is often referred to as shotcrete which will be used henceforth. The extent of the reinforcement is divided in reinforcement classes that determine the number of bolts and the thickness of the shotcrete lining depending on both the extent of the blasting and the rock quality. The the shotcrete is applied with a machine and the bolting is performed manually by the workers (Swedish Transport Administration, 2020b). The reinforcement is illustrated in Figure 2.9.

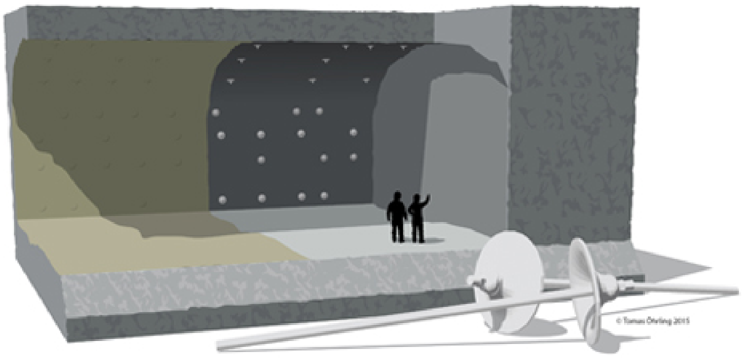


Figure 2.9: Illustration of the third phase in the tunnelling process, *Reinforcement*. Source: Copyright 2015 by Tomas Öhrling with permission.

The three phases in the tunnelling process and their involved activities are summarized in the Table 2.1.

Table 2.1: The phases and activities involved in the tunnelling process

Phases	**Activities**
Phase 1: Pre-grouting	
	1. Drilling
	2. Grouting
Phase 2: Blasting cycle	
	4. Drilling
	5. Charging
	6. Blasting
	7. Ventilation
	8. Mucking
	9. Scaling
Phase 3: Reinforcement	
	10. Shotcrete
	11. Bolting

2.2 Tunnel Profile Blasting

Overbreak is defined as the amount of rock excavated outside the theoretical tunnel profile after blasting (Foderà, Voza, Barovero, Tinti, & Boldini, 2020; Jang & Topal, 2013; Olofsson, 2017). An illustration of overbreak can be seen in Figure 2.10. Foderà et al. (2020) explains that overbreak can be divided in two main parts; geological overbreak, generated by geological conditions of the rock, and technical overbreak which is generated by tunnelling, e.g, drill-and-blast tunnelling. Jang and Topal (2013) enhance this by arguing that overbreak, to some extent, always occur when performing tunnelling, since the causing factors are both geological and from blasting techniques. Thus, the overbreak can be controlled by adapting the blasting technique based on the rocks conditions (Foderà et al., 2020; Jang & Topal, 2013).

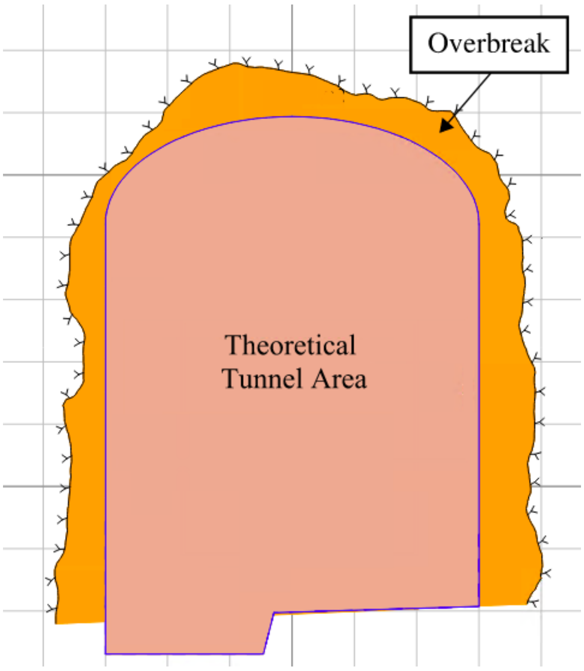


Figure 2.10: Illustration of overbreak in relation to the theoretical tunnel area. Source: Created by the authors.

It is important to keep track on the amount of overbreak since the increase in tunnel volume need to be calculated (Karlzén & Johansson, 2011). This because the contractor only gets paid for the theoretical amount of excavated rock meaning that amount of overbreak is a direct loss in profit for the contractor. It is also important to keep track on the amount of overbreak since additional blasted rock mass need to be reinforced by shotcrete and bolts to both keep the desirable theoretical tunnel profile and to support the surrounding rock (Olofsson, 2017).

Over the years there have been many studies with the aim to find the most preferable blasting techniques of the tunnel profile to control the amount of overbreak (Jang & Topal, 2013; Olofsson, 2017). *Smooth blasting* was developed in Sweden during the fifties and is today the most common blasting technique used to control the amount of overbreak (Olofsson, 2017). Smooth blasting involves blasting the tunnel profile together with the whole tunnel face in the blasting round (Bergutbildarna, 2012; Jang & Topal, 2013; Olofsson, 2017). However, even if this technique exist on today's market, it is still challenging to control overbreak. This since the damage created from the blasting is dependent on many discontinuous factors, i.e the rock's quality, conditions, damage zones, and zone of weakness in the rock (Bergutbildarna, 2012; Jang & Topal, 2013). Olofsson (2017) argues that the drilling and charging of the contour holes affects the amount of overbreak which in turn is affected by the quality of the surrounding rock. Therefore, the main goal in order to control the amount of overbreak is to minimize the tensions, zones of weakness, and the damage zones outside of the theoretical tunnel profile. This by balance the charging and optimize the drilling of both the contour holes and the holes close to them (Olofsson, 2017).

Consequently, when controlling and optimising the overbreak, with lower amount of explosives and more narrow drilling and blasting rounds, the opposite of overbreak may occur, called *intrusion*. Intrusion is defined as the amount of rock mass still remaining inside of the theoretical tunnel profile after the blasting round (Foderà et al., 2020; Olofsson, 2017). An illustration of intrusion can be seen in Figure 2.11. By keeping track on the amount of intrusion the proportion of the decrease in tunnel profile can be calculated (Karlzén & Johansson, 2011). Foderà et al. (2020) further argues that overbreak occurs more frequently than intrusion. This since intrusion needs to be either scaled or blasted additionally in order to keep the desirable tunnel profile outcome (Foderà et al., 2020).

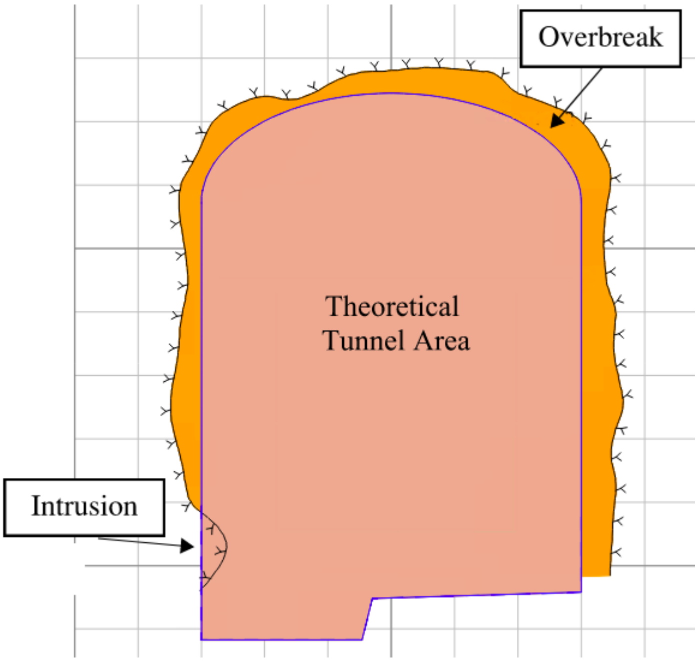


Figure 2.11: Illustration of intrusion in relation to the theoretical tunnel area and overbreak. Created by the authors.

The regulations of overbreak and intrusion, the amount of explosives and distance in drilling of the contour-holes are prescribed in the technical specifications applied in the contract, where the rock excavation is required to be performed according to the *'Allmän Material och Arbetsbeskrivning'*, called AMA, directly translated to General Material- and Work-Specifications (Swedish Building Centre, 2020). AMA is a reference system that lay the basis for the technical specifications in the industry, which describes execution, material requirements and work specification for civil engineering works. AMA is updated every third year and provides a standard framework generating a safer and more consistent quality in the construction process (Swedish Transport Administration, 2020a; Swedish Building Centre, 2020). Thus, the client sets the requirements for the contractor in the tendering process regarding which obligation of AMA they should follow.

2.2.1 Rock Excavation Classes

This subsection is mainly based on Swedish Building Centre (2020) which, as previously described, is a well-proven technical specification, specified for the Swedish market for procurement and execution of civil engineering, construction and installation works.

As mentioned, the requirements on the tunnel profile blasting are normally regulated by the client through the technical specifications of the project, which in turn, are governed by the requirements set in AMA (Bergutbildarna, 2012; Swedish Building Centre, 2020). In AMA, the general requirements of drilling and blasting the tunnel profile can be found in chapter CBC.6/1 *'Rock Excavation in Tunnelling'* and are regulated through the rock excavation class system. The rock excavation class system regulate the maximum allowed mean distance between the theoretical tunnel profile, ordered by the client, and the actual excavated profile, performed by the contractor. Meaning that AMA regulates the maximum allowed distance between c and d, making the precision and angle of drilling the contour holes crucial in order to meet the requirements. This regulation is illustrated in Figure 2.12 (Swedish Building Centre, 2020).

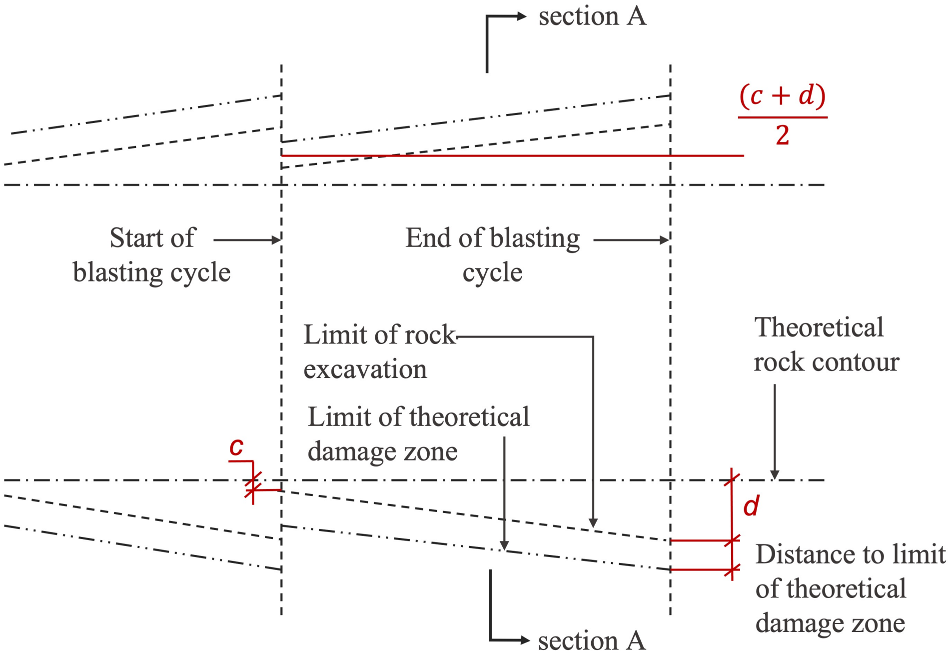


Figure 2.12: Illustration of the allowed mean distance between the excavated rock and the theoretical rock at start of blasting cycle (c) and allowed mean distance between the excavated rock and the theoretical rock at end of blasting cycle (d). Source: Created by the authors with inspiration from Swedish Building Centre (2020).

Furthermore, the rock excavation classes regulate the maximum allowed distance between the drilled holes, allowed amount of explosives and maximum allowed damage zones. Accordingly, the rock excavation classes will determine and regulate the drilling and charging of the contour holes since changing the distance between the drilling contour-holes and amount of explosives will affect the outcome of the blasting. This may increase or decrease the strength of the blasting and thus the size of the damage zones (Olofsson, 2017). The total rock excavation classification scheme can be seen in Table 2.2.

Table 2.2: Rock Excavation Classes according to AMA Anläggning -20 regulations.

Class	**Allowed deviation excavated rock**	**Allowed charging emulsion**	**Allowed distance drilling holes**	**Damage zone**
1	0.25 m	0.1-0.2 kg/m	0.3 m	0.2 m
2	0.3 m	0.2-0.3 kg/m	0.6 m	0.3 m
3	0.35 m	0.3-0.4 kg/m	0.6 m	0.5 m

The rock excavation class system is developed and based on many practical tests done with explosives and how the explosives affect the surrounding remaining rock and the damage zones. These testings have generated knowledge on how the different explosives react depending on the diameters on the drilling hole and the rock quality. Accordingly, the regulations of allowed damage zones provided in AMA are based on this extensive testing of explosives (Bergutbildarna, 2012). The damage zones are characterised by considerable changes in the remaining rock's conditions due to an adjacent blasting. These changes have an influence on the remaining rock's geological, hydro-geological, chemical and thermal conditions and will in turn have an impact on the later reinforcement requirements of the rock (Kim et al., 2013). The extent of the damage zone is dependent on several parameters, such as the in-situ stress conditions in the rock, and the ratio between the amount of explosives and the diameter of the drilling hole (Bergutbildarna, 2012; Kim et al., 2013).

2.2.2 Explosives

This subsection is mainly based on Olofsson (2017) and Bergutbildarna (2012) which is considered as standard handbooks in the construction industry for blasting works.

Over the years, explosives has been developed and modified in order to be suitable for different purposes of blasting as well as different work environments (Olofsson, 2017). In the middle of 1860, Alfred Nobel invented the dynamite explosive when he experimented with nitroglycerin. This was a big revolution for the usage of explosives, since the dynamite was seen as more secure to use and to transport. In 1860 the dynamite explosive was invented which was a more secure nitroglycerin explosive to handle and transport In the 1950, a even safer version of nitroglycerin was invented, called Gurit. Gurit is based on nitroglycerin powder enclosed in rigid plastic pipes with small pipe diameters. The plastic pipes provides a well balanced charge in the drilling holes and reduces the risk for overcharging resulting in e.g overbreak. Accordingly, Gurit is commonly used for more gentle blasting in drilled holes with smaller diameter. Nevertheless, the big step in the development of explosives came during the 1960s when nitroglycerin was replaced with ammonium nitrate and fuel oil, called ANFO. ANFO is a very powerful explosive and is sensitive to water which makes it difficult to handle below ground level. Therefore, a more gentle explosive was discovered in the middle of 1970, called emulsion. Emulsion is also ammonium nitrate based but are mixed with oil and wax. Thus, emulsion is not water sensitive. The emulsion is sensitized after the charging, making it easy to transport and handle on site. Today, one type of emulsion called bulk emulsion dominate the Swedish market of explosives (Bergutbildarna, 2012; Olofsson, 2017). The comparison between different explosives and their damage zones and diameter of drilling holes are shown in Figure 2.13.

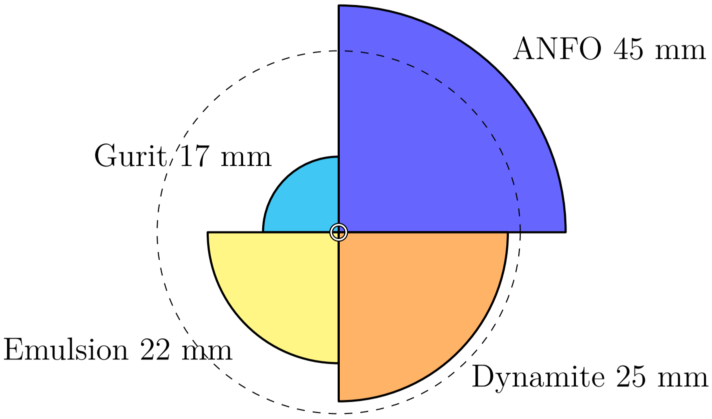


Figure 2.13: Shows the damage zone created by the different charging of explosives in the respective drilling hole diameters. Created with inspiration from Olofsson (2017).

For tunnelling, the most common explosives used are Bulk Emulsion and Gurit. Gurit is mainly used in the contour holes for Rock Excavation Class 1. This due to the strict regulations in AMA regarding the damage zone and amount of charging (Swedish Building Centre, 2020). For Rock Excavation Class 3, Bulk Emulsion is commonly used in the contour holes. This since Bulk Emulsion creates a damage zone smaller than ANFO, but larger than Gurit, and has the advantages that it enables a good water resistance and is relatively cheap. Bulk Emulsion is also within the regulations of AMA regarding the amount of charging and damage zone for Rock Excavation Class 3 (Bergutbildarna, 2012; Olofsson, 2017).

2.3 Cost, Time and Risk Management in Tunnelling

Cost-overruns are common in large complex infrastructure projects. According to Bruzelius, Flyvbjerg, and Rothengatter (1998), and Flyvbjerg (2014), nine out of ten projects experience cost-overruns. Flyvbjerg (2014) argues that cost-overruns of

50 to 100% of the initial budget are common and over 100% are not uncommon. Overall, cost and time evaluations in complex projects are crucial since cost and time are interrelated. In general, the main reason behind cost overruns, in complex projects, is the time frame of the project, where big delays are generated (Bruzelius et al., 1998). Comparatively, Paraskevopoulou and Boutsis (2020) argues that the tendering price and the size of the project can be used as a tool to determine the projects complexity.

According to Paraskevopoulou and Boutsis (2020) tunnelling projects differ from other infrastructure projects. For tunnelling projects the complexity is often caused by the rock excavation, which entails uncertain geology conditions, tunnel face collapses, water intrusion and machine breakdown. These disturbances can cause major problems for all the involved parties (Eskesen et al., 2004; Isaksson & Stille, 2005; Paraskevopoulou & Boutsis, 2020). Paraskevopoulou and Boutsis (2020) also indicate the importance of a thoroughly performed engineering geological mapping prior to the start of the tunnelling process, to determine the budget of tunnelling projects. This since the geological conditions are the biggest challenge in tunnelling and the major factor for cost overruns. Further, this implies that tunnelling projects rarely keep their initial budget requirements, but instead often leads to cost overruns, similar to the most complex infrastructures project (Eskesen et al., 2004; Isaksson & Stille, 2005; Paraskevopoulou & Boutsis, 2020). The tunnelling process is also sensitive to disturbances due to the procedure of activities. If one activity causes standstill, the rest of the cycle will also be affected. Accordingly, risks, uncertainties and unforeseen events can affect the tunnelling pace and consequently lead to cost and time overruns, and thereby affect the final cost of the project (Paraskevopoulou & Boutsis, 2020). Hence, it is of high importance to evaluate the risk factors included in the tunnelling process (Isaksson & Stille, 2005).

2.3.1 Cost Management

Both contractors and clients in large infrastructure projects wants to reduce the costs and estimate the right price beforehand to avoid cost and time overruns (Kim, 2017). One effective management accounting method used in the construction industry to calculate the cost is Activity Based Costing, ABC. ABC is an accounting method used to identify the costs involved in each particular activity. This since resources (e.g number of employees) are assigned to different activities (e.g, drilling) and every activity has cost objects (e.g, the number of drilling holes) (Kim, 2017). Accordingly, the ABC method can be an effective tool to evaluate the total cost for each activity in a construction project. This since ABC links the cost drivers (the causes) with changes in costs (the effects). This provides information that the cost is driven by other factors than just the volume of units produced. Thus, resources creates activities and both resources and activities can be integrated in the cost calculation with direct and indirect costs. In order to perform an ABC calculation, both the direct and indirect costs need to be considered (Kim, 2017).

The direct cost involves direct labour, material, and equipment along with other.

These costs are linked to the construction workers and machines efficiency (Lindén & Josephson, 2013). This since construction workers are hourly paid and the monthly rent of the machines can be recalculated to a cost for their efficiency rate of operating. The indirect costs involves rent, employees, site offices, and administration, among others (Kim, 2017). These costs are not directly linked to productivity but are costs that needs to be paid whether the tunnelling process is proceeding or standing still (Lindén & Josephson, 2013). Hence, to be able to evaluate the total costs of rock excavation correctly, the whole tunnelling process' activities, with direct and indirect costs, need to be considered (Olofsson, 2017).

As previously mentioned, the tunnelling process activities are always affected by the prior working steps. Meaning that if the costs for an activity are minimized, the risk increases for additional costs in the tunnelling process's following activities(Karlzén & Johansson, 2011; Olofsson, 2017). This may in the end cause a higher total cost. According to Olofsson (2017) the activities *blasting* and *reinforcement* are the activities that affects the costs of the blasting cycle the most. One aspect that is of extra interest, when calculating the costs in tunnelling, is the amount of overbreak (Olofsson, 2017). This since a high amount of overbreak generates even more blasted rock that needs to be handled and transported. This, gives rise to additional costs since overbreak is an instantly loss of profit for the contractor. Another reason why high amounts of overbreak increases the costs even further, is the need to replace this with more shotcrete than expected (Foderà et al., 2020; Karlzén & Johansson, 2011; Olofsson, 2017). To lower these costs and the time needed, the activities *drilling* and *blasting* are crucial. Conversely, this results in higher drilling and blasting costs to gain more control over the performance and results of subsequent activities. In addition to those costs are extra scaling, mucking, and reinforcement needed. These are also subjects for costs that increases together with high amount of overbreak (Olofsson, 2017). Thus, the amount of overbreak and the costs for the following steps are interrelated (Karlzén & Johansson, 2011; Olofsson, 2017).

2.3.2 Time Management

As previously mentioned, cost and time overruns are associated with large infrastructure projects and are common in tunnelling projects due to their complexity (Eskesen et al., 2004; Isaksson & Stille, 2005; Paraskevopoulou & Boutsis, 2020). Moreover, Isaksson and Stille (2005) explains that the tunnelling process is sensitive to time overruns since every meter in the tunnel need to be excavated in sequences to move forward. Therefore, to be able to estimate the time for the tunnelling process it is important to evaluate the time needed for each activity in the tunnelling process (Maidl et al., 2013).

Project Management Institute (2017) points out that the fundamentals in construction projects are to have the right resources at the right place and in the right time. Thus, it is important to consider the resources needed for each activity and how they are distributed in the tunnelling process to meet the desirable goals (Karlzén

& Johansson, 2011; Maidl et al., 2013; Project Management Institute, 2017). Further, Project Management Institute (2017) define project resource management as "*Project Resource Management includes the processes to identify, acquire, and manage the resources needed for the successful completion of the project.*" (p. 310). Accordingly, to be able to stay within the given time frame, budget, and to moderate risks is vital in order to have good logistics planning of resources and use the full capacity of the available resources (Sullivan, Barthorpe, & Robbins, 2010). Hence, failing in both managing the resources and to distribute them in an efficient way, is a risk and can affect the final budget, project planning, quality and may also affect customer satisfaction (Project Management Institute, 2017).

2.3.3 Risk Management

Project Management Institute (2017) highlights the importance of risk management in projects in order to analyse, identify and handle the possible risks. The author continues with "*All projects are risky since they are unique undertakings with varying degrees of complexity that aim to deliver benefits*" (p. 390). Thus, tunnelling projects involves many risks that affect and can cause major problems for all parties due to the tunnelling's complexity (Isaksson & Stille, 2005; Eskesen et al., 2004; SveBeFo, 1999). Accordingly, it is of high importance to evaluate the risk factors included in the tunnelling project (Isaksson & Stille, 2005).

The possible risks in construction projects are many but the major risks involved in tunnelling projects are contractual conflicts, interference of authorities, interference of third part, accidents, unforeseen geological conditions, failure in machinery, design errors, environmental accidents, economical loss, and delay (Eskesen et al., 2004). These risk factors and disturbances are mainly due to geological, economical, organizational and technological conditions (Isaksson & Stille, 2005; SveBeFo, 1999). Furthermore, SveBeFo (1999) explains that another risk may be a combination of the geological conditions and human factors caused by insufficient communication or lack of knowledge when making decisions. Accordingly, the connections between risks are in themselves complex and therefore it is highly important for the organisation to consider all possible risk in tunnelling projects (SveBeFo, 1999; Project Management Institute, 2017).

If you narrow it down even further, Karlzén and Johansson (2011) highlights the risks involved in the blasting cycle and explains that there are risks in controlling and keeping a high quality when performing rock excavation. This since the contractor aim to minimise the amount of overbreak because overbreak generates a high cost for the contractor as earlier mentioned (Karlzén & Johansson, 2011). The overbreak can be minimised by optimising the angle in drilling, i.e distance between d and c, as previously explained in Section 2.2.1 (Karlzén & Johansson, 2011; Olofsson, 2017). However, the consequence of optimising the angle in drilling are that the risk of intrusion increases (Karlzén & Johansson, 2011; Olofsson, 2017). When, the tunnel becomes narrower after each blasting round, this leads to difficulties in maintaining a good quality in the drilling of each hole with the drilling rig. This since the space becomes limited to be able to position the drilling rig in a good angle (Karlzén & Johansson, 2011). Moreover, Karlzén and Johansson (2011) and Olofsson (2017) both explains that by having control of the drilling, the risk reduces of large drilling deviations which can lead to high amount of overbreak.

Karlzén and Johansson (2011) highlight that even if the drilling is of high quality and the blasting is performed gentle, the geological conditions govern the outcome. Hence, this can be interpreted as the biggest risk in blasting is the uncertain geological conditions since the geology will not be fully determined until the start of the tunnelling process (Paraskevopoulou & Boutsis, 2020). This in turn can generate big consequences in time and cost (Karlzén & Johansson, 2011). Hence, SveBeFo (1999) mentions that extended prognoses of engineering geological mapping before the project starts, will limit the uncertainties in geological conditions and is one very important aspect in successful tunnelling projects. Thus, it is evident that risk management has a big influence on the handling of possible disturbances or hazards of the project and will by that affect the project's final quality and result (Eskesen et al., 2004).

2.3.4 Health & Safety

This section is mainly based on Swedish Work Environment Authority which is assigned the task, by the Swedish Government and Parliament, to ensure that laws about the work environment and working hours are obeyed by companies and organisations.

Health & safety aspects are crucial in the construction industry. According to Swedish Work Environment Authority (n.d.) construction workers are involved in twice as many accidents compared to other employees. In order to prevent this, there exists regulations and general guidelines that should be followed. Construction works performed in rock is a demanding work environment with manual operations, noise, dust and handling of explosives (Swedish Work Environment Authority, 2005, 2007, 2010, 2015). Therefore, there exists special regulations and guidelines for mining and rock works with several measures concerning the construction workers working environment when tunnelling.

Arbetsmiljöverket (2022) highlight that tunnelling works often involves many risks in health & safety for construction workers. They mention risk for falling rocks, air pollution, chemicals, and ergonomic risks since the work space is limited and with many moments that includes heavy manual handling or lifting, among others (Arbetsmiljöverket, 2022). Arbetsmiljöverket (2022) further explains that it is possible to prevent some of the risks from happening with good planning, ventilation, emergency exists, regular checks for danger, reinforcement and with a good work rotation. They also mention that there today exists ongoing developments of minimizing manual works in tunnelling, due to the manual work being heavy for the workers (Arbetsmiljöverket, 2022).

Swedish Work Environment Authority (2010) mentions in the regulations and guidelines for mining and rock works, that measures must be taken so that the methods and equipment for the construction worker enables good working positions and movements. The regulations also mentions that measures must be taken to lower the risk to encounter undetonated explosives when scaling, mucking, and drilling (Swedish Work Environment Authority, 2010). This is important since the explosives of today are safer to handle but also harder to initiate. Thus, there is a higher frequency of undetonated explosives which still may detonate if encountered. The Swedish Work Environment Authorities also mentions in their regulations and guidelines that explosives as Gurit that contains Nitroglycerin, should be handled carefully since skin contact with the explosives or inhalation of their vapors can cause headaches through the explosives' ability of lowering blood pressure (Dyno Nobel Sweden AB, 2006; Swedish Work Environment Authority, 2007).

2.4 Environmental Management

Sustainability is regarded in three perspectives: the economic, the environmental, and the social (Pero et al., 2017). The economic perspective is about to be able to maintain a high level of production to ensure consistent cash flow in the market (Dyllick & Hockerts, 2002; Harris, 2003; Pero et al., 2017). The environmental perspective refers to preserving the earth and to prevent overexploitation of natural resources, reduce the emissions and greenhouse gases from production and protect the ecosystem services (Dyllick & Hockerts, 2002; Harris, 2003; Pero et al., 2017). The social perspective concerns actions taken towards social exclusion and discrimination, adding value to the society and equally providing services for the community (Dyllick & Hockerts, 2002; Harris, 2003; Pero et al., 2017). Hence, it is evident that the construction industry affects all three perspectives of sustainability and has a major impact on the environment (Ofori, 2000; Pero et al., 2017).

Today there exists several drivers to address the construction industry´s impact on the environment and how it can be developed to become more sustainable (Pero et al., 2017). The Swedish transport administration have addressed and studied how the construction phase of infrastructure project can become more sustainable and concluded that the technology of today could be used to reduce approximately 50% of the generated emissions. However, to reach net zero emission, innovations are required which involves major investments in new technology (Fossilfritt Sverige, 2018). Further, Fossilfritt Sverige (2018) argues that the life cycle perspective of a project including their costs must be considered when implementing new materials or alternative construction methods without compromising the final quality.

2.4.1 Climate Impact Tunnelling

The climate impact generated by the tunnelling process is mainly due to the production and usage of materials such as steel and cement (Fossilfritt Sverige, 2018). Fossilfritt Sverige (2018) explains that shotcrete, involving cement and steel, contributes to half of a construction project's total emissions. Hence, the manufacture, transport, and usage of materials affect the climate impact. Therefore, the decision on which materials to use and how to transport them is important to reduce the projects climate impact (Fossilfritt Sverige, 2018). The usage of cement and steel occurs in the phases Pre-grouting and Reinforcement as well as in the activity Drilling, involved in the phase Blasting Cycle. Therefore, the usage of material will depend on the amount of drilled holes, overbreak and the needed amount of reinforcement, i.e number of bolts or shotcrete.

Transports, on the other hand account for a smaller but still significant part (Fossilfritt Sverige, 2018). However, the transports is fundamental in all the activities in the tunnelling process since all material is transported to and from the project. For example, the activity mucking affects the amount of emissions since the volume of blasted rock determine the number of transports needed. This is important since the climate impact generated by transports in infrastructure projects are often affected by the volume of rock masses and may for large volumes answer for a bigger part of the project's total climate impact (Fossilfritt Sverige, 2018).

Furthermore, performing tunnelling also generates emissions from blasting. This since the blasting of explosives releases nitrogen emissions from both the blasting, the waste of explosives when charging, and from undetonated explosives which leaks out to the ground water system (Holmberg & Nobel, 1997; Tilly, Ekvall, Ch, & Finn Ouchterlony, 2006). The impact of nitrogen emissions is a complex issue due to all the parameters that nitrogen affect on plant and animal life with e.g over-fertilization (Tilly et al., 2006). However, the nitrogen emission generated from the blasting and charging are quite small compared to the emission generated by cement, steel, and transports (Holmberg & Nobel, 1997; Tilly et al., 2006).

2.4.2 Life Cycle Assessment, LCA

Life Cycle Assessment, LCA, is a common method used to describe and enable an overview on the climate impact of a product or a system (Toller, 2020). LCA enable a way to make comparison between analysed objects and by that find better solutions for the environment (Baumann & Tillman, 2004). This may be especially useful when deciding between different alternatives which produce the same function. In a LCA the climate impact of a product, a component or a service throughout its life cycle, are compiled and evaluated (Fossilfritt Sverige, 2018; Toller, 2020). According to Klöpffer Klopffer1997LifeState, LCA intends to include the products or functions, total environmental impact during its life cycle, from "*cradle to grave*" (p.223). However, Baumann and Tillman (2004) points out that the LCA does not consider the impact on a site specific environment nor economic-, social- or risk aspects. A LCA is performed in four steps: defining goals and scope, inventory analysis, environmental impact assessment, and interpretation and presentation of the results of each step (Klöpffer, 1997). Within the regulations concerning the LCA process, a LCA can be conducted through several different methods (Toller, 2020). The standardized principles and framework for LCA is described in the European Standard ISO 14040-14043 and contributes to the United Nations Sustainable Development Goal 13, Climate Action (International Organization for Standardization, n.d.).

The first step, defining goals and scope, is where the crucial boundaries and the context of the LCA´s system are specified (Baumann & Tillman, 2004; Klöpffer, 1997). It is important that the boundaries and the context of the LCA's system are transparent and well defined (Baumann & Tillman, 2004). According to Toller (2020), if the LCA´s boundaries were set to the production of a product, excluding the following phases of operation and final disposal, it is called "*cradle to gate*" (p. 9). Thus, the "cradle to gate" is a common way to make the analysis in roads- and railway projects since demolition of infrastructure rarely occurs (Toller, 2020). The second step, inventory analysis, concerns the in- and outflows of the analysed system such as raw materials, extraction, products, energy, waste and emissions as well as the used products own in- and outflows (Baumann & Tillman, 2004; Klöpffer, 1997). This is often done by general data from international data bases together with more specific data about the resources used and the emissions that are created in the specific case (Toller, 2020). The second step results in a calculation of the amounts of resources performed (Baumann & Tillman, 2004).

The third step, environmental impact assessment, involves three main sub-steps: Classification, Characterisation and Weighting (Baumann & Tillman, 2004). Classification evaluates the potential environmental impacts and sorts them in categories depending on the environmental impact they contribute to (Toller, 2020). Characterisation implies that the different categories' total environmental impact is calculated (Klöpffer, 1997; Baumann & Tillman, 2004). This number then shows which environmental impacts that the product or service contribute to the most and to what extent. This is further done in weighting, where the environmental impacts are weighted against each other to rank them after importance (Baumann & Tillman, 2004)). The final step of the LCA system is the interpretation and presentation of the results, where different analysing methods are used to evaluate the results to draw conclusions (Toller, 2020).

2.4.3 Climate Impact Estimation Model

The Swedish Transport Administration has developed a *Climate Impact Estimation model* based on a method for LCA with the basic principles applied. The purpose is to establish the Swedish Transport Administration's working methodology when assessing the impact of infrastructure projects and the energy usage and climate impact through a life cycle perspective. The Climate Impact Estimation shall according to governing documents be establish for investment- and reinvestment measures for

50 million or more (Eklöf, 2018; Fossilfritt Sverige, 2018).

The idea behind the model is to enable consistent calculations from a life cycle perspective regarding the size of the climate impact and energy use caused by production, operation, and maintenance of the transport infrastructure (Toller, 2020). This by calculate the climate impact based on standard working procedures, building components, or project specific quantity data for material and energy resources as well as maintenance of the construction project (Toller, 2020). The used resources are measured and multiplied with the current emission factor for these resources which describes the emissions that are caused (Eklöf, 2018). The emission factors include raw material extraction, processing, and transports of material and energy resources, as well as from the combustion of the energy resources (Eklöf, 2018). The model shall be used for individual investments which then may be summarized for the total climate impact and energy use from several projects as the national plan for the transport infrastructure (Toller, 2020). The model is also used to, in a consistent and efficient approach, work with continuous improvement when planning, implementing measurements, following up, present results, and to set requirements in procurement.

The Climate Impact Estimation consists of resource templates which describes the components involved in different type solutions and the material- and energy resources that are engaged in which construction component (Toller, 2020). The different basis and needs of input when calculating climate impact are divided to four different calculation levels: A, B, C, and D. The level A is based only on the mentioned resource templates, while level B is based on more detailed information regarding the amount of construction parts and components used in the project. Level C is a more flexible level, meaning that one can use data with different detail levels. Lastly, level D provides climate impact calculation on maintenance, based on detail importation (Toller, 2020). Furthermore, the application of a more environmentally friendly construction part can be visualised by using this tool, since it shows the impact on the emission factor (Toller, 2020).

A climate impact estimation is performed several times during the project. The climate impact estimation is created in the action-choice study where it forms the basis for a sustainable choice of action for the development of infrastructure (Eklöf, 2018). The climate impact estimation is then renewed four times during a project, where three of them is during the planning process. The first renewal of the climate impact estimation is produced to form a basis for the climate requirements of infrastructure projects (Eklöf, 2018). The second renewal of the climate impact estimation is made to investigate how the different infrastructure alternative's climate performance may be affected by different options and solutions prior to the decision of which measure to continue with (Eklöf, 2018). The third renewal of the climate impact estimation is performed to form the basis for how the infrastructure measure should be implemented as well as total cost of it (Eklöf, 2018). The fourth and final renewal of the climate impact estimation is then performed together with the tender documents by the contractors in the procurement (Eklöf, 2018).

A Climate Declaration is the final Climate Impact Estimation which is established in the when the project is finalised (Eklöf, 2018). This is made with the actual amount of used material- and energy resources. This may contribute to knowledge transfer of the most effective solutions as well as to enable updates and calibrations for the Climate Impact Estimation model (Eklöf, 2018).

3 | E05 Contract Korsvägen

This chapter presents E05 contract Korsvägen which is the object of this case study. First, the chapter introduces the background of contract Korsvägen. After, more in-depth information, with regard to the scope of this thesis, will be presented. Moreover, this chapter is mainly based on information collected from the project, the project's governing documents, and the Swedish Transport Administrations website.

3.1 Contract Area Korsvägen

The project Västlänken is a part of the national plan of the Swedish Transport System, as well as the West Swedish Agreements, which involves investments in public transport, rail and road (Swedish Transport Administration, 2021c). Västlänken will also contribute to a regional growth and an expansion of the labour market (Sweden Underground, n.d.-b; Swedish Transport Administration, 2021c). This since shorter commuter times with train will enable more inhabitants of Gothenburg and Western Sweden to reach workplaces within and outside of Gothenburg (Sweden Underground, n.d.-b). The project is consisting of eight kilometres new double track railway, with six of the kilometers in a railway tunnel, beneath the city of Gothenburg (Swedish Transport Administration, 2021c). Contract Korsvägen is a 3,2 kilometres long section of Västlänken. The rock tunnel parts are consisting of a rail tunnel as well as a service and rescue tunnel in parallel. The section also includes an underground station, Korsvägen, with one platform and two tracks. The construction phase of contract Korsvägen has in the project been estimated to generate approximately 27 000 tonnes of CO_2 equivalents with all components included in the tender for the contract area Korsvägen. An overview of the contract area Korsvägen are shown in Figure 3.1.

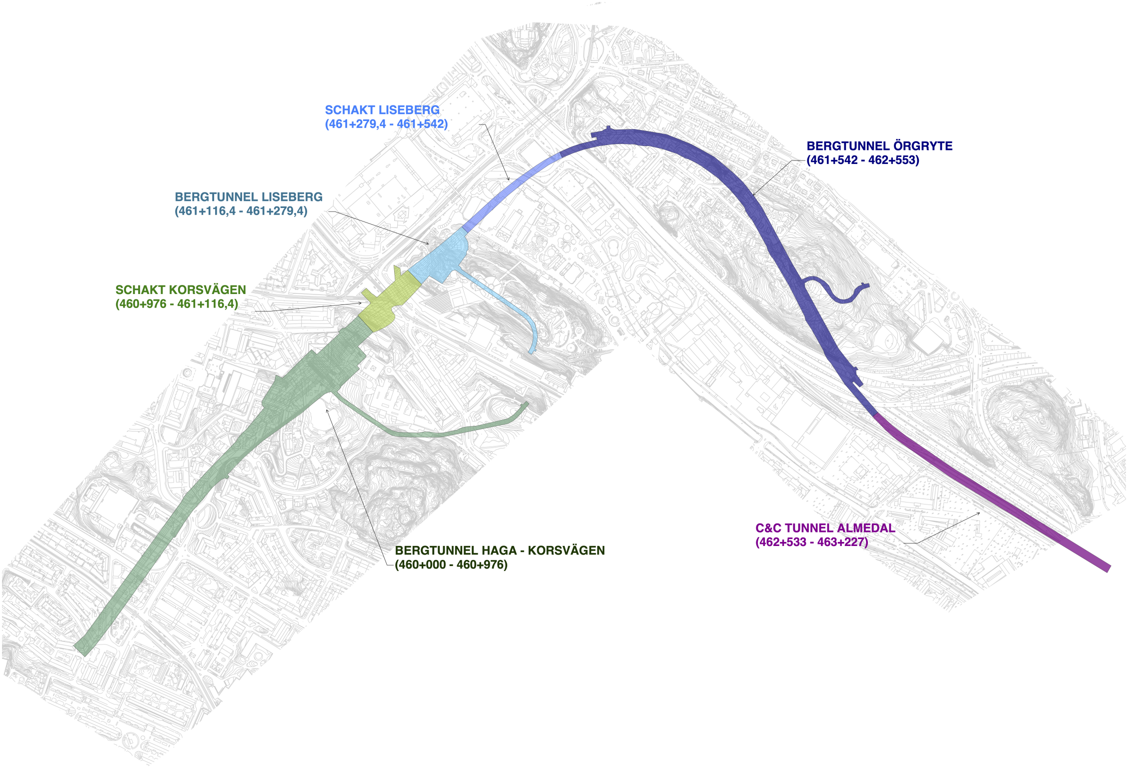


Figure 3.1: Map of the contract area showing each section of Korsvägen. Source: Conducted from the project.

As seen in Figure 3.1, the contract Korsvägen are divided into five tunnel areas; Rock Tunnel West, Station Korsvägen, Concrete Tunnel Liseberg, Rock tunnel Örgryte, and Rock Tunnel/Concrete Tunnel Almedal. The contract sum is 3,8 billion SEK, making this partial part of Västlänken one of the largest parts of Västlänken. The size of the contract sum reveals many challenges and thus the project is defined as complex. In literature there exists many definitions on how a construction project can be defined as complex. Vidal and Marle (2008) defines the complexity of construction projects as "*the property of a project which makes it difficult to understand, foresee and keep under control, its overall behavior, even when given reasonably complete information about the project system*" (p. 1101). Further, Briesemeister (2018) describes complex construction projects as "*A complex project seems to be a labyrinth with many hidden dangers and is difficult to manage.*" (p. 5). This complies well with the Contract Korsvägen since it is located in a dense urban area, with an already large existing public transport connections. Also, the project has challenges with the many actors that are involved and affected. Furthermore, the total rock mass excavation is estimated to be 650 000 cubic meters, the same volume as 11 filled Scandinavium (Got Event, n.d.). Nevertheless, the challenging rock quality underneath Gothenburg makes the area complex to design and construct. Hence, the contract Korsvägen, in the project Västlänken is defined as a complex project and thereby complies with both definitions.

3.1.1 Governing Documents

The order of the governing documents is very important for all parties in a construction project since clear and well established contracts reduce the risk for misunderstandings and conflicts between the involved parties (Rosseau & McLean Parks, 1993). The contract Korsvägen is governed by the standard agreement called AB 04, which stands for general conditions of contract for Design and Construction Contracts for Building, Civil Engineering and Installation Works. The standard agreement is applied together with the technical specifications and the *'Allmän Material och Arbetsbeskrivning'*, called AMA, directly translated to General Material and Work Specifications. The Swedish Building Centre provides AMA, which is specified for the Swedish construction market regarding well-proven procedures for procurement and execution of civil engineering, construction and installation works. AMA is updated every third year and provides a standard framework generating a safer and more consistent quality in the construction process (Swedish Transport Administration, 2020a; Swedish Building Centre, 2020). In AMA-Anläggning chapter CBC.6 exist the standard regulations on how the contractor should perform rock excavation in tunnelling. This involves all parts in the tunnelling process and regulations on how the excavation impact the surrounding areas (Swedish Building Centre, 2020). Furthermore, the technical specifications are structured according to the AMA´s structure and are important additions to the project´s drawings and other documents.

3.2 Production Challenges

The production challenges in Korsvägen are many, but the major concerns are: long project time with strict deadlines, complex business model, large organization, large number of stakeholders, many geological uncertainties, big impact on and from third part surroundings, and lastly the concerns with difficult technical constructions and unexpected changes. The challenges are mainly due to the contract Korsvägen being located in central Gothenburg. Hence, when performing tunnelling in central of Gothenburg, there exists strict time limit intervals that the project need to adapt to. For blasting, the works are limited to Monday to Friday between 07:00 to 22:00, while for drilling or similar, that generates noise and structural borne sound, the works are limited Monday to Friday between 07:00 to 19:00.

Moreover, the work site area is very limited and narrow due to the dense urban area which makes it problematic to store and handle rock material on site. Thus, all excavated rock masses need to be transported from the site. Therefore the rock masses are transported to a crush-center located 18 kilometers from the site. Furthermore, the transport of rock masses is not allowed during rush hours since they may affect the accessibility for the public transportation, roads, and bicycle traffic. Also, the client has decided that the weight of the transport vehicles must not exceed 30 tons, since the public roads may be damaged. Therefore, if the weight exceeds 30 tons, the contractor will be fined. A solution to many of these problems is that the contractor uses work shifts to make the production as efficient as possible. Due to the restricted time-limitations of blasting and drilling, the contractor transport the majority of all rock masses during the night shift to not affect the traffic in the city.

3.2.1 Engineering Geological Mapping

In Korsvägen, the Q-system together with an investigation of the weakness zones, are used. Hence, in the contract Korsvägen, the client has in beforehand performed an engineering geological mapping to give this information to the contractor. This includes core drilling, scan line surveys, and inspections of archives. Accordingly, the rock mass quality in the contract Korsvägen has, prior to the construction phase, been divided into five rock quality classifications, as seen in Table 3.1.

Table 3.1: Rock Mass Classification scheme in the contract Korsvägen with the characterization of the rock mass by the Q-system.

Rock classification	**Q-value**	**Rock Quality**
I	Q >10	Good
II	4< Q <10	Acceptable
III	1< Q <4	Bad
IV	0.1< Q <1	Very bad
V	Q < 0.1	Extremely bad

By the engineering geological mapping, the rock quality in the tunnel after each blasting and the dimension of the reinforcement for rock support, can be decided upon. The dimensions of reinforcement are regulated in reinforcement classes with requirements on the thickness of the shotcrete layer, distance between bolts, and the length of the bolts. This with the addition of standard industry requirements such as strength and bolt dimensions. Accordingly, the choice of reinforcement class during the contract period is directly linked to the rock quality, the amount of blasting and the desired end-result. Therefore, in the contract Korsvägen, the client decide which reinforcement class that shall be applied by geological mapping, as previously mentioned. The client also decides if the reinforcement class should be applied to a whole section of the project or only a specific part of the tunnel.

The reinforcement classes are, as a standard for contract Korsvägen, established by four different reinforcement classes and divided between three different tunnel span classes: class A with a tunnel width of 5-10 meters, class B with a width of 10-17 meters, and class C with a width of 17-21 meters. This to accommodate track tunnels, service tunnels, transition areas between track tunnels and stations, as well as unexpected overbreak. However, adapted reinforcement can also be applied to certain sections of the contract Korsvägen with a lower rock quality class. This due to complicated technical conditions, for example under sensitive properties or underground nearby construction. The connection between the tunnel span classes, reinforcement classes and rock quality classes can be seen in Table 3.2 and Table 3.3.

Table 3.2: Span Classes.

Span class	**Width of the tunnel, B**
A	5<B<10 m
B	10<B<17 m
C	17<B<21 m

Table 3.3: Reinforcement classes depending on rock class and the span classes.

Rock Quality Class	**5<B<10 m**	**10<B<17 m**	**17<B<21 m**
I	I-A	I-B	I-C
II	II-A	II-B	II-C
III	III-A	III-B	III-C
IV	IV-A	IV-B	IV-C

Furthermore, an example from the dimensions of reinforcement in the tunnel span class A can be seen in Table 3.4 below.

Table 3.4: Span Class A, Reinforcement classification scheme in the contract Korsvägen.

Reinforcement Class	**Q-value**	**Shotcrete thickness**	**Bolt distance**	**Bolt length**
I-A	>10	60 mm	2.5 m	3 m
II-A	4<Q<10	60 mm	2 m	3 m
III-A	1<Q<4	100 mm	1.7 m	3 m
IV-A	0.1<Q<1	150 mm	1.3 m	4 m

4 | Methodology

This chapter describes the methodology behind the thesis. First the design of the research is presented before the chosen methods are explained more in-depth. These methods are a frame of reference, a case study, a cost calculation, a climate impact estimation, and a qualitative interview study. Lastly, this chapter presents the assumptions made, reflections about validation, and ethical considerations.

4.1 Research Design

To answer the research questions formulated, the following analysis methodology was applied. The approach used have been an explorative abductive reasoning where the knowledge about the topic have been gradually grown by using both theory as well as empirical data and experience gained by observations and interviews through the performed case study. Therefore, the research setting for the thesis have been on site with the joint venture West Link Contractors in the project E05 Korsvägen. Accordingly, this research setting was chosen to get the best possibly insight in the project and tunnelling process. First, a Frame of Reference was developed to support our analysis. This was performed looking into the existing literature about both the technical aspects of rock excavation processes in drill-and-blast tunnelling and the theoretical parameters that may affect the following management aspects: cost, time and sustainability. Then a qualitative interview study was performed to extend the knowledge even further with the experience of key stakeholders.

Further, a case study was performed by studying four tunnels in the contract Korsvägen. Based on the case study, an cost calculation was produced using the ABC methodology in the program Microsoft Excel. A climate impact estimation was also performed based on the case study regarding the tunnelling process' environmental impact for the construction phase. This was done in a model provided by the Swedish Transport Administration and provided a result of the construction projects environmental footprint in CO_2 equivalents. When these were finalized, an analysis was performed based on the result provided by the frame of reference, the qualitative interview study, the case study, the cost calculations, and the climate impact estimations. The analysis was applied to answer the purpose and the research questions of this thesis. Figure 4.1 below shows a map of the performance of the chosen methodology.

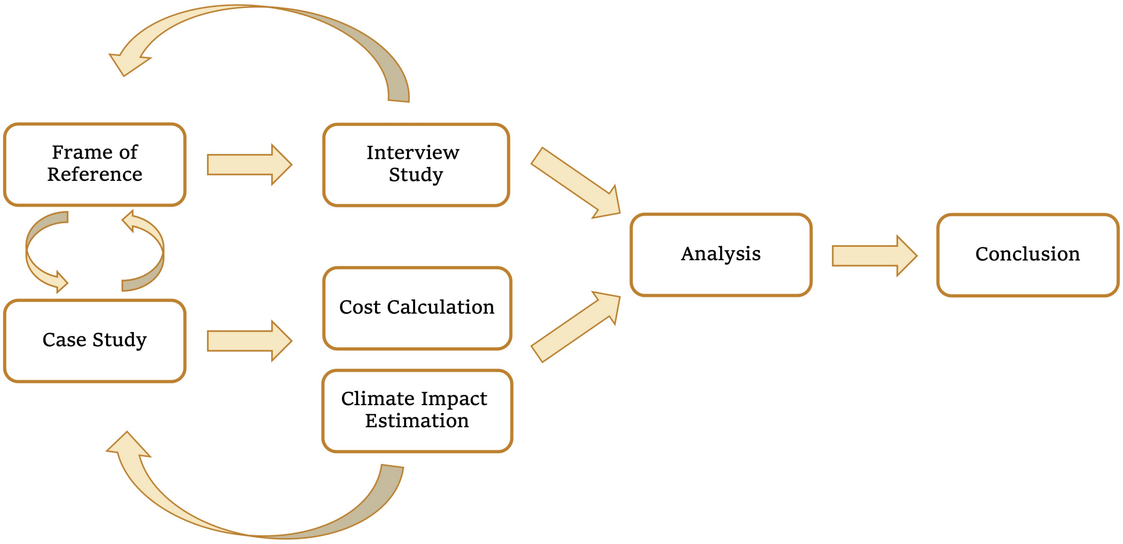


Figure 4.1: Map of methodology. Source: Created by the authors.

4.2 Frame of Reference

The Frame of Reference was developed to support the researchers in their analyses. This was formed by collecting, analysing and evaluating existing literature and information through books, educational material from blasting technical educations, databases such as Google Scholar, Chalmers Library and ScienceDirect, and the Swedish Transport Adminstration's website. The books utilized were Business Research Methods by Bell, Bryman, and Harley (2019), Forskningsmetodik by Säfsten and Gustavsson (2019), Modern Bergsprängningsteknik by Olofsson (2017), Managing Complex Construction Projects by Briesemeister (2018), PMBOK guide by Project Management Institute (2017), and Skriva för lära by Dysthe, Hertzberg, and Løkensgard Hoel (2011). The education material used is Bergutbildarna's (2012) guidebook Sprängarens Lilla Röda. Berutbildarna AB is a independent consultant and educational company in rock, drill- and blasting techniques with experience from more than 25 years and is approved as trainers and certifiers. The information gathered from the databases was mainly obtained from reports, scientific papers, and journals.

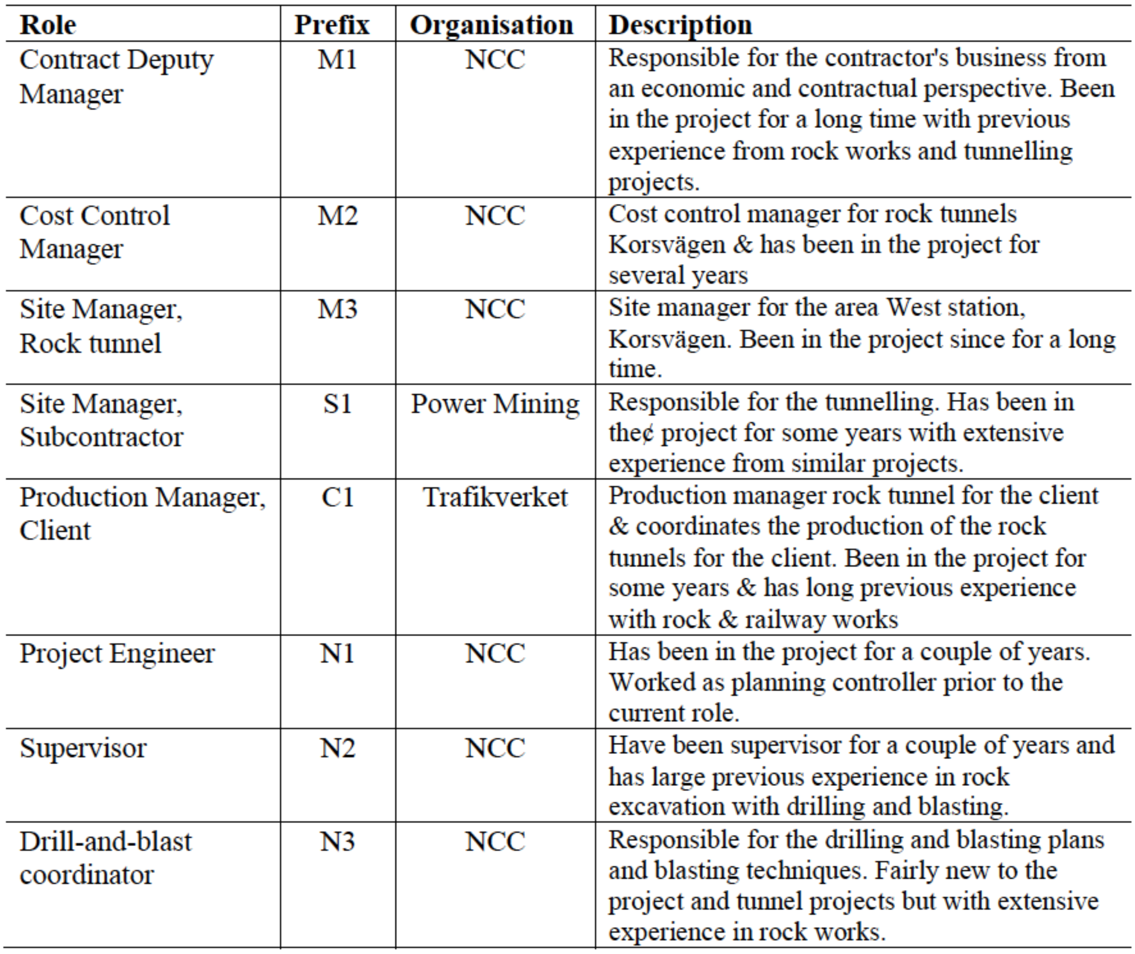
4.3 Qualitative Interview Study

The frame or reference was supported with a qualitative interview study. This qualitative research method was chosen due to the high density of knowledge in the project and the substantial and elaborated answers that qualitative interviews commonly provide (Bell et al., 2019). As Bell et al. (2019) observes, qualitative interviews puts a higher level of focus on the interviewees, their opinions and interpretations by the less structured interviews. This does not mean that the interviews were not prepared for, but rather that the interviews were not standardized (Bell et al., 2019).

The researchers were in that way present at the interview and could choose the order and how to formulate the questions depending on the context as well as to follow up what the interviewee have expressed with follow-up questions (Bell et al., 2019).

The interviews were semi-structured meaning that questions and topics were prepared before the interview but without a solid order (Bell et al., 2019). The interviews were structured to the extent that all the prepared questions and topics were dealt with similar formulations but with the freedom on how it was done (Bell et al., 2019). This due to the qualitative interviews' approach, flexibility, and the possibility it provided for elaborated answers and follow-up questions on the interviewees perspective on the subject. Thus, the chosen method was appropriate for the study's purposes which were: to gain knowledge about the experiences of using the different rock excavation classes, risks when performing rock excavation, the costs, and how the climate impact estimation model work as well as the reason behind different requirements set in the procurement. The qualitative interview study was performed by an thematic analysis through identifying, examining and lastly presenting the collected data in patterns (Säfsten & Gustavsson, 2019).

The interviewed were mainly white collar workers from contract Korsvägen with the roles shown and described in Figure 4.2. The eight interviewees were chosen due to their expertise of the project, diversity in roles, and their knowledge regarding drill-and-blast tunnelling. The participants in the interview study were from different contractors involved in the project as well a representative for the client. The initial plan was to have a more equal representation of the different actors involved in the project but due to the sensitivity of the project and this thesis topic, it was challenging to find the same range of representatives from the client's perspective. However, the participant from the client´s perspective represents great knowledge of rock works and contract Korsvägen. All interviews except one were performed in-person and was recorded with the consent of the interviews. The interview which was not conducted in-person was performed through Microsoft Teams. The interviews were then transcribed briefly to be able to capture the complete information provided during the interviews (Bell et al., 2019). The interview guide can be find in Appendix A.



Role	Prefix	Organisation	Description
Contract Deputy Manager	M1	NCC	Responsible for the contractor's business from an economic and contractual perspective. Been in the project for a long time with previous experience from rock works and tunnelling projects.
Cost Control Manager	M2	NCC	Cost control manager for rock tunnels Korsvägen & has been in the project for several years
Site Manager, Rock tunnel	M3	NCC	Site manager for the area West station, Korsvägen. Been in the project since for a long time.
Site Manager, Subcontractor	S1	Power Mining	Responsible for the tunnelling. Has been in the¢ project for some years with extensive experience from similar projects.
Production Manager, Client	C1	Trafikverket	Production manager rock tunnel for the client & coordinates the production of the rock tunnels for the client. Been in the project for some years & has long previous experience with rock & railway works
Project Engineer	N1	NCC	Has been in the project for a couple of years. Worked as planning controller prior to the current role.
Supervisor	N2	NCC	Have been supervisor for a couple of years and has large previous experience in rock excavation with drilling and blasting.
Drill-and-blast coordinator	N3	NCC	Responsible for the drilling and blasting plans and blasting techniques. Fairly new to the project and tunnel projects but with extensive experience in rock works.

Figure 4.2: Descriptions of the interviewees

4.4 Case Study

The case study are the essential part of the analysis conducted in this master thesis. This since the case study is used for a in-depth analysis to build on the existing literature and the qualitative data collected and challenge it (Bell et al., 2019; Tellis, 1997). Hence, case studies based on one specific case need to be investigated thoughtfully to be creditable (Tellis, 1997). The case study of this thesis is based on the contract Korsvägen. Due to the unique geological conditions of the area where contract Korsvägen is located, the approach of this study is ideographic (Bell et al., 2019). This leads to that the case study of this master thesis could be seen as a intrinsic case study (Bell et al., 2019). However, the case study of contract Korsvägen include multiple case studies within the case since the contract Korsvägen is very complex with several tunnels which been studied in this thesis (Bell et al., 2019). Accordingly, four tunnels within the project have been chosen to investigate more thoughtfully and with high precision.

The four investigated tunnels are:

- Service Tunnel 101 East (ST 101), section 1/210 to 1/520 (310 meters)
- Service Tunnel 207 (ST 207), section 0/20 to 0/330 (310 meters)
- Eastern Station Centre Pilot (ES C-Pilot), section 461/120 to 461/170 (50 meters)
- Western Station Centre Pilot (WS C-Pilot), section 460/901 to 460/920 and 460/940 to 460/960 (39 meters)

These four tunnels were chosen due to that they all had information such as Q-values and outcome of overbreak available and that the two tunnels ST 101 and ST 207 were excavated with Rock Excavation Class 1, and the other two, ES C-pilot and WS C-Pilot, with Rock Excavation Class 3. These four tunnels were also chosen in order to perform a descriptive case study by pattern-matching the four tunnels attributes (Tellis, 1997). This to in the end conduct the relationship between overbreak, rock quality by Q-values, and choice of rock excavation method.

To be able to investigate how the overbreak depends on the geological conditions formulated in the Q-value, a boxplot where performed based on the information collected of the four tunnels. The boxplot was performed to graphically analyse how the overbreak was distributed between the different Q-values on the four total tunnel sections. This to summarize the information gathered about the overbreak outcome depending on the Q-value of the rock where the four tunnels were located. To understand how the choice of rock excavation method affect the outcome in overbreak, a boxplot was used a second time. This time the boxplot was performed based on the Q-values sorted by the two rock excavation classes. The Q-values of ST 101 and ST 207 composed Rock Excavation Class 3, while the Q-values for ES C-Pilot's and WS C-Pilot's formed Rock Excavation Class 1. This boxplot resulted in a graphically relation of how the overbreak are distributed based on the two rock excavation classes and their sorted Q-values. Hence, the median, upper limit and lower limit in overbreak distribution based on rock excavation class were found.

Further, by pattern-matching similarities between the four tunnels, information gathered in the project, and supportive literature some important assumptions were made. This since some variables needed to be fixed in order to perform a comparable cost calculation and climate impact estimation depending on only the choice of each rock excavation class. The mentioned variables that needed to be fixed were:

- Tunnel Profile Size
- Tunnel Length
- Theoretical Tunnel Cubic
- Profile Perimeter
- Blasting Length
- Theoretical Surface Area
- Grouting Class
- Reinforcement Class
- Number of Grouting Reinforcement Cycles
- Number of Blasting Cycles

- Thickness Shotcrete
- Density Rock

4.4.1 Cost Calculation

The cost calculation was based on ABC methodology, were the information implemented were obtained from the case study. Thus, the cost calculation was divided in two parts, the direct costs and the indirect costs. The cost for each parts were connected to the activities involved in each rock excavation class. The direct costs were considered as the cost for material & subcontractors, while the indirect costs were formed by the cost for the time, i.e the cost for resources, involving all machines (including maintenance), labour, and other costs such as site offices, rent, and other administrative work. The reason behind identifying these was to establish the parameters the cost of each rock excavation class were depending upon. After, the cost for material & subcontractor and the cost for resources were summarised. This to determine the final and total cost for each rock excavation class. Lastly, an analyse was performed on how the cost for resources stands in relation to the cost for material & subcontractor.

4.4.2 Climate Impact Estimation

The Swedish Transport Administration's tool *Climate Impact Estimation* was used to identify the tunnelling process climate impact and driving factors for the four selected tunnels in the project. The calculation level performed was level B and in version 7.0 of the Climate Impact Estimation tool. This since level B and version 7.0 generated the most accurate template regarding the later stage in the construction phase and a more trustworthy climate declaration. After the level and version were determined, analyses were made based on the results from the case study and cost calculation. This since the case study together with the cost calculation generated how the activities differentiated between the Rock Excavation Class 3 and 1. This made it possible to choose the correct construction components sorted under *6.3 Tunnels* in the Climate Impact Estimation tool.

The construction components chosen to perform the climate impact estimation, were the fixed parameters: cement for grouting and rock anchorage bolt 3 meters. The varying parameters chosen were the excavated rock mass and shotcrete which depend on the amount of overbreak. The amount of excavated rock were chosen as case B, meaning that the excavated rock was not reused in the project but instead transported. While the other components were put in their respectively category. Lastly, the climate impact estimations of the median, the upper and lower limits were finalized by exporting the Climate Impact Estimation to excel files, which were analysed.

4.5 Assumptions

The assumptions made for the cost calculation and climate impact estimation have been decided on the basis of the case study. As for the theoretical dimensions of the tunnel a fixed tunnel profile was assumed of 100 square meters, a length of 80 meters, a perimeter of 25 meters and a theoretical surface area of 2 000 square meters. As for the conditions for the tunnelling process, pre-grouting was not being considered to affect the choice of rock excavation class and was therefore assumed as grouting class I. Further, the reinforcement class was assumed to be class II-A, since the tunnel span class was chosen to be class A and the rock quality is considered acceptable. Hence, the number of bolts in reinforcement class II-A was assumed to be 12,5 pieces per meter tunnel and the thickness of the shotcrete was assumed to be 6 centimeters, both independent of the rock excavation class. It was assumed that the reinforcement happen after four blasting cycles and not after each, the same goes for the grouting cycles. Thus, the blasting length was assumed to be 5 meters since this was a regular blasting length in the industry and the number of blasting cycles for 80 meters tunnel was set to then be 16. Moreover, the rock density was assumed to be 2,7 ton/m^3, which was a elaborated number found from experience in the project.

In terms of the differences between Rock Excavation Class 3 and 1, the number of boreholes per blasting round was assumed to be 30% more in class 1 than class 3. This number was based on the blasting journal. Moreover, the amount of charging depending on rock excavation class was based on the blasting journal and the ratio was assumed to be 7% Gurit and 93% Emulsion in Rock Excavation Class 1. Additionally, the time and material cost for grouting and reinforcement bolting were assumed to not differ between the two rock excavation classes. This since these were assumed to not have an impact on the choice of rock excavation class. Further, the time for on and off establishment was assumed to take 1 hour for each activity needed. These assumptions was also made in the climate impact estimation.

4.6 Reflections About Validation

According to Bell et al. (2019) have writers stated that studies of qualitative approach shall be assessed by the two criteria: trustworthiness and authenticity. To assess the thesis' trustworthiness, Bell et al. (2019) argues that four criteria are used for evaluate a study of qualitative nature.

These four criteria are:

- Credibility
- Transferability
- Dependability
- Confirmability

In terms of credibility Bell et al. (2019) and Shenton (2004) states that credability seeks information on how consistent the findings of the study are with the reality. This study has been validated through respondent validation where the participants of the research has corroborated the findings. Triangulation have also been applied to the thesis to cross-check the results. This have been performed by interviews and several sources of data to determine the findings with greater certainty.

Transferability examines the ability of the thesis findings to be generalised and applied to situations in other contexts according to Bell et al. (2019) and Shenton (2004). For the reader to be able to decide if the findings are applicable to other situations Bell et al. (2019) argues that detailed statements of the study's circumstances needs to be provided. Shenton (2004) mentions that numerous of authors highlights the importance for the researchers to clarify the boundaries and conditions for the reader. Therefore, the information of the number of organisations participating in the study and their location; the implemented method of data collection; the quantity and span of the data collection process; and the time frame when the data was accumulated shall be provided. However, the applicability of the findings of this thesis to other geographical areas than the studied, has not been considered. This since the scope of the thesis is limited to contract Korsvägen in sense of organisation and location. Despite this, the findings of this study may be practised by the company NCC, or Joint Venture WLC in other project. This as they possesses the information and knowledge this thesis is based upon.

Considering dependability Shenton (2004) argues that the details of the study shall be recorded in such quality that future researchers shall be able to repeat the work. Bell et al. (2019) further highlights the importance of auditors along the period of the thesis and in the end to address to what extent the proper research research procedures have been applied. The thesis dependability has been affected of the procedures that have been taken due to protect the anonymity and personal integrity of the interview objects in terms of interview transcripts. However, can the interview guide be found in Appendix. The study has also along the way been reviewed several times by the researchers supervisor and peers from the same masterclass by a peer review.

Confirmability concerns the objectivity of a qualitative study according to Shenton (2004). Bell et al. (2019) mentions that it should be explicit that no personal beliefs or opinions should affect the performance or findings from the study. The thesis have been performed with no prior knowledge of the topic or the work methods which confirms that no personal values or hypothesis affected the execution or findings of the study. The method of the study have also been reviewed by supervisor during the process.

4.7 Ethical Considerations

The ethical principles of the master thesis have been evaluated by the four ethical principles raised by Bell et al. (2019). These four are:

- Whether there is harm to the people
- Whether there is a lack of informed consent
- Whether there is an invasion of privacy
- Whether deception is involved

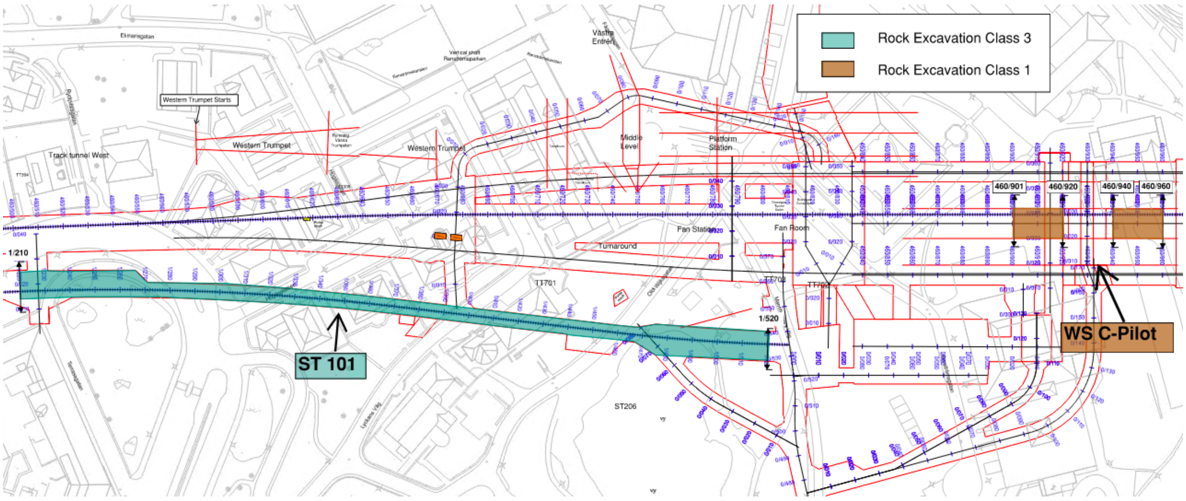
In order to ensure no harm to the participants in our study and to protect the interviewees are no field notes or transcripts attached to the master thesis as appendices. The interviewees were informed about the study and its purpose and were offered to see the interview guide in beforehand. In the beginning of the interview were the interviewees asked about their consent of their interview being recorded as well as if anonymity was preferred. The participants of the interview study were also able to review the results of the master thesis to be able to approve any reference, quotation or withdraw their participation to respect their privacy.

5 | Results Case Study

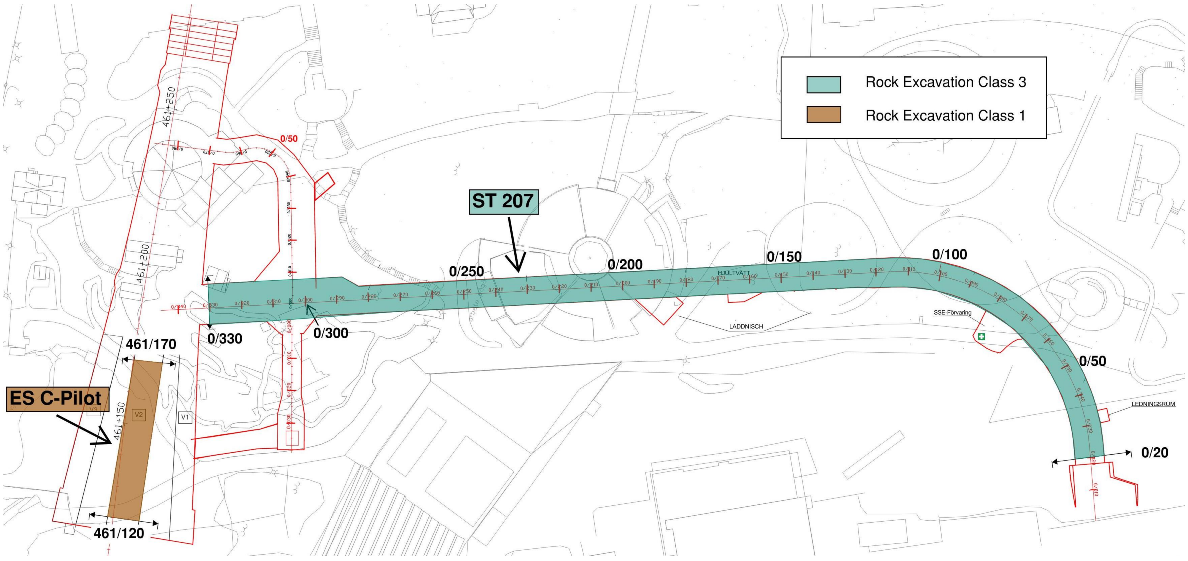
The following chapter will present the results from the case study. First, this chapter presents the four studied tunnels followed by the rock quality distribution in Q-values for each of the studied tunnels. Second, the overbreak distribution for each tunnel is presented and summarised in a total overbreak distribution for each rock excavation class. Lastly, this chapter presents the result of the cost calculation and climate impact estimation for the two studied rock excavation classes. Moreover, the results presented from this case study are based on experience and information gathered from the project.

5.1 The Four Studied Tunnels

The case study analysed the four studied tunnels *ST 101*, with a distance of 310 meters; *ST 207*, with a distance of 310 meters; *ES C-Pilot*, with a distance of 50 meters; and *WS C-Pilot*, with a distance of 39 meters. An overview of the four tunnels studied are illustrated in Figure 5.1.



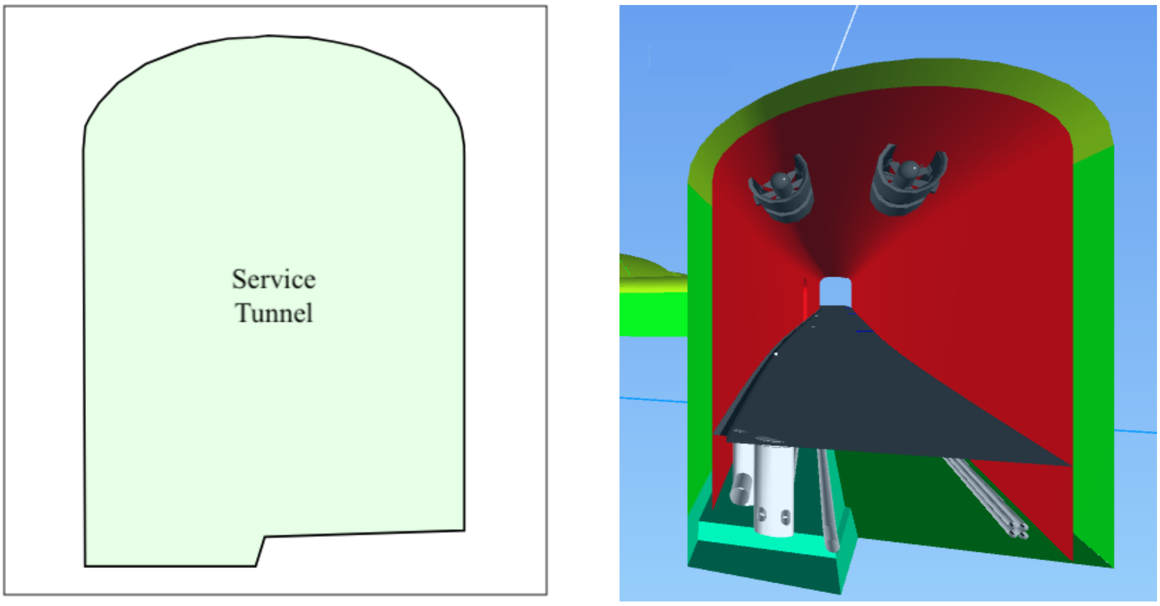
(a) Western part of the contract Korsvägen



(b) Eastern part of the contract Korsvägen

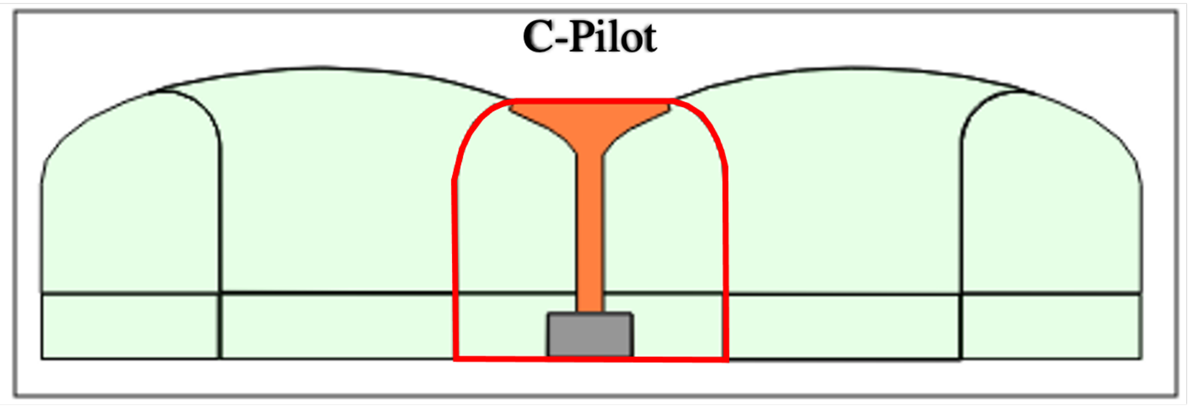
Figure 5.1: Overview of the tunnels studied in this case study

Both ST 101 and ST 207 were performed with Rock Excavation Class 3. The choice of Rock Excavation Class 3 in the Service Tunnels was made since the subsequent works are not crucial and therefore the requirements on the damage zones are not as strict. The profile of these tunnels is illustrated in Figure 5.2. However, both the ES C-pilot and WS C-pilot were performed with Rock Excavation Class 1. The choice of Rock Excavation Class 1 in the centre pilots was made in regard to the subsequent works since they are crucial for the future station of Korsvägen. This can be seen in Figure 5.3.

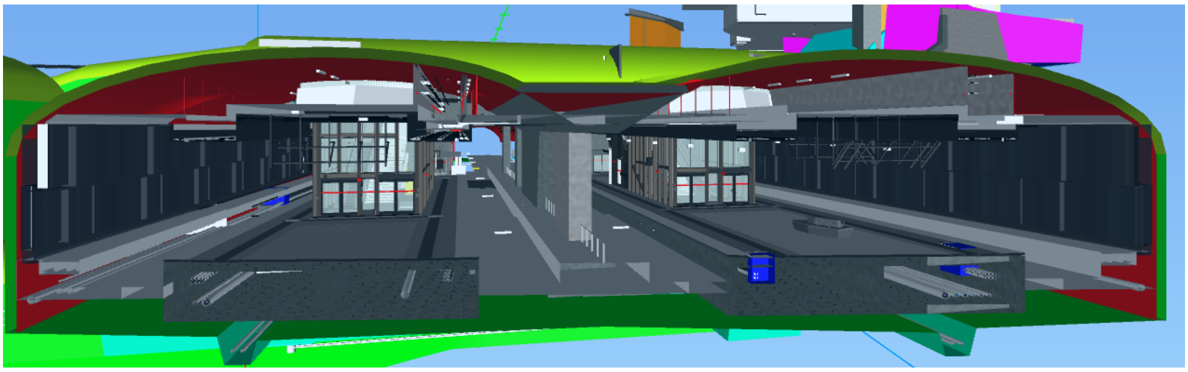


(a) Service Tunnel 2D (b) Service Tunnel 3D

Figure 5.2: Illustrations of service tunnels, in 2D and 3D



(a) Centre Pilots Station Area (marked in red) 2D

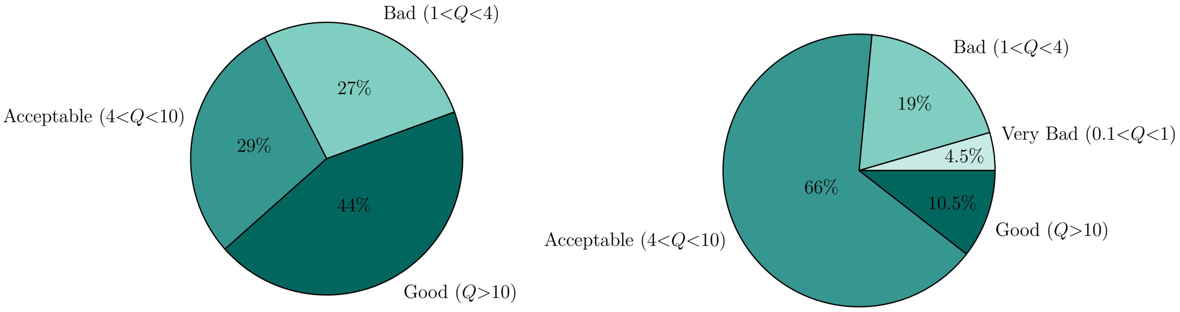


(b) Centre Pilots Station Area 3D

Figure 5.3: Illustration of centre pilots located in station areas, in 2D and 3D

5.2 Rock Quality Distribution

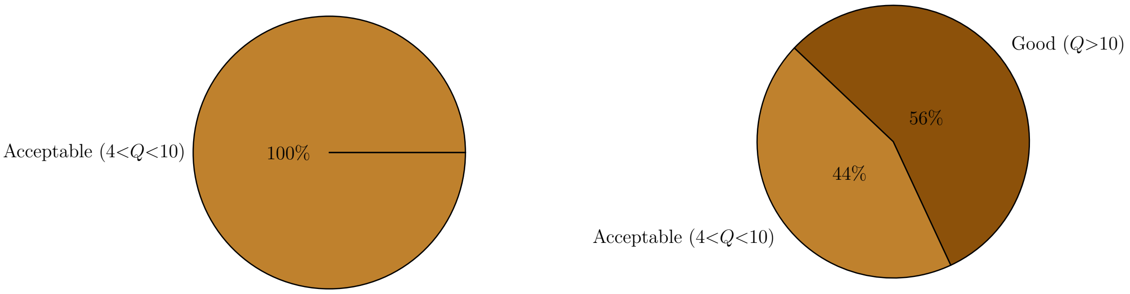
Moreover, with regard to the scope of this thesis, the four tunnels have also been studied in more detail regarding the tunnels' rock quality and overbreak outcome. From the Q-values found in the engineering geological mapping, both of the two tunnels', ST 101 and ST 207, rock quality were determined. In ST 101 the Q-values ranged from good rock quality to bad rock quality. While in ST 207 the Q-values were between the range of good rock quality to very bad rock quality. The two tunnels rock quality can be found in Figure 5.4. Furthermore, both of the two pilots, ES C-pilot and WS C-pilot, were also determined based on their Q-values. In ES C-pilot the rock quality was found to only be in the acceptable rock quality and for WS C-Pilot the Q-values were determined to be in the range of rock quality good and acceptable. The distribution of the two tunnels rock quality can be found in Figure 5.5.



(a) ST 101

(b) ST 207

Figure 5.4: Rock quality distribution for ST 101 and ST 207



(a) ES C-Pilot

(b) WS C-Pilot

Figure 5.5: Rock quality distribution for ES C-Pilot and WS C-Pilot.

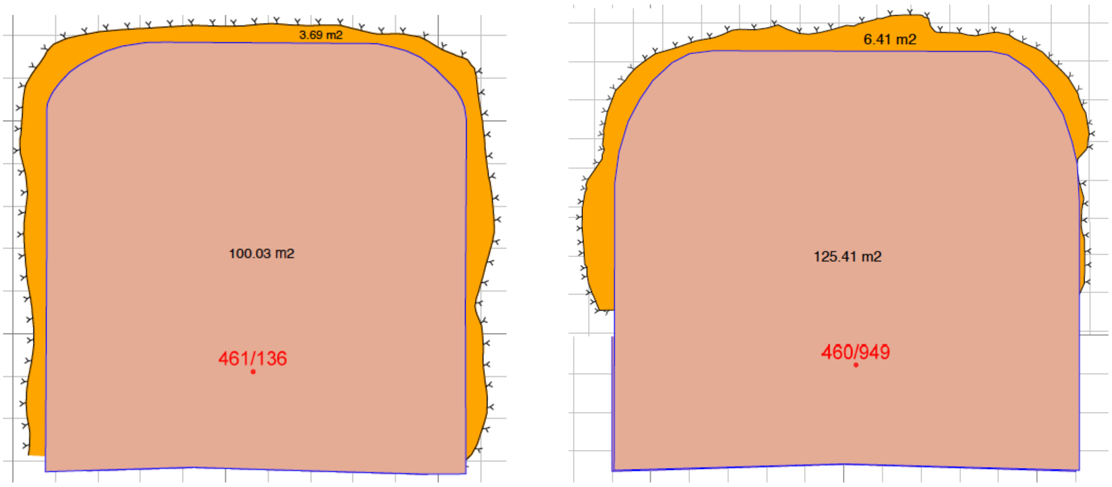
As seen in Figure 5.4 and Figure 5.5 *'Acceptable'* rock quality stands for the majority of the rock quality conducted when studying all four tunnels. However, the WS C-pilot are still in the progress of rock excavation and therefore only the Q-base values were available for information. As known, the Q-base value are usually higher than the Q-value due to Q-base not taking all parameters to account. Hence, it is important to mention that this tunnel distance can, in a later stage, be determined with lower rock quality than this case study has calculated for.

5.3 Overbreak Distribution

Due to the majority of acceptable rock quality in the tunnels studied it was decided to base the thesis' calculations of the tunnelling process in only acceptable rock quality. Therefore, the information gathered from the scannings of the performed tunnels, as illustrated in the Figure 5.6 and Figure 5.7, was only of the overbreak in relation to the Q-values of acceptable rock quality for the four tunnels.

(a) ST 101 section 1/277 **(b)** ST 207 section 0/123

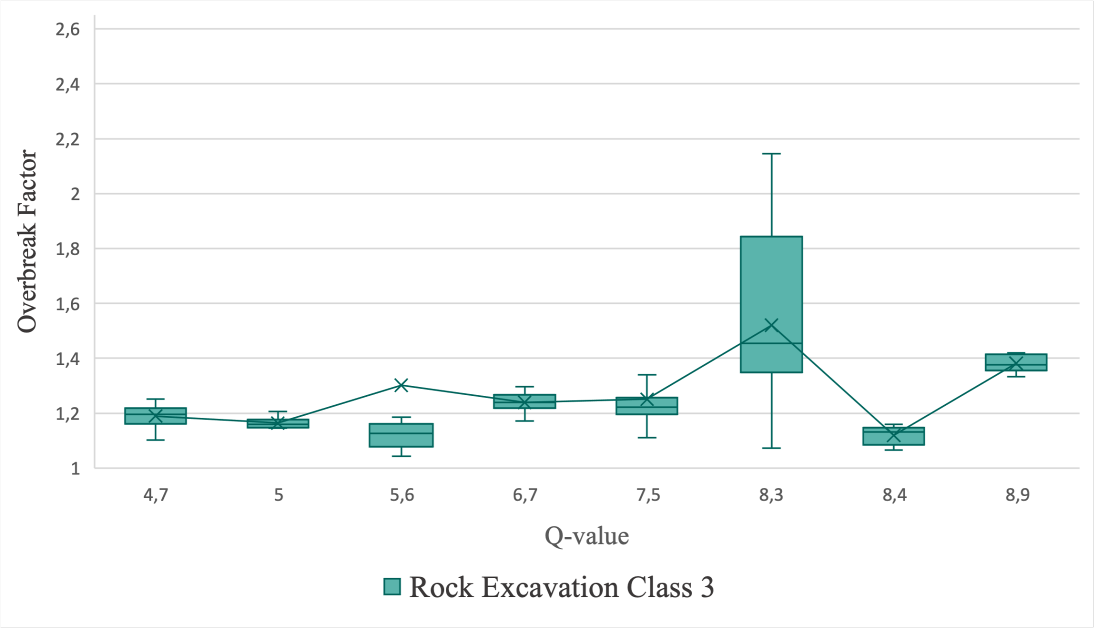
Figure 5.6: Illustrations of the overbreak distribution, in acceptable rock quality, for Rock Excavation Class 3 .



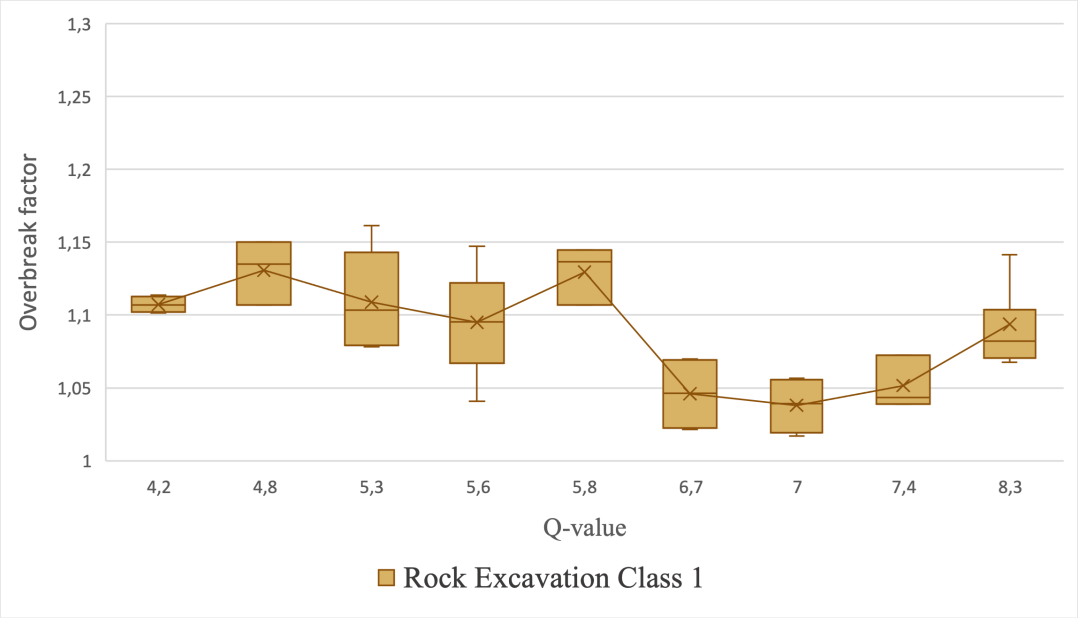
(a) ES C-Pilot section 461/136 **(b)** WS C-Pilot section 460/949

Figure 5.7: Illustrations of the overbreak distribution, in acceptable rock quality, for Rock Excavation Class 1 .

The overbreak studied in the scannings, together with the determined Q-values within acceptable rock quality from the engineering geological mappings, resulted in the two boxplots for each rock excavation class shown in Figure 5.8. Here one can see the result that the distribution in overbreak varies non-linear to the Q-value. The boxplot further shows the distribution of overbreak for the median (line), the upper limit and lower limit (the box) as well as the average value (marked as x in the figure).



(a) Overbreak distribution for Rock Excavation Class 3



(b) Overbreak distribution for Rock Excavation Class 1

Figure 5.8: Distribution of overbreak for the varied Q-values in range of the rock quality *Acceptable* in both rock excavation classes.

The two box-plots shown in Figure 5.8, resulted in two summarised box-plots for the total overbreak distribution, in each rock excavation class, for all the Q-values put together in the range of the acceptable rock quality. These are shown in the Figure 5.9.

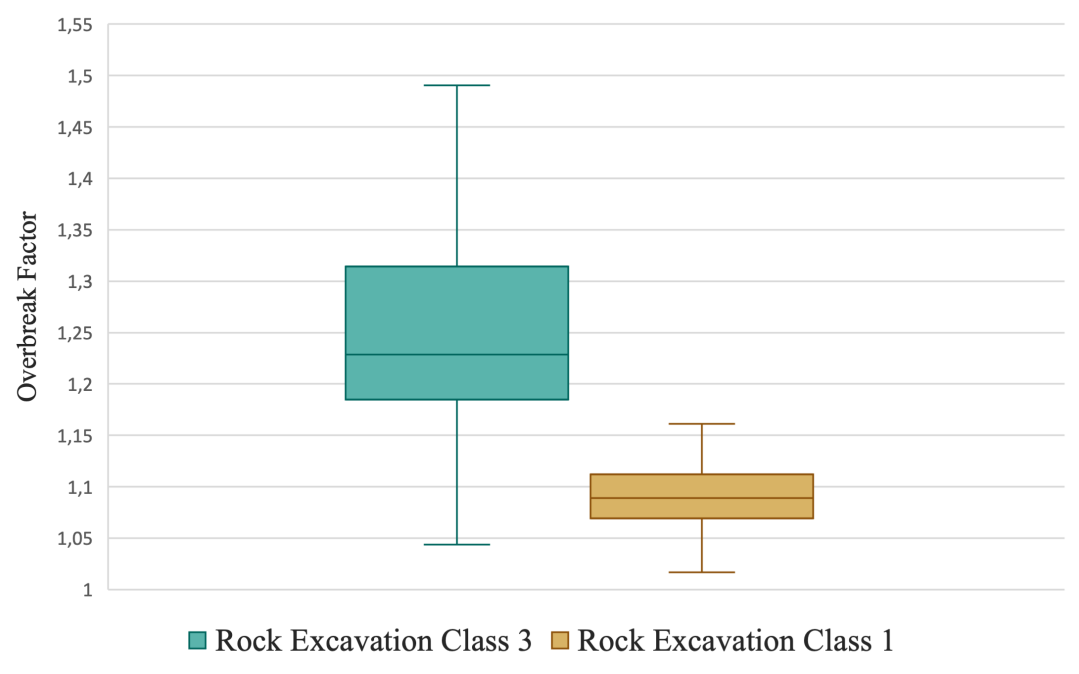


Figure 5.9: Illustrations of the overbreak distribution for the summarised Q-values in the range of rock quality *Acceptable* in both rock excavation classes.

The summarised box-plots resulted in total values in overbreak for each rock excavation class in the rock quality acceptable. For Rock Excavation Class 3 the total median overbreak was 23%, the upper limit was 31%, and the lower limit was 18%. As seen for the Rock Excavation Class 3, the total value in outcome of overbreak varied with 13% for Q-values in the range of rock quality acceptable. Moreover, for Rock Excavation Class 1 the total median value of overbreak was 9%, the upper limit was 11%, and the lower limit was 7%. Hence, the range in overbreak for Rock Excavation Class 1 varied with 4% for Q-values in the range of rock quality acceptable. The results from the total outcome in overbreak for each rock excavation class are shown in Table 5.1.

Table 5.1: Total outcome in overbreak for Q-values in the range of rock quality acceptable.

Overbreak	**Rock Excavation Class 3**	**Rock Excavation Class 1**
Median	23%	9%
Upper limit	31%	11%
Lower Limit	18%	7%

5.4 Input Variables

Previous results showed that the majority of the distance in all four tunnels had Q-values in the range of rock quality *"Acceptable"*. Hence, the rock quality was added as a fixed variable. The case study resulted in several similarities that generated fixed variables. Thus, the fixed variables can be found in Table 5.2 and was later applied to the cost calculation and climate impact estimation.

Table 5.2: Fixed variables for the tunnel

Parameter	**Dimension or Class**
Rock Quality	II
Reinforcement	II-A
Grouting class	I
Tunnel profile	100 [m^2]
Tunnel Length	80 [m]
Theoretical tunnel cubic	8000 [m^3]
Blasting length	5 [m]
Number of grouting & reinforcement cycles	4 [pcs]
Number of blasting cycles	16 [pcs]
Perimeter profile	25 [m]
Theoretical surface area	2000 [m^2]
Density rock	2,7 [ton/m^3]
Thickness shotcrete	0,06 [m]

5.5 Cost calculation

The cost calculation were based on a combination of the provided results in the case study, experience and information gathered from the project, as well as industry standard values. However, all the costs provided are fictitious but the differences between them are authentic. This since the differences lays the basis for the comparison between the two rock excavation classes. Moreover, the activities which were observed to differ between the two studied rock excavation classes were the activities drilling, charging, mucking, scaling, and reinforcement with shotcrete. Furthermore, the activities grouting and reinforcement bolts resulted to not differ between the two studied rock excavation classes.

5.5.1 Material & Subcontractor cost

The costs concerning materials & sub-contractors for the two studied rock excavation classes included the direct costs for the different activities. The result of the cost calculation for materials & subcontractors indicated that the activities that differs in cost between the two studied rock excavation classes were drilling, charging, mucking, and reinforcement shotcrete. Moreover, grouting, scaling and reinforcement bulting was found to not differ between the two rock excavation classes and were therefore disregarded. In median overbreak this result can be seen in Figure 5.10.

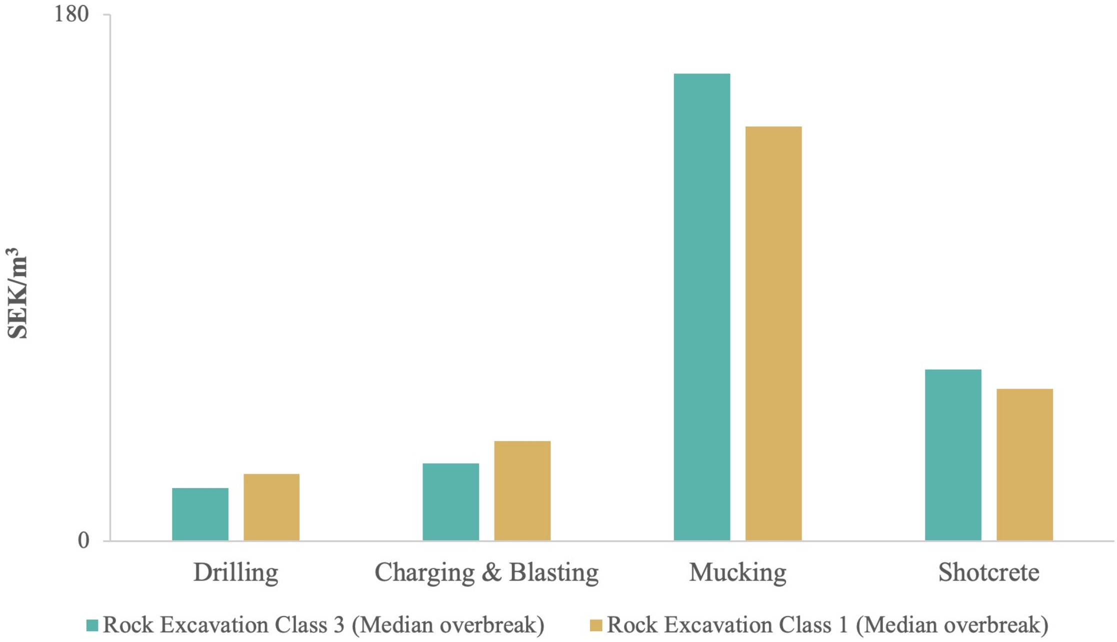


Figure 5.10: Differences in Material & Subcontractor costs [SEK/m^3] for the activities that differ depending on the median overbreak for Rock Excavation Class 1 and 3.

Concerning the drilling, the material cost varied between the two rock excavation classes regarding the drill steel, where Rock Excavation Class 1 required a higher cost due to the higher amount of drilling holes and thereby a longer drilling distance for each blasting cycle. The material cost for Rock Excavation Class 1 was also higher for charging and blasting due to that more drilling holes were needed to be charged but also since the explosives required in the contour holes for Rock Excavation Class 1 was more expensive. Further, the mucking, which in this study is the subcontractor cost, differ between the two studied rock excavation classes. This since Rock Excavation Class 3 required more mucking due to the larger amount of overbreak generated and thereby a higher amount of rock mass was needed to be loaded and transported compared to Rock Excavation Class 1. The higher amount of overbreak for Rock Excavation Class 3 also generated higher costs for material, as a result of the extra shotcrete that was needed to reestablish the desirable theoretical tunnel profile.

5.5.2 Time Analysis

The analysis of the time to perform tunnelling indicated that the activities which differed in time between the two studied rock excavation classes were: *Drilling*, *Charging & Blasting*, *Mucking*, *Scaling*, and *Shotcrete*. An illustration of this, for 80 meters tunnel, can be seen in Figure 5.11. Furthermore, the activities *Mucking* and *Shotcrete* were found to be the only two activities that variate depending on the amount of overbreak. Hence, the time for the other activities stayed the same regardless of the amount of overbreak outcome.

Figure 5.11: Time distribution in hours, for performing rock excavation with each rock excavation class, with median overbreak, for 80 meters tunnel in acceptable rock quality.

The total time it takes to execute 80 meters tunnel, in acceptable rock quality with median overbreak, was found to be 33.7 days in Rock Excavation Class 3 and 35 days in Rock Excavation Class 1. For the upper limit in overbreak, Rock Excavation Class 3 took 34.3 days to perform and for Class 1 35.1 days. For the lower limit, Rock Excavation Class 3 was calculated to take 33.3 days to perform and for class 1 34.9 days. The time for the two rock excavation classes difference is visualised in Figure 5.12.

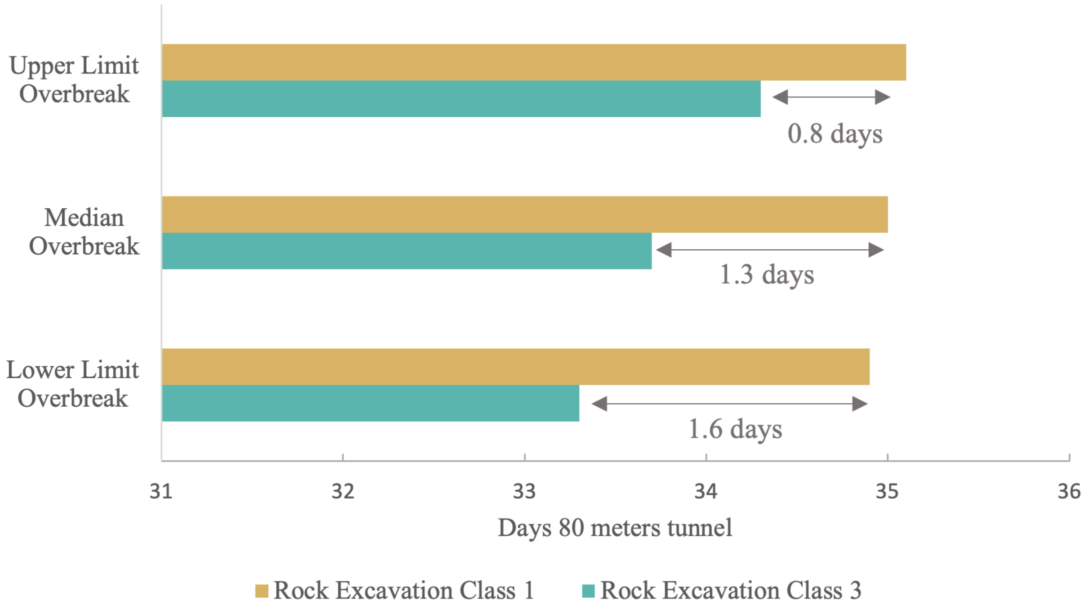


Figure 5.12: Total time distribution in hours, for performing rock excavation with each rock excavation class for 80 meters tunnel in acceptable rock quality.

5.5.3 Total Cost for each Rock Excavation Class

The outcome from the differences between the two rock excavation classes in material and time, resulted in that the cost for time, i.e cost for resources, stands for approximately 80% of the total costs in both rock excavation classes. Hence, the cost for materials and subcontractors stands for 20% of the total cost. How the cost for resources stands in relation to the direct cost, i.e materials and subcontractor, regarding the total costs of the tunnelling process for each rock excavation class are presented in Figure 5.13 below.

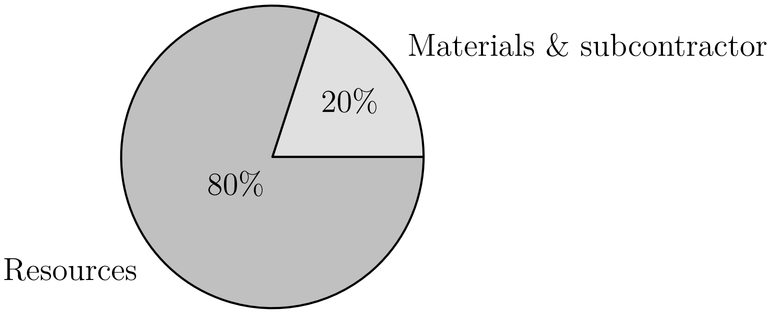


Figure 5.13: Relation in cost between resources and material & subcontractor costs

The cost calculations for material & subcontractor and resources resulted in a total cost for the two studied rock excavation classes depending on the outcome in overbreak. It was shown that a tunnel performed with rock excavation class 1 was more expensive than rock excavation class 3, in a tunnel of 80 meters performed in acceptable rock quality. Thus, with median overbreak rock excavation class 1 are 2.1% more expensive than rock excavation class 3. For upper limit rock excavation class 1 are 0.3% more expensive and for lower limit 3.1% more expensive. The result of the total costs for each rock excavation class based on the outcome of overbreak is illustrated in Figure 5.14.

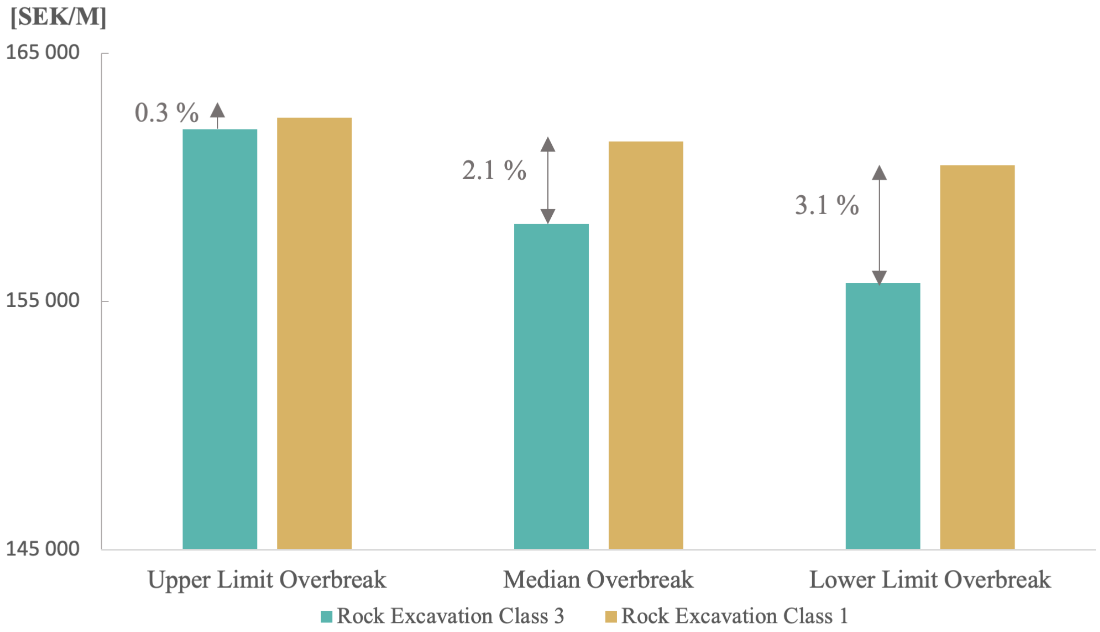


Figure 5.14: Total costs in SEK/meter tunnel, for the tunnelling process.

5.6 Climate Impact Estimation

The following section presents the results conducted from the Climate Impact Estimation in the contract Korsvägen, Project Västlänken. This is performed in the Climate Impact Tool developed by the Swedish Transport Administration.

The results produced by the Climate Impact Estimation showed that a tunnel construction of 80 meters with Rock Excavation Class 3 and median overbreak created emissions of 224.8 tons CO_2 equivalents as shown in Figure 5.15. Regarding Rock Excavation Class 1, a tunnel construction gave a climate impact of 201.8 tons of CO_2 equivalents. This showed a difference between the two studied rock excavation classes of 23 tons of CO_2 equivalents. Accordingly, Rock Excavation Class 1 had a lower climate impact concerning CO_2 equivalents.

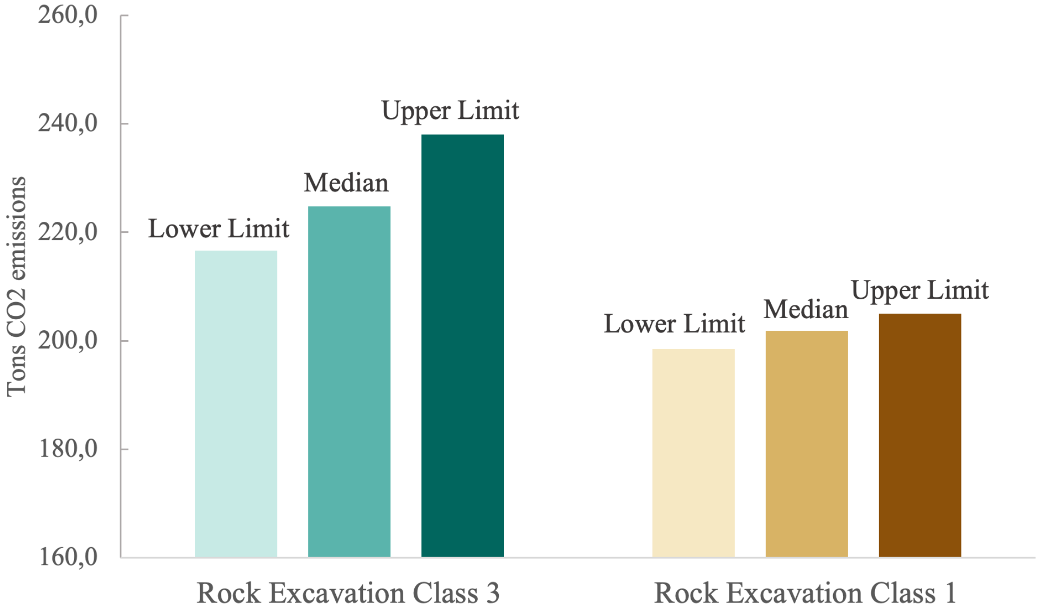


Figure 5.15: CO_2 Equivalents in tons for 80 meter tunnel depending on the different Rock Excavation Classes

The distribution of the CO_2 equivalents divided between diesel, cement, steel, explosives, crushed aggregate, and electrics for both rock excavation class was similar. The result showed that the distribution between the involved components did not vary between the two studied rock excavation classes even though a construction with Rock Excavation Class 3 had a total of a higher amount of CO_2 equivalents. The distribution are shown in Figure 5.16

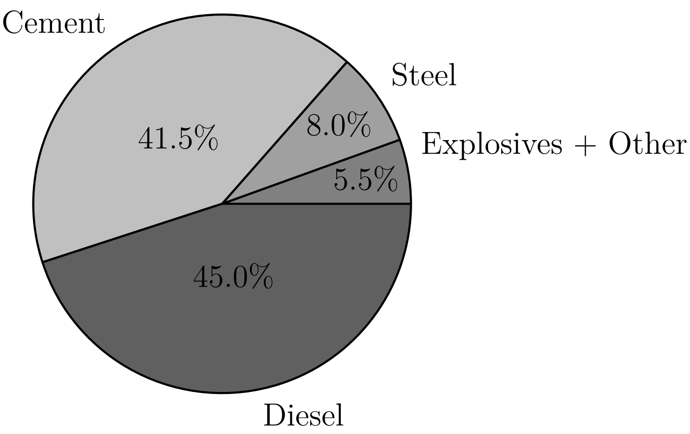


Figure 5.16: Distribution between the different components CO_2 amount for both Rock Excavation Class 1 and 3.

This resulted in that cement and diesel were the two biggest contributors to CO_2 equivalents for tunnelling. The differences in transports and shotcrete between the two rock excavation classes was summarized in Figure 5.17 and Figure 5.18. Important to mention is that this is only the result from the transport for rock masses and the amount of shotcrete used in the tunnelling process. Thus, this does not consider the transport involved in the production of the materials nor the cement used in the Pre-grouting.

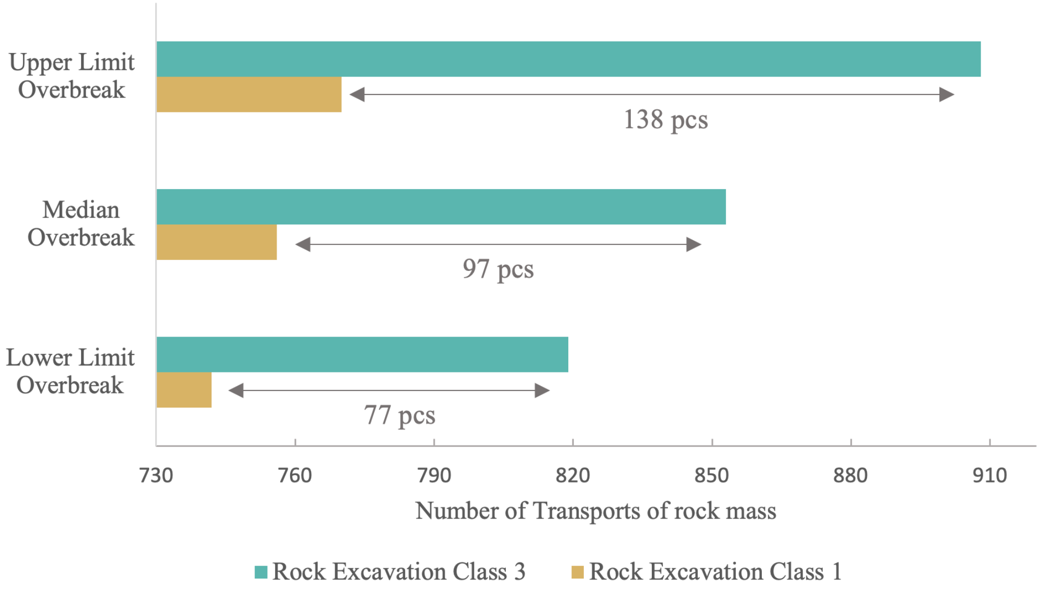


Figure 5.17: Number of transport for the rock mass generated from 80 meters tunnelling for each rock excavation class.

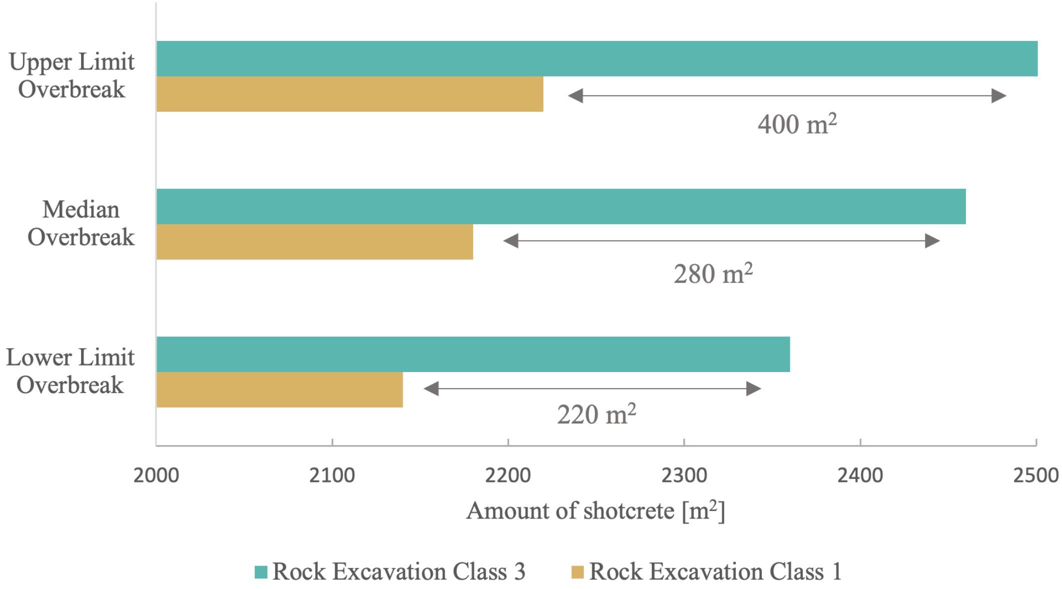


Figure 5.18: Amount of shotcrete for from 80 meters tunnel in each rock excavation class.

6 | Results Interview Study

The following section presents the results conducted from the interview study in the E05 contract Korsvägen. The section is divided by three identified subjects based on the analysis of the qualitative data. The following three themes were identified:

1. The choice of Rock excavation class and its impact on overbreak, cost & time
2. The risks concerning the tunnelling process
3. Sustainability in rock excavation, in the contract Korsvägen

6.1 The choice of Rock excavation class

The subject regarding how the choice of rock excavation class affect the tunnelling process consider its affect on overbreak, cost, and time. Further, the advantages and disadvantages for the two rock excavation classes are elaborated.

6.1.1 The impact on Overbreak

Many interviewees determined that the outcome of overbreak is associated with the geological conditions. In good geological conditions the rock excavation classes are highly related to the outcome of overbreak. All interviewees answered that Rock Excavation Class 3 generates a larger amount of overbreak since the larger amount is a result of the bigger damage zone created when blasting. Hence, many interviewees highlighted that the overbreak outcome is smaller in Rock Excavation Class 1. This since in good geological conditions Rock Excavation Class 1 will generate a smoother blasting and by that a more precise tunnel profile closer to the desired theoretical one, due to its drilling and charging. Therefore, Rock Excavation Class 1 is argued to be preferable to use when the amount of overbreak is critical due to, for example, later concrete works:

"*In good rock conditions there can be a big profit in using Rock Excavation Class 1 instead of class 3 when it comes to the amount of overbreak. This since Rock Excavation Class 1 generates more precise tunnel profiles.*" - N2

However, in bad geological conditions, several interviewees argued that it can be hard to see the relationship between overbreak and the choice of rock excavation class. This since in bad geological conditions the precision of the tunnel profile is hard to control. One interviewee highlighted that in bad geological conditions it does not matter how precise the drilling is, still it will be hard to see differences between the two rock excavation classes. Hence, all interviewees argued that in bad conditions the overbreak will happen anyway:

"*It is the rock quality that governs the outcome. In good rock quality the Rock Excavation Class 1 is more favorable since the drilling of the rock excavation class optimises the tunnel profile. However, if the rock quality is bad, the effect of using Rock Excavation Class 1 becomes less significant. Hence, the result will be a worse end product anyway, even if you try to drill and charge more carefully.*" - S1

On the contrary, it was highlighted that the client usually orders Rock Excavation Class 1 in bad geological conditions, since they argued that it still exists a noticeable difference in overbreak between the two rock excavation classes. Hence, it was evident that there exists different opinions regarding the relationship between rock excavation classes and overbreak distribution.

6.1.2 The impact on Cost

In good geological conditions, where Rock Excavation Class 3 tends to generate more overbreak, the interviewees explain that Rock Excavation Class 3 lead to higher costs for mucking and usage of shotcrete. Moreover, the interviewees mention that the material costs for Rock Excavation Class 1 are lower than for Class 3. This since, there are less time spent on mucking, scaling, and reinforcement due to the smaller amount of overbreak. Further, the interviewees highlight that Rock Excavation Class 1 generates more material costs in drilling steel compared to Class 3, due to the extra drilling required for Class 1. However, the cost for drilling steel is small compared to the cost for mucking, scaling and reinforcement. Some interviewees also mentioned that the explosives used in Rock Excavation Class 1 are more expensive than the explosive used for Class 3.

Furthermore, one interviewee highlighted that the overhead costs are the biggest costs for the project. This since, the site offices, wages and other indirect costs generates large expenses for the project. One interviewee also highlighted that some costs, regarding tunnelling and how they are connected to the choice of rock excavation class, may be hidden and not be detected until the excavation is already performed. A summary of the interviewee's answers regarding advantages and disadvantages for how the two rock excavation classes affect the cost and progress in the tunnelling process are shown in the Table 6.1 and Table 6.2 below.

Rock Excavation Class 1

Pros	Cons
Generates less overbreak –> Minimized damage zone	Higher risk for health & safety conditions for the workers
Less mucking –> less time spent on mucking	Risk for undetonated explosives
Less scaling –> less time spent on scaling & easier for the workers	Higher risk for intrusion & re-blasting
Less reinforcement –> less time & material spent on scaling	Increased cost of explosives
Result closer to desirable tunnel profile	Inefficient execution & tunnelling process
Higher end quality	More drilling –> higher noise & vibrations
Better conditions for the subsequent works	More time on charging

Table 6.1: Pros and Cons of Rock Excavation Class 1

Rock Excavation Class 3

Pros	Cons
Better health & safety conditions for the workers	Generates more overbreak –> higher damage zone
Lower risk for intrusion and re-blasting	more mucking –> more time & costs spend on mucking
Decreased cost of explosives	more scaling –> more time spent on scaling & easier for the workers
More efficient execution and tunnelling process –> Much more established and standardized in the industry –> Takes shorter time to execute –> more experience	more reinforcement & shotcrete –> more time & more material spent on scaling
Less drilling –> lower noise & vibrations	Risk for not fulfilling the desired tunnel profile
Less time on charging	Risk for lower end quality
	Worse conditions for the subsequent works

Table 6.2: Pros and cons of Rock Excavation Class 3

6.1.3 The impact on Time

The majority of the interviewees agreed on that drilling is the activity that affects the tunnelling progress the most. This since drilling generates vibrations, structural borne sounds, and noise which is a challenge in dense urban areas and causes time restrictions for when you are allowed to perform the drilling. Accordingly, several interviewees highlighted that Rock Excavation Class 1 causes longer drilling times and may, in combination with the time restrictions, have a negative impact on the overall tunnelling process. Thus, the Rock Excavation Class 1, is seen by the interviewees, as more ineffective which they believe has a negative impact on the final cost when tunnelling:

"*Drilling can have a big impact on the tunnelling progress. In the worst case, it could be that you lose almost an entire cycle and must start over.*" - N2

One of the interviewees pointed out that minimising the drilling angle, meaning lowering the distance between c and d as Rock Excavation Class 1, will generate a tunnel profile closer to the theoretical one. This in turn may lower the time needed for the activities mucking, scaling, and shotcrete, since minimising the drilling angle will generate less rock mass to transport, scale, and a smaller surface to cover with shotcrete. However, the interviewees continue with highlighting that minimising the drilling angle will increase the risk of intrusion, which affects the tunnelling process in terms of cost and time. This since the intrusion need to be handled and as a result cause disturbances in the tunnelling process. Furthermore, the interviewees problematise this relationship between advantages and disadvantages in optimising the drilling and mentions that the contractor needs to find a balance that is suitable for the conditions of the project:

"*So, it is everyone's interest to optimise the drilling. But there exists a sensitive limit, when you have troubles with intrusion instead, which is not financial either... so this is a balance act which is very difficult*" - S1

On the contrary, the interviewees mention that to minimise the risk of intrusion, the drilling angle is instead increased as in Rock Excavation Class 3. Nevertheless, they highlight that this may also have negative impact on cost and time since increasing the drilling angle will generate more overbreak. Since the contractor only is compensated for the theoretical amount of excavated rock and not for the generated overbreak this leads to increased costs. The amount of overbreak affect the tunnel progress in terms of extra time due to the increased transports of rock mass, extra need for scaling and shotcrete. However, they highlight that the mucking usually is performed during night-time which does not disturb the tunnelling progress as much as extra drilling would do. Instead, they highlight that mucking is expensive due to payment of transports.

6.2 The risks concerning the tunnelling process

The subject of risks when performing rock excavation in the contract Korsvägen consider a reflection on what risks that may occur when performing rock excavation and how the risks can depend on the choice of rock excavation. Further, the biggest risk area in the contract Korsvägen is also reflected upon and why that area is considered as crucial.

6.2.1 Risks with performing rock excavation

As seen in Table 6.1, all interviewees answered that *"worse geological conditions than expected"* are the biggest risk for unexpected costs when performing rock excavation. They further explained that the geological conditions are a risk that may result in large consequences and lead to other risks. One risk the interviewees mentioned worse geological conditions may lead to is the *"need for additional reinforcement measures"*, which was ranked as the second biggest risk for unexpected costs when performing rock excavation. Further they mention that measures as pre-reinforcement, limited blasting distances or pilots are measures that often reduces the progress capacity since the planning are established on the tunnels process forward in meters. Some interviewees mentioned that the more measures that needs to be taken, the more time consuming will the progress become, and the efficiency of the tunnelling process will thereby drop, which they state will affect the final cost.

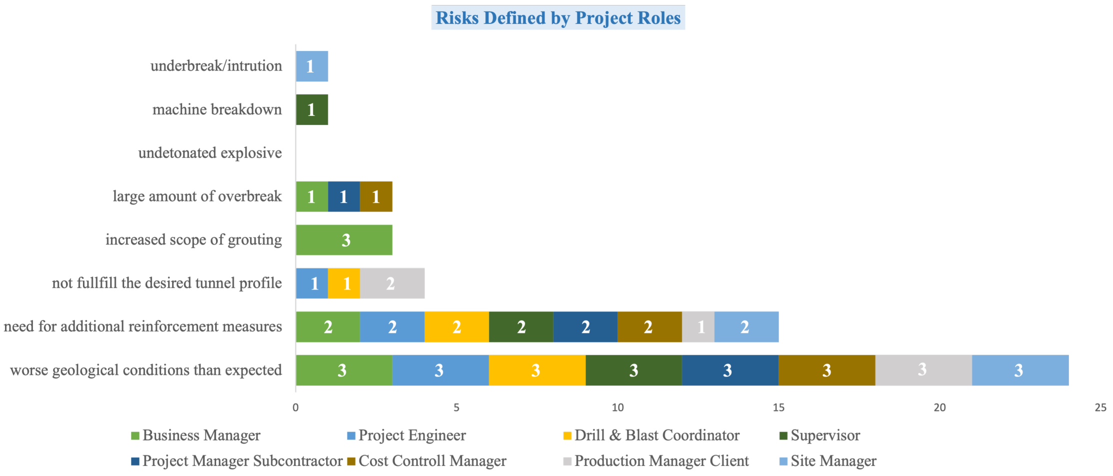


Figure 6.1: Summary of how the interviewees ranked the risk for unexpected costs when performing rock excavation.

The third biggest risk was distributed differently between the participants, as seen in Table 6.1. For example, three of the interviewees put *'large amount of overbreak'* as the third biggest risk, while two others instead put the risk of *'not meeting the customer´s requirement for the desirable tunnel profile'*. Moreover, one interviewee put *'machinery breakdown'* and another *'intrusion'* as the third biggest risk for unexpected costs in tunnelling. However, many interviewees mentioned that many of the risks are closely related to each other:

"*I get the feeling that the geological conditions have the greatest consequences. It steers all the other risks on this list, as the risk to not meet the desired tunnel profile and the need for extra reinforcement measures, but also the risk for overbreak. I believe they all come together.*" - N1

Another important risk that was highlighted by several interviewees was the risk in health & safety for the construction workers. One interviewee mentions that the reinforcement with bolts, that is independent of the choice of rock excavation class, is a risky activity to construction workers health since it requires heavy manually works. However, some interviewees mentions that Rock Excavation Class 1 affects health & safety of the construction workers since it requires manually work above the shoulder to charge the explosives. Further, several interviewees especially mentioned the risks of falling rocks after blasting when scaling and during reinforcement but also the effects of nitro-glycerine on the construction workers causing headaches:

"*If you use the explosive Gurit, used in Rock Excavation Class 1, there is an increased risk for the workers' health. This since the nitro-glycerine has the effect called "dynamite head" making the workers blood pressure go down.*" - N3

Furthermore, some interviewees mentioned even more risks when performing rock excavation. For example the risks for affecting third parties and the risk in delay due to time restrictions for drilling, blasting, and vibrations. Two interviewees also mentioned the risk

6.3 Sustainability in rock excavation, in the contract Korsvägen

The subject of sustainability in rock excavation in the contract Korsvägen consider how the tunnelling process affect sustainability and how the choice of rock excavation class can affect the climate impact. The interviewees got the opportunity to reflect on the possibilities and the challenges that exist regarding sustainability and rock excavation. Important to notice is that none of the interviewees have responsibilities regarding or are experts on NCC´s and the Swedish Transport Administration´s environmental works. Accordingly, the results must be viewed and determined as speculations.

6.3.1 How the tunnelling process affects sustainability

The majority of the interviewees thought that concrete, which includes cement and steel, and the transportation of rock mass are the highest contributors to CO_2 emissions in the tunnelling process:

"*Concrete is probably one of the largest contributors to the tunnelling process negative climate impact. This since the shotcrete contains cement and steel. Then, of course, transport of rock mass also has a very large climate impact.*" -M1

Many interviewees also answered that the amount of concrete and transportation are highly related to the amount of overbreak and choice of rock excavation class. This since overbreak generates a larger amount of rock mass and that later needs to be filled with shotcrete in order to succeed with the clients' requirements on the desirable tunnel profile. Furthermore, some interviewees discussed that, despite transportation and shotcrete, the explosives used when charging generates a negative impact on the climate due to the nitrogen emissions. Moreover, some interviewees also mentioned that they thought that leakage of hydraulic oils, other chemicals and lowering of groundwater levels affect the climate negatively. One interviewee also highlighted that the blasting generates micro-plastics, which may also have a negative impact on the climate, but perhaps is not so often thought of.

Several of the interviewees also mentioned that structure-borne sound generated from drilling, noise from scaling, and vibrations from blasting contribute to the surrounding of the project negatively. Some mentioned how the tunnelling process for example affect surrounding buildings due to the vibrations and the lowering in groundwater causing settlements. Others mentioned that the consequences of drilling and blasting affect third parties, such as citizens, in Gothenburg negatively due to the vibrations and noise generated when tunnelling.

6.3.2 Climate impact of rock excavation classes

Most of the interviewees thought that the reason behind the choice of rock excavation class did not have anything to do with the climate impact. Instead, many discussed the incitements behind the choice of rock excavation class for the contractor. They referred to that the contractor has a large possibility to optimise the tunnel profile and decrease the amount of overbreak. Overall, all interviewees agreed upon that the reason behind the choice of rock excavation class today is not made in concern to the climate impact, but they thought that this could be an incentive for the choice between them in the future.

When the interviewees got the question if the client could order a specific rock excavation class concerning the climate impact of tunnelling, there were mixed opinions. One interviewee thought that the client already has high regulations on the contractor concerning climate impact, while another interviewee thought the opposite, that the client instead can make that demand on the contractor:

"*Yes, the client could do that. But as I mentioned before, it depends on the geological conditions. In areas where you know there are good rock conditions, the client could order Rock Excavation Class 1 to get a better result with less overbreak. However, in bad rock conditions, the risk in outcome is unsure.*" - M3

Furthermore, one interviewee highlighted that the regulations the client set on the contractor regarding climate impact is a difficult balance in such a complex project as Korsvägen, since the consequences can be unknown. But in the end, all the interviewees agree that this decision lies with the client.

7 | Analysis

This chapter contains an analysis performed by an interpretation of the results in relation to the frame of reference. The analysis will be presented in three sections based on the following research questions:

- Section 7.1: How does the choice of rock excavation class affect the outcome of overbreak when performing rock excavation in contract Korsvägen?
- Section 7.2: How does the two studied rock excavation classes affect the outcome of cost and sustainability when performing rock excavation in contract Korsvägen?
- Section 7.3: What are the risks with regard to cost and sustainability for the two studied rock excavation classes when performing rock excavation in contract Korsvägen?

7.1 How the choice of rock excavation class affects the outcome of overbreak

As seen in the result of the interview study, Rock Excavation Class 1 and 3 are opposites of each other when it comes to their advantages and disadvantages. From the results of the interview study, it is evident that in good geological conditions, Rock Excavation Class 3 generates more overbreak and has a bigger damage zone than Rock Excavation Class 1. This goes in line with the frame of reference since Olofsson (2017) mentions that Rock Excavation Class 1 often generates less overbreak, as the damage zone is smaller than for Rock Excavation Class 3. This corresponds with the results from the case study that showed that Rock Excavation Class 3 has a larger overbreak distribution in acceptable rock quality than Class 1. As seen in Table 5.1 Rock Excavation Class 1 and Rock Excavation Class 3 have a difference in median overbreak of 14 percentage points.

However, it is evident that in bad geological conditions the outcome in overbreak, depending on the choice between the two rock excavation classes, is complicated and can be discussed. Thus, based on Olofsson (2017) one can argue that in bad rock conditions rock excavation class 1 can be a preferable technique due to the smaller damage zone. On the other hand, Foderà et al. (2020) argue that in bad geological conditions the overbreak will happened anyway. This is more in line with the result of the interview study, since many of the interviewees highlighted that the outcome of overbreak in bad geological conditions may not differ between the two studied rock excavation classes. Regardless, the result of the case study was only based on the overbreak distribution in acceptable rock quality. Thus, in this thesis, the relationship between the outcome of overbreak and the choice of rock excavation classes in bad rock quality is not investigated. Accordingly, it is not possible to investigate this hypothesis further. Therefore, a conclusion cannot be drawn that the choice of rock excavation class does not matter in terms of overbreak distribution in bad rock quality, since our case study proves the opposite.

Furthermore, the phenomenon of overbreak and its relationship to the choice of rock excavation class is an important subject that should be even more investigated in practice. This since this thesis only provides result of the outcome in terms of acceptable rock quality based on the values of four tunnels. It is important to consider that the contract Korsvägen is an ongoing project and that these was the values that was available. Although, the result showed that the relationship between overbreak and rock quality is not linear, meaning that there is not only the rock quality that affect the outcome of the overbreak. Hence, as the frame of reference mentions the drill- and blast technique may also have a big influence on the amount of overbreak (Foderà et al., 2020; Karlzén & Johansson, 2011; Olofsson, 2017) which is something that could be investigated even further.

7.2 How the two studied rock excavation classes affect the outcome of cost and sustainability

This section contains an analysis regarding research question number two, based on the results presented in chapter five and six and the knowledge gained in frame of reference. The analysis are divided between costs and sustainability.

7.2.1 Costs

The majority of the interviewees argued that it is in the contractor's interest to be as close to the theoretical tunnel profile as possible. This mainly due to that the contractor only gets paid on the theoretical amount of excavated rock. Accordingly, the amount of overbreak generated from the blasting is a direct loss of revenue for the contractor. This is agreed upon in the literature, both Karlzén and Johansson (2011) and Olofsson (2017) argues that overbreak generates a high cost for the contractor. This since the higher amount of overbreak involves more blasted rock that need to be handled, transported, and later be replaced with shotcrete, which all gives rise to additional costs. Accordingly, the literature argue, that overbreak are caused due to both geological conditions and the drill- and blast technique. Thus, the amount of overbreak can be minimised by optimising the drilling angle (Karlzén

& Johansson, 2011; Foderà et al., 2020; Olofsson, 2017), but also by extending the geological mapping prognoses (Foderà et al., 2020). Accordingly, there is a balance that is needed between the drilling angle and the charging. This to minimise the expected overbreak outcome as the interviewees also agreed upon. In acceptable rock quality, as studied in this thesis, minimising the distance between c and d would optimise the tunnel profile for both rock excavation classes and lower the amount of overbreak. Less amount of overbreak would in turn lower the cost for mucking, scaling and reinforcement as seen for Rock Excavation Class 1 in the cost calculation.

As mentioned by Olofsson (2017) the activities blasting and reinforcement, are the two activities that affect the direct costs the most. This is also evident in the cost calculation, where mucking and the shotcrete used for reinforcement are two of the biggest direct costs in the tunnelling process. The results of the cost calculations shows that the large amount of overbreak caused by Rock Excavation Class 3 generates additional costs for reinforcement. The amount of overbreak also results in increased costs for mucking since it generates a larger amount of excavated rock mass which needs to be transported. The transports are paid for, as mentioned related to the amount of excavated rock mass, to a subcontractor. Thus, a difference in 14 percentage points, as seen in the case study of median overbreak between the two studied rock excavation classes, implies a big difference in costs and time between the outcome of mucking and reinforcement.

If the project with an approximate of 650 000 cubic meters excavated rock mass stands for a total of eleven Scandinavium, one need to put the difference of 14% overbreak in a larger perspective. 14% more overbreak then stands for approximate two additional Scandinavium filled with rock mass for Rock Excavation Class 3. As evident, Rock Excavation Class 3 has the most expensive direct costs. These costs then exceed the extra cost Rock Excavation Class 1 generates with the more expensive explosives and the extra drilling steel. Hence, Rock Excavation Class 3 is more expensive in terms of direct costs, i.e. material costs and subcontractors, since Class 3 involves more mucking and shotcrete, which is connected to the amount of overbreak. Accordingly, one can understand that the amount of overbreak is a large cost for the contractor. This agrees well with the literature since Olofsson (2017) also specifies that the amount of blasted rock outside the theoretical tunnel profile is the interesting aspect in terms of additional costs. On the contrary, this was proven in the cost calculation to not affect the final total cost.

Even if the two activities mucking and reinforcement are the biggest direct costs, the result of the cost calculation shows that the cost for time is the most crucial in the tunnelling process. This since resources stands for 80% of the total costs, while cost of material & subcontractor stands for 20%. It was found in the cost calculation that Rock Excavation Class 1, in median overbreak, is 2.1 percentage more expensive than Rock Excavation Class 3. This since it takes approximately one day longer to execute 80 meters of tunnel in Rock Excavation Class 1 compared to Class 3. The activities that resulted in generating extra time for Rock Excavation Class 1 were the time for drilling and charging. Accordingly, the time for these two activities exceeds the extra time for mucking and shotcrete done in Rock Excavation Class 3. Hence, this agrees with the results from interview study since the interviewees argued that Rock Excavation Class 3 is more production effective than Rock Excavation Class 1. This also goes in line with the Frame of Reference as well since Lindén and Josephson (2013) states that the production efficiency of the tunnelling process is crucial since the indirect costs need to be paid for even if one activity causes a standstill.

It is in both the client's and the contractor's interest to make sure that the resources used in the tunnelling process are well distributed to make the production efficiency as effective as possible and by that minimise the total costs. All interview participants agree with this and highlight that the resources need to be used as optimal as possible. This since the differences in the time it takes for the blasting cycle can have a big consequences if not a machine or a construction worker can be maximal used. This is agreed by Paraskevopoulou and Boutsis (2020) who mentions, that the tunnelling process is sensitive to disturbances and these disturbances will generate additional costs, that in the end may cause cost overruns in the project. As seen, Rock Excavation Class 1 generates 1.3 day's extra production time for 80 meters tunnel in median overbreak distribution compared to Class 3. In the bigger perspective, the total production of the whole tunnel length in the project, the additional time results in that Rock Excavation Class 1 will take 52 days extra to execute compared to Rock Excavation Class 3. This corresponds, with full production, to over 2.5 months of extra production time. Important to highlight is that this is only extra time in excavating the rock mass for 80 meters tunnel. Thus, after the excavation later parts of the construction phase need to have access to the tunnel in order to start with the subsequent work.

Furthermore, one can discuss the incentives of when the one class should be used before the other and how the choice of rock excavation class may affect the total cost of the tunnelling process in the contract Korsvägen. This since many interviewees pointed out that there is an incentive for using Rock Excavation Class 1 when it is crucial to reach the desirable tunnel profile due to subsequent work. In acceptable rock quality, the case study showed that using Rock Excavation Class 1 will generate a higher precision of the tunnel profile compared to Rock Excavation Class 3. Accordingly, it is evident that the extra time generated only by choosing the Rock Excavation Class 1 is more expensive than the more efficient Rock Excavation Class 3, but this depends on what subsequent works that comes next. Hence, sometimes it can be hidden additional costs if the focus is only on production efficiency and not the final quality. Therefore, this is a highly important aspect to consider for all involved parties in this big complex project, since the production efficiency and the time frame is crucial in succeeding and staying within the estimated budget as the literature also implies (Bruzelius et al., 1998; Paraskevopoulou & Boutsis, 2020). At the same time, the quality of the tunnel profile is also highly important.

Nevertheless, this thesis only focuses on the cost generated in the tunnelling process. Hence, it is not investigated if the extra damage zone created by Rock Excavation

Class 3 provides any other consequences in costs for later constructions. Perhaps, that extra damage zone generated by Rock Excavation Class 3 takes more time to repair than the 2.5 months of extra production time Rock Excavation Class 1 generates. Accordingly, this thesis does not involve those possible consequences, although they are important to highlight since they do in fact exist.

7.2.2 Sustainability

As seen in the result of the climate impact estimation, mucking and shotcrete are the two activities in the tunnel process that contributes the most to CO_2 equivalents. This goes in line with Fossilfritt Sverige (2018), who argues that the usage of cement, steel and the number of transports to and from the construction site are the largest contributor to CO_2 emissions during the construction phase. Henceforth, the interview study shows that the majority of the interviewees thought that the transports and usage of shotcrete are the largest contributors to climate impact in the tunnelling process. As evident, one can conclude that mucking and shotcrete are the two activities in the tunnelling process that generates most CO_2 equivalents. Moreover, the climate impact estimation shows that Rock Excavation Class 3 generates 23 tons more CO_2 equivalents, which corresponds to 97 pcs of extra transports, and 280 square meters extra shotcrete, on a tunnel length of 80 meters. This since, as mentioned, Rock Excavation Class 3 usually generates a higher amount of overbreak, which in turn has the consequence of more transportation and more usage of shotcrete to achieve the desirable tunnel profile set by the client.

Furthermore, one need to put the CO_2 equivalents in a larger perspective. The total length of the tunnel in E05 contract Korsvägen is approximately 3,2 kilometers. This shows that Rock Excavation Class 3 generates approximately 920 tons more CO_2 equivalents than Rock Excavation Class 1. One can argue that this is a large number, but as shown in Figure 7.1 (Naturvårdsverket, n.d.-a), in an even larger perspective, this is a small number compared to how much the rock tunnel part of E05 Contract Korsvägen is estimated to generate. However, hopefully the project Västlänken will contribute to an minimisation of CO_2 emissions for travels in the future. This since more people, that today may use the car, will have the opportunity to travel by train instead, which will provide opportunities to connect communities as well. This is often the case when calculating a climate impact estimation of a project, to determine how the emissions generated during the construction phase will be compensated after the construction is finalised.

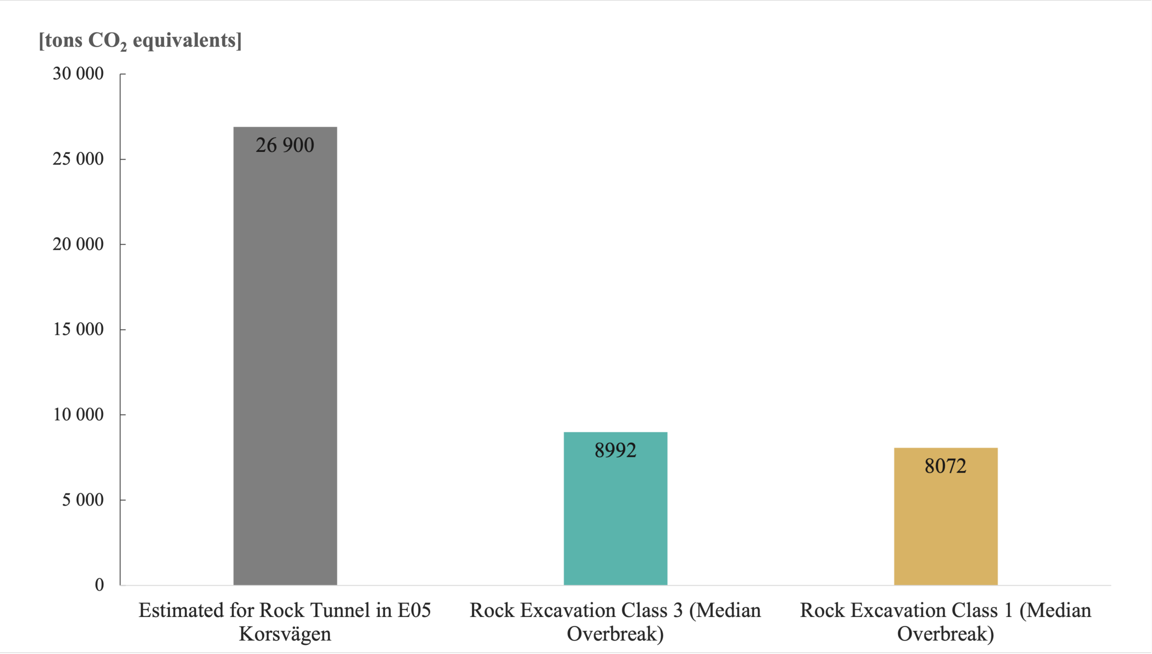


Figure 7.1: The CO_2 equivalents generated by the two studied rock excavation classes in median overbreak for 3.2 km of tunnels, compared to the estimated for rock tunnel E05 Korsvägen.

Moreover, it would be interesting to investigate the possibilities to urge the incentives for contractor to lower the rock excavation's climate impact. An option could be for the client to offer a reward to the contractor if the contractor minimise the amount of overbreak and thereby lower their climate impact. This to encourage and drive the incentive to perform more optimised rock excavation, with lower climate impact, even further. One suggestion could be to divide the reward geographically or by contract area. This since some geological areas are more challenging than others, due to the differences in geological conditions, and since each contract area in Västlänken has different contractors with individual incentives. Nevertheless, as mentioned before, every contractor has the incentive to be as close to the theoretical tunnel profile as possible, since the contractor only gets paid for the theoretical amount of excavated rock. By that, theoretically one can argue that the contractor should be interested in minimising the amount of overbreak, without an extra reward for it. However, this is not the case, since the contractor is interested in being production efficient to both lower the production costs and the time. As evident in the results, it is more expensive for the contractor to use Rock Excavation Class 1, which as shown has a lower CO_2 emissions. This compared to use the more efficient Rock Excavation Class 3, with higher CO_2 emissions. Hence, to increase the incentive for the contractor to use Rock Excavation Class 1, the climate reward would need to cover the extra cost that Rock Excavation Class 1 will generate for the contractor.

Comparatively, the complexity of sustainability needs to be taken into consideration. Hence, the rock excavation classes impact on the other two perspectives *social* and *economic* need to be discussed. Regarding the economic perspective, the production efficiency is an important aspect. As previously stated, it takes 52 days longer to excavate a tunnel of 3,2 kilometers, in median overbreak, with Rock Excavation Class 1, compared to Rock Excavation Class 3. The longer time for Class 1's tunnelling process results in a negative impact on the economic outcome. This since the longer time for the tunnelling process implies a longer time of construction, which has a negative impact on the community and society of Gothenburg, lowering the living conditions for the inhabitants. As highlighted before, time is the most critical aspect to consider, and one need to discuss what extra construction time may generate. Therefore, as seen in the cost calculation in the case study, it is not possible to avoid the extra costs Rock Excavation Class 1 generates. This since the method requires longer time for drilling and charging. Therefore, as for the economic perspective of sustainability one could discuss if Rock Excavation Class 1 generates a higher or lower value of the inhabitant's tax money. This since it may be more ecological sustainable, but the tunnelling process will take longer time and the higher capacity of the railway system will be accessible later than if Class 3 was performed.

The health & safety aspects are an important aspect regarding social sustainability and the results from the interview study indicates a considerable difference between the studied rock excavation classes. The interviewees mentions that Rock Excavation Class 1 has a negative impact on social sustainability due to the manual works, often above shoulder height. Further the interviewees mentions the risks for contamination of nitro-glycerine. Therefore, it is confirmed both by the interviewees and the literature that Rock Excavation Class 1 causes a bad working environment (Dyno Nobel Sweden AB, 2006; Swedish Work Environment Authority, 2007). This indicate the importance of development regarding the Rock Excavation Class 1 if it is not possible to follow the regulations in AMA, where Gurit is the only explosive that obeys AMA. This needs to be feasible without compromise on the construction workers working environment which seems not be possible as of today. Instead this requires further development of Class 1.

7.3 The risks with regard to cost and sustainability for the two studied rock excavation classes

It is evident, from both the literature and the interview study, that uncertainties regarding geological conditions are the biggest risk when performing tunnelling. This since the actual geology cannot be determined until the tunnelling process starts, as Paraskevopoulou and Boutsis (2020) argues. Accordingly, one can understand that uncertain geological conditions lead to many other risks that consequently can cause cost and time overruns. However, in the cost calculation, it was evident that the geological conditions do not govern the outcome in cost. This since the cost for time, independent on the amount of overbreak, stands for the biggest part of the total cost. Nevertheless, one could see in the cost calculation that the amount of overbreak has a negative effect on the direct costs and therefore it is possible to conduct that the geological conditions may affect the outcome of the total costs for tunnelling. Although, it is important to mention, that the cost calculations are based on Q-values in the range of acceptable rock quality, and do not consider the risks with worse geological conditions further than that. Perhaps, in bad geological conditions the direct costs will exceed the cost for the time, but this can only be speculated upon.

Besides the big risks involved in uncertain geological conditions, the literature also highlights the existing risks involved when controlling and keeping a high quality on the drilling during rock excavation (Karlzén & Johansson, 2011; Olofsson, 2017). From the interview study it is evident that Rock Excavation Class 1 generates a higher risk for intrusion. When the contractor aims to optimise the drilling angle, with using Rock Excavation Class 1 and thus minimise the amount of overbreak, the risk for intrusion increases. This in turn may generate risks in disturbing the tunnelling process, as mentioned by both the interviewees and the literature. Disturbances of the tunnelling process can cause major problems for all involved parties (Eskesen et al., 2004; Isaksson & Stille, 2005; Paraskevopoulou & Boutsis, 2020). In turn, this may affect the following activities or cause standstill which affects the whole tunnelling process. This is one of the causes that may generate major cost and time overruns (Paraskevopoulou & Boutsis, 2020). Hence, cost and time overruns may also have a negative influence on both economic and social sustainability. Thereby choosing Rock Excavation Class 1 may risk to not enable consistent cash flow, nor adding value to the society with providing services and connecting communities as Dyllick and Hockerts (2002), Harris (2003), and Pero et al. (2017) argues are fundamental for economic and social sustainability. Furthermore, Rock Excavation Class 1 also involves increased risks in health & safety aspects, as mentioned which also needs to be evaluated in terms of social sustainability.

On the contrary, Rock Excavation Class 3 generates a higher risk for larger outcome in overbreak, which as seen in the Climate Impact Estimation generates larger CO_2 emissions. Thus, Rock Excavation Class 3 may have a negative influence on the environmental perspective due to the larger amount of emissions and usages of material. Further, high climate impact contrasts with what Dyllick and Hockerts (2002), Harris (2003), and Pero et al. (2017) argues is fundamental for environmental sustainability. However, based on the results of the cost calculation, the interviewees and from literature, the Rock Excavation class 3 is more production efficient. Thus, one can question if choosing Rock Excavation Class 3 may enhance social and economic sustainability in comparison to Rock Excavation Class 1. Nevertheless, the larger amount of overbreak caused by using Rock Excavation Class 3 may increase risks in not fulfilling the desirable tunnel profile set by the client. This may lead to risks in increased cost due to the extra material that is needed. It may also lead to hidden costs since class 3 in theory will increase the risk for larger damage zones.

Thus, one can understand that both rock excavation classes have different opportunities and challenges, and that all risks need to be analysed and reasoned when choosing between them. The literature support this by highlighting that it is important for the organisation to consider all possible risk in tunnelling projects (Isaksson & Stille, 2005). This is also supported in the interview study, since the interviewees distributed the risk differently between them. Moreover, it is evident that risks in tunnelling projects is complex and need to carefully be evaluated when choosing between different methods for rock excavation (Project Management Institute, 2017; SveBeFo, 1999).

8 Conclusion

8.1 Answering the Research Questions

How does the choice of rock excavation class affect the outcome of overbreak when performing rock excavation in contract Korsvägen?

To answer how the choice of rock excavation class affects the outcome of overbreak, one needs to consider the difference between Rock Excavation Class 1 and Class 3. As seen in the case study, the difference in overbreak concerning the two rock excavation classes variate between 11 to 20%. It was proven that Rock Excavation Class 3, with Q-values in the range of acceptable rock quality, has a larger overbreak distribution than Rock Excavation Class 1. This depends on the difference in performance, where Rock Excavation Class 1 is gentler, with more precision in drilling and blasting. Furthermore, in worse rock quality, the relationship between overbreak distribution and rock excavation class is complicated and needs to be further investigated in order to be concluded. Thus, it was evident that the relationship between rock quality and overbreak is not linear and other factors, such as drilling angle and charging amount, also have an influence on the outcome of overbreak. Nevertheless, the case study only investigated the overbreak distribution in acceptable rock quality. To conclude, choosing Rock excavation Class 3, in acceptable rock quality, will most likely generate a larger outcome in overbreak compared to choosing Class 1, when performing rock excavation in the contract Korsvägen.

How does the two rock excavation classes affect the outcome of cost and sustainability when performing rock excavation in contract Korsvägen?

As evident, Rock excavation class 3 generates a larger overbreak and was therefore proven to be the most expensive choice in terms of direct costs. This since, the extra overbreak generates additional costs for the activities mucking and in reinforcement shotcrete. These additional costs exceed the direct costs for Rock Excavation Class 1, regarding extra drilling and more expensive explosives. However, even if the two activities mucking and reinforcement are the biggest direct costs, it was evident that the time in the tunnelling process is the most crucial aspect affecting the final cost. This since the cost for resources stands for 80% of the total costs, while the direct costs stands for only 20%. Accordingly, the production efficiency is an important aspect that needs to be taken into consideration since the cost for resources are affected by time. It was proven that the time for the activities drilling and charging differs between the two studied rock excavation classes and thereby affects the production efficiency the most. Thus, Rock Excavation Class 1 has a higher total cost due to the longer time the method requires for drilling and charging.

On the contrary, it was proven that Rock Excavation Class 1 are the most sustainable method regarding CO_2 emissions due to less transports and lower usage of shotcrete. However, as evident, sustainability is complex and all aspects need to be taken into consideration, not only the CO_2 emissions. Hence, Rock Excavation Class 1 has a negative influence on social sustainability due to the health & safety aspects with the required heavy manual works and contamination of nitro-glycerine, from the Gurit explosives. In addition, Rock Excavation Class 1 is less production efficient, leading to longer production time, which in the long run affects the whole city of Gothenburg. Accordingly, one can conclude that Rock Excavation Class 1 may not necessarily be more sustainable than Rock Excavation Class 3, due to the complexity of sustainability.

What are the risks with regard to cost and sustainability for the two rock excavation classes when performing rock excavation in contract Korsvägen?

It is evident, that unexpected geological conditions are the biggest risk due to the uncertainties it entails regarding the tunnelling process. However, in the cost calculation, it was evident that the geological conditions do not govern the outcome. This since the cost for resources, independent on the amount of overbreak, stands for the biggest part of the total cost due to the tunnelling process being sensitive to disturbances. Nevertheless, even if it is not visible in the cost calculation, one can understand that uncertain geological conditions are the underlying cause of other risks, that consequently may disturb the sensitive tunnelling process. Furthermore, when comparing the risks of the two rock excavation classes, it was evident that Rock Excavation Class 1 generates bigger risks since the method disturbs the sensitive tunnelling process more than Class 3. This may lead to large cost and time overruns which also may affect the sustainability in the social and economic perspectives. Even if Rock Excavation Class 3 generates larger CO_2 emissions, the production efficiency is, as proven before, a crucial aspect. On the contrary, it is evident that choosing Rock Excavation Class 3 increase the risks in jeopardising the final quality of the tunnel profile, which may lead to hidden costs and affect the sustainability due to increased material usage. To conclude, there exists many risks when performing tunnelling that can lead to big consequences and it is evident that both rock excavation classes have their advantages and disadvantages. Hence, the contractor needs to be aware of all risks when choosing between the two rock excavation classes.

8.2 Recommendations

This recommendation is based on the perspective of performing rock excavation for a tunnelling project, in acceptable rock quality, in Swedish dense urban areas. When analysing the possibility for the contractor to finance Rock Excavation Class 1 by themselves, it is important to emphasise the increase of risks regarding additional costs using Rock Excavation Class 1. This since Class 1 jeopardises the tunnelling process. This may cause big consequences, such as cost and time overruns, and eventually affect the inhabitants of Gothenburg. However, a recommendation is to apply Rock Excavation Class 1 where it is crucial to minimise damage zones due to sensitive subsequent works. Another recommendation would be to increase the incentive for the contractor minimise the amount of overbreak with an climate reward. However, if that is the case, it is important for the reward to cover the extra cost that a longer production time with more optimised drilling and blasting generate for the contractor.

Nevertheless, based on the purpose of this thesis our recommendation is to comprehensively consider the risks that affects the production efficiency of the tunnelling process, when choosing between the two rock excavation classes. As evident, Rock Excavation Class 3 is more cost and time efficient. Therefore, our recommendation is to perform Rock Excavation Class 3, when it is possible. This to optimise the production efficiency of the tunnelling process and thereby decrees the risk for time overruns. Although, it is still of high importance to consider the incentives and how sensitive the subsequent work will be.

8.3 Future Research

The phenomenon of overbreak and its relationship to the choice of rock excavation class has been proven to be a complex subject that should be even more investigated in practice. This to find more solutions for tunnelling projects to become production efficient. Through out this study, several areas were identified that could be interesting for further research. This thesis only provides results of the outcome in overbreak, for Q-values in the range of acceptable rock quality. Hence, it would be beneficial to study how other rock qualities affect the outcome in overbreak and how the distribution variate between Rock Excavation Class 1 and 3. Thus, this could be done by investigating information from other tunnels within the project. Furthermore, an interesting future study could be to do an assessment with other similar projects located in dense urban areas. This to analyse the effects in distribution of overbreak and the connection to the rock excavation classes.

Another interesting future research would be to comprehensively analyse the drilling plans and thus the drilling angles relationship to the outcome in overbreak. Moreover, different grouting- and reinforcement- classes could also be investigated to analyse their effects on cost, time, sustainability, and on overbreak. Other possible future research would be to analyse if it is possible to optimise the mucking of rock masses, to lower the number of transports. Additionally, as seen in this thesis, time restrictions are challenging due to the complexity of construction in dense urban areas. Hence, it would be interesting to analyse the efficiency of the tunnelling process more thoroughly with extensive time analyses, for example by clocking the activities. Thus, it may be possible to find other activities in the tunnelling process that could be optimised to result in a more efficient the tunnelling process.

Reference

Andersson, P., & Sellner, A. (2000). *Tätning av bergtunnlar-förutsättningar, bedömningsgrunder och strategi vid planering och utformning av tätningsinsatser.* (Swedish Transport Administration).

Arbetsmiljöverket. (2022). *Arbete under jord, i tunnlar, brunnar och rör.* Retrieved from `https://www.av.se/produktion-industri-och-logistik/bygg/risker-vid-byggnad--och-anlaggningsarbeten/vanliga-riskfyllda-arbetsmoment-vid-byggnads--och-anlaggningsarbete/arbete-under-jord-i-tunnlar-brunnar-och-ror/` (Date accessed: 10/05/2022)

Baumann, H., & Tillman, A.-M. (2004). *The hitch hiker's gudie to LCA: An orientation in life cycle assessment methodology and application* (10th ed.). Lund: Studentlitteratur.

Bell, E., Bryman, A., & Harley, B. (2019). *Business research methods* (5th ed.). Oxford: Oxford University Press.

Bergutbildarna. (2012). *Sprängarens lilla röda.* Vaxholm: Svenska Bergteknikföreningen.

Briesemeister, J. K. (2018). *Managing complex construction projects : A systems approach* (1st ed.). Boca Raton, Florida: Auerbach Publications.

Broere, W. (2016). Urban underground space: Solving the problems of today's cities. *Tunnelling and Underground Space Technology*, *55*, p. 245–248. doi: 10.1016/J.TUST.2015.11.012

Bruzelius, N., Flyvbjerg, B., & Rothengatter, W. (1998). Big decisions, big risks: Improving accountability in mega projects. *International Review of Administrative Sciences*, *64*(3), p.423–440. doi: 10.1177/002085239806400306

Commission on Environment. (1987). *Report of the World Commission on Environment and Development: Our Common Future Towards Sustainable Development 2. Part II. Common Challenges Population and Human Resources 4.* Oxford University Press: New York.

Dyllick, T., & Hockerts, K. (2002). Beyond the business case for corporate sustainability. *Business Strategy and the Environment*, *11*(2), p.130–141. doi: 10.1002/bse.323

Dyno Nobel Sweden AB. (2006). *Hälsa, miljö och säkerhet.* Retrieved from `https://www.oricaminingservices.com/uploads/Information%20Nordics/Helse%20Miljo%20Sikkerhet%20sv%20Aug%202006.pdf` (Date accessed: 14/04/2022)

Dysthe, O., Hertzberg, F., & Løkensgard Hoel, T. (2011). *Skriva för att lära* (2:1 ed.). Lund: Studentlitteratur.

Eklöf, H. (2018). *Riktlinje 1 Klimatkalkyl - Infrastrukturhållningens energianvändning och klimatpåverkan i ett livscykelperspektiv.* Retrieved from `https://trvdokument.trafikverket.se/Versioner.aspx?spid=5059&dokumentId=TDOK%202015%3a0007` (Date accessed: 07/06/2022)

Eskesen, S. D., Tengborg, P., Kampmann, J., & Holst Veicherts, T. (2004). Guidelines for tunnelling risk management: International Tunnelling Association, Working Group No. 2. *Tunnelling and Underground Space Technology*, *19*(3), 217–237. doi: 10.1016/j.tust.2004.01.001

Flyvbjerg, B. (2014). *What you should know about megaprojects and why: An overview* (Vol. 45) (No. 2). doi: 10.1002/pmj.21409

Foderà, G. M., Voza, A., Barovero, G., Tinti, F., & Boldini, D. (2020). Factors influencing overbreak volumes in drill-and-blast tunnel excavation. A statistical analysis applied to the case study of the Brenner Base Tunnel – BBT. *Tunnelling and Underground Space Technology*, *105*. doi: 10.1016/j.tust.2020.103475

Fossilfritt Sverige. (2018). *Bygg- och anläggningssektorn - Färdplan för fossilfri konkurrenskraft.* (Byggföretagen).

Got Event. (n.d.). *Arenafakta | Fakta om Scandinavium | Got Event.* Retrieved from `https://gotevent.se/arenor/scandinavium/arenafakta/` (Date accessed: 16/05/2022)

Harris, J. M. (2003). *Sustainability and sustainable development.* International Society for Ecological Economics.

Holmberg, R., & Nobel, D. (1997). *Miljöaspekter vid användning av tändmedel och sprängämnen.* Bergteknik, BK-Dagen.

International Organization for Standardization. (n.d.). *ISO - ISO 14040:2006 -*

Environmental management — Life cycle assessment — Principles and framework. Retrieved from `https://www.iso.org/standard/37456.html` (Date accessed: 04/02/2022)

Isaksson, T., & Stille, H. (2005). Model for estimation of time and cost for tunnel projects based on risk evaluation. *Rock Mechanics and Rock Engineering*, *38*(5), p.373-398. doi: 10.1007/s00603-005-0048-5

Jang, H., & Topal, E. (2013). Optimizing overbreak prediction based on geological parameters comparing multiple regression analysis and artificial neural network. *Tunnelling and Underground Space Technology*, *38*, 161–169. doi: 10.1016/j.tust.2013.06.003

Karlzén, R., & Johansson, E. (2011). *Svensk Kärnbränslehantering AB Slutrapport från drivningen av TASS-tunneln.* Äspö: Svensk Kärnbränslehantering AB. ISSN 1402-3091.

Kim, Rutqvist, J., Jeong, J.-H., Choi, B.-H., Ryu, D.-W., & Song, W.-K. (2013). Characterizing excavation damaged zone and stability of pressurized lined rock caverns for underground compressed air energy storage. *Rock Mechanics and Rock Engineering*, *46*(5), p.1113–1124. doi: 10.1007/s00603-012-0312-4

Kim, Y. W. (2017). *Activity based costing for construction companies.* John Wiley & Sons, Incorporated.

Klöpffer, W. (1997). Life cycle assessment: From the beginning to the current state. *Environmental science and pollution research international*, *4*(4), 223–228. doi: 10.1007/BF02986351

Lindén, S., & Josephson, P. E. (2013). In-housing or out-sourcing on-site materials handling in housing? *Journal of Engineering, Design and Technology*, *11*(1), p.90–106. doi: 10.1108/17260531311309152

Lindfors, U., Swindell, R., Rosengren, L., Holmberg, M., Sjöberg, J., Edelbro, C., … Evins, P. (2019). *Projektering av bergkonstruktioner* (1.1 ed.). Swedish Transport Administration. ISBN 978-91-7725-412-6.

Maidl, B., Thewes, M., & Maidl, U. (2013). *Handbook of tunnel engineering I : Structures and methods.* Wilhelm Ernst & Sohn Verlag fur Architektur und Technische.

Naturvårdsverket. (n.d.-a). *Hur kan jag minska min klimatpåverkan?* Retrieved from `https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/omraden/klimatet-och-konsumtionen/hur-kan-jag-minska-min-klimatpaverkan/` (Date accessed: 27/04/2022)

Naturvårdsverket. (n.d.-b). *Klimatet och bygg- och fastighetssektorn.* Retrieved from `https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/omraden/klimatet-och-bygg--och-fastighetssektorn` (Date accessed: 20/05/2022)

NGI. (2015). *Using the Q-system - rock mass classification and support design.* NGI Publication, Oslo.

Ofori, G. (2000). Greening the construction supply chain in Singapore. *European Journal of Purchasing and Supply Management*, *6*(3-4), p.195–206. doi: 10.1016/S0969-7012(00)00015-0

Olofsson, S. O. (2017). *Modern bergsprängningsteknik.* Nora: Orica.

Paraskevopoulou, C., & Boutsis, G. (2020). Cost overruns in tunnelling projects: Investigating the impact of geological and geotechnical uncertainty using case studies. *Infrastructures*, *5*(9). doi: 10.3390/infrastructures5090073

Pero, M., Moretto, A., Bottani, E., & Bigliardi, B. (2017). Environmental collaboration for sustainability in the construction industry: An exploratory study in italy. , *9*(1). doi: 10.3390/su9010125

Project Management Institute. (2017). *A guide to the project management body of knowledge (PMBOK guide)* (6th ed.). Newtown Square, Pennsylvania: Project Management Institute, Inc.

Rosseau, D. M., & McLean Parks, J. (1993). Rosseau and Parks - The contracts of individuals and organizations. *Research in Organizational Behaviour*, *15*, p.1–43. Retrieved from `https://web.mit.edu/curhan/www/docs/Articles/15341_Readings/Justice/TheContractsOfIndividualsAndOrganizations_RosseauParks.pdf` (Date accessed: 07/06/2022)

Säfsten, K., & Gustavsson, M. (2019). *Forskningsmetodik - för ingenjörer och andra problemlösare* (1:1 ed.). Lund: Studentlitteratur.

Shenton, A. K. (2004). Strategies for ensuring trustworthiness in qualitative research projects. *Education for Information*, *22*(2), 63–75. doi: 10.3233/EFI-2004-22201

Strand, C., & Lexén, A. (2016). *Ingenjörsgeologisk prognos, Västlänken.* Swedish Transport Administration.

Strømsvik, H., & Gammelsæter, B. (2020). Investigation and assessment of pre-grouted rock mass. *Bulletin of Engineering Geology and the*

Environment, *79*(5), 2543–2560. doi: 10.1007/S10064-019-01722-9

Sullivan, G., Barthorpe, S., & Robbins, S. (2010). *Managing construction logistics.* Wiley-Blackwill.

SveBeFo. (1999). *Risk analysis approaches in underground construction - Four papers SveBeFo Report 44.* Swedish Rock Engineering Research. ISSN 1104-1773.

Sweden Underground. (n.d.-a). *Technology & Construction – Sweden Underground.* Retrieved from `https://swedenunderground.com/how/technology-construction/` (Date accessed: 28/02/2022)

Sweden Underground. (n.d.-b). *West Link, Gothenburg – Sweden Underground.* Retrieved from `https://swedenunderground.com/tunnel/west-link-gothenburg/` (Date accessed: 03/02/2022)

Swedish Building Centre. (2020). *AMA Anläggning-20* (Svensk Byggtjänst, Ed.). Svensk Byggtjänst.

Swedish Transport Administration. (2020a, 7). *AMA Anläggning – allmänn material- och arbetsbeskrivning för anläggningsarbeten .* Retrieved from `https://www.trafikverket.se/for-dig-i-branschen/teknik/Tekniska-dokument/AMA---allman-material--och-arbetsbeskrivning/` (Date accessed: 01/02/2022)

Swedish Transport Administration. (2020b). *Tunneldrivning - Trafikverket (Tunneling).* Retrieved from `https://www.trafikverket.se/nara-dig/Orebro/vi-bygger-och-forbattrar/hallsberg-degeron/hallsbergstenkumla/tunnelbygget/tunneldrivning/` (Date accessed: 03/02/2022)

Swedish Transport Administration. (2021a). *Att bygga i berg - Trafikverket.* Retrieved from `https://www.trafikverket.se/nara-dig/Vastra-gotaland/vi-bygger-och-forbattrar/Vastlanken---smidigare-pendling-och-effektivare-trafik/Om-Vastlanken/sa-bygger-vi-vastlanken/att-bygga-i-berg/` (Date accessed: 03/02/2022)

Swedish Transport Administration. (2021b). *Det här ska vi bygga i Korsvägen - Trafikverket.* Retrieved from `https://www.trafikverket.se/nara-dig/Vastra-gotaland/vi-bygger-och-forbattrar/Vastlanken---smidigare-pendling-och-effektivare-trafik/aktuellt-i-ditt-omrade/deletapp-korsvagen/det-har-ska-vi-bygga/?fbclid=IwAR0rLkqGyxN`

`-VgfaM6cysObBYMTByYdkD58QvbND3swfSV9uuYQ5uUX6NLo` (Date accessed: 03/02/2022)

Swedish Transport Administration. (2021c). *The west link project (Västlänken) - Trafikverket.* Retrieved from `https://www.trafikverket.se/en/startpage/projects/Railway-construction-projects/The-West-Link-ProjectVastlanken/` (Date accessed: 02/02/2022)

Swedish Work Environment Authority. (n.d.). *Building and civil engineering work - Arbetsmiljöverket.* Retrieved from `https://www.av.se/en/production-industry-and-logistics/building-and-civil-engineering-work/` (Date accessed: 10/05/2022)

Swedish Work Environment Authority. (2005). *Buller, Arbetsmiljöverkets föreskrifter om buller samt allmänna råd om tillämpningen av föreskrifterna.* AFS 2005:16.

Swedish Work Environment Authority. (2007). *Sprängarbete, Arbetsmiljöverkets föreskrifter om sprängarbete samt allmänna råd om tillämpningen av föreskrifterna.* AFS 2007:1.

Swedish Work Environment Authority. (2010). *Berg- och gruvarbete, Arbetsmiljöverkets föreskrifter om berg-och gruvarbete samt allmänna råd om tillämpningen av föreskrifterna.* AFS 2010:1.

Swedish Work Environment Authority. (2015). *Hälsorisker av bergdamm, kunskapssammanställning.* RAP 2015:15. ISSN: 1650-3171.

Tellis, W. M. (1997). The qualitative report the qualitative report introduction to case study introduction to case study. , *3*(2), p. 1–14. doi: 10.46743/2160-3715/1997.2024

Tilly, L., Ekvall, J., Ch, G., & Finn Ouchterlony, B. (2006). *Vattenburna kväveutsläpp från sprängning och sprängstensmassor.* Swedish Rock Engineering Research. ISSN 1104 – 1773.

Toller, S. (2020). *Klimatkalkyl - Beräkning av infrastrukturens klimatpåverkan och energianvändning i ett livscykelperspektiv Modellversion 7.0.* Swedish Transport Administration.

United Nations. (n.d.). *Sustainable development goals | United Nations development programme.* Retrieved from `https://www.undp.org/sustainable-development-goals` (Date accessed: 20/05/2022)

Vidal, L.-A., & Marle, F. (2008). Understanding project complexity: implications on project management. , *37*(8), p. 1094–1110. doi: 10.1108/03684920810884928

A | Interview Guide

Inledande frågor:

- Är det okej att spela in intervjun?
- Vill du vara anonym?
- Vad är ditt namn?
- Vad har du för idigare erfarenhet av tunnelprojekt/projekt i berg?
- Vad är din roll i projektet?
- Hur länge har du varit i projektet?

Information om hur intervjun kommer att gå till väga:
Första delen av intervjun består av en tabell där vi vill att du ska ranka de tre största riskerna för oväntade kostnader i tunneldrivningen. Därefter kommer två efterföljande frågor där vi vill att du ska punkta upp fördelar och nackdelar för de olika bergschaktningsklasserna 1 och 3. Efter detta moment kommer vi följa upp med frågor baserade på dina svar.

Andra delen av intervjun består av mer klassiska intervjufrågor på temana: kostnader, tid och risker samt klimatpåverkan.

DEL 1:

1. Vilka är de tre största riskerna för oväntade kostnader i tunneldrivningen? Ranka de tre du anser är viktigast av riskerna nedan:

Table A.1

Risken för...	**Ranka mellan: 1 (minst) - 3 (störst)**
...sämre geologiska förutsättningar än förväntat	
...att inte uppnå beställarens krav på önskvärd tunnelprofil	
...behov av extra förstärkningsåtgärder	
...stor andel överberg	
...odetonerat sprängmedel	
...maskinhaveri	

Punkta upp i tabellerna nedanför vad du anser gällande de olika bergschak-

tningsklasserna 1 och 3:

2. Vad anser du att bergschaktningsklassen har för påverkan på tunneldrivningens kostnad?

Table A.2

Bergschaktningsklass:	**Fördelar/Nackdelar:**
Bergsschaktningsklass 1	Fördelar: Nackdelar:
Bergschaktningsklass 3	Fördelar: Nackdelar:

3. Vad anser du att bergschaktningsklassen har för påverkan gällande framdrivningen av tunneln?

Table A.3

Bergschaktningsklass:	**Fördelar/Nackdelar:**
Bergschaktningsklass 1	Fördelar: Nackdelar:
Bergschaktningsklass 3	Fördelar: Nackdelar:

Efterföljande frågor:

4. Du satte [...] som största risken vid tunneldrivning, kan du utveckla varför du anser att det är den största riskfaktorn?
    - Hur påverkar den risken tunneldrivningen?

5. Finns det andra risker som du anser är viktiga att ta i beaktning vid tunneldrivning?

- Finns det några risker gällande hälsa säkerhet?
- Hur är de riskerna kopplade till bergschaktningsklasserna?

6. Vilka aktiviteter i tunnelcykeln tycker du påverkar den totala kostnaden mest?
    - Varför påverkar dessa aktiviteter kostnaden?
    - Har bergschaktningsklassen någon påverkan på dessa aktiviteter?
    - Vad finns det för osäkerhetsfaktorer gällande dessa aktiviteter?

7. Vilka aktiviteter i tunnelcykeln tycker du påverkar framdrivningen av tunneln mest?
    - Varför påverkar dessa aktiviteter framdrivningen?
    - Har bergschaktningsklassen någon påverkan på dessa aktiviteter?
    - Vad finns det för osäkerhetsfaktorer gällande dessa aktiviteter?

8. Hur räknar man på kostnader kopplat till osäkerhetsfaktorer?
    - Vilka aktiviteter är mest osäkra i tunnelcykeln?
    - Vad baseras uträkningen för osäkerhetsfaktorer på?
    - På vilket sätt räknas detta med i kostnadskalkylen?

9. Vilka aktiviteter är mest osäkra eller känsliga i tunnelcykeln?
    - Vilka är de störningar som kan generera extra kostnader i tunnelcykeln?

DEL 2:

TEMA: KOSTNAD, TID & RISKER

10. Anser du att det finns det något sätt att minska kostnaderna i tunnelcykeln?
    - På vilket sätt kan man göra det?
    - På vilket sätt kan det bidra till minskade kostnader?

11. Hur ser ni som entreprenör på risktagandet när man går in i ett bergtunnelprojekt?
    - Finns det några risker med olika ersättningsformer?

12. Finns det risker med att ha målet att minska mängden överberg?
    - Om ja, Varför är det en risk?
    - Hur skulle den gå att förebygga?

13. Påverkar precisionen av tunnelkonturen kostnaden?
    - På vilket sätt?
    - Går det att förebygga?

14. Går det att bestämma i förväg, korrelationen mellan överberg och intrång?
    - Om ja, Kan man göra det på ett mer effektivt sätt?
    - Om ja, hur kan man utföra det?
    - Om ja, hur följs denna korrelation upp för fortsatt framdrift av tunneln?

  - Om nej, skulle man kunna göra det på något sätt?

15. Går det att kontrollera mängden utschaktat berg vid bergschaktning?
    - Hur kan man kontrollera det?
    - Går det i förväg att bestämma korrelationen mellan överberg och intrång?
    - Faller det ut mer överberg beroende på vilken bergschaktningsklass man använder, trots att det är bra bergkvalité?

16. Hur ofta hanterar ni stora mängder överberg?
    - Hur påverkar överberg tunnelcykeln i form av tid kapacitet?

17. Vad är dimensionerna på lastbilarna?
    - Hur mycket schaktat berg kan de lasta?

18. Hur ofta hanterar ni intrång?
    - Hur påverkar intrång tunnelcykeln i form av tid kapacitet?

19. Hur påverkar stora mängder överberg användningen av sprutbetong?
    - Hur påverkar det förstärkningen?

Visar en översiktskarta av tunnlarna i etapp korsvägen

20. Vart på kartan används bergschaktningsklass 1 respektive 3?

21. Vilken del av tunnlarna på kartan anser du att de största riskerna för framdrivningen av tunneln befinner sig?
    - Vad är detta för risker?
    - Varför finns dessa risker?

22. Är det någonstans på kartan som det är störst risk för överberg eller för intrång?

TEMA: KLIMAT

23. Vilka aspekter i tunnelcykeln anser du har störst klimatpåverkan?

24. Hur mycket tänker ni på NCC på åtgärder gällande klimatpåverkan i tunneldrivningsprocessen?
    - Vad tror du är bakomliggande faktorer för detta?

25. Vad händer med bergmaterialet som ni spränger ut?
    - Hur långt färdas materialet efter sprängning?
    - Återanvänds något av materialet ni spränger ut?

26. Har klimatpåverkan någon betydelse för val av bergschaktningsklass?

  - Varför? / Varför inte?

27. Skulle man som beställare kunna beställa till Bergschaktningsklass med hänsyn till klimatet?

28. Hur skulle man som beställare kunna ställa högre krav på entreprenören gällande lägre klimatpåverkan i tunneldrivning?

ÖVRIGT

29. Vilken bergschaktningsklass föredrar du och varför?

30. Har vi missat att ställa någon fråga som du hade ställt till dig själv i vår sits? Eller vill du lägga till något?

31. Har du något du vill fråga oss?

Tack för din medverkan! Vi kommer att skicka vår rapport till dig så du kan godkänna hur vi använt dina svar i rapporten.

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se