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E16 Sandvika-Wøyen:

Analysis of tunnel excavation, achieved contour quality and influence of applied initiation system.

Master degree thesis

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FOREWORD

This master thesis was written as a part of my exchange studies in Norway. Participating in the selected courses focused on the Norwegian tunneling method at the Norwegian University of Science and Technology shaped the concept of the dissertation.

In Poland, my home country, geology is not propitious for many underground constructions, particularly for tunnels excavated with the drill and blast method, which fascinated me from the beginning of my stay in Norway.

Many people were involved in this master thesis, and I would like to express my sincere gratitude to all of them.

I would like to thank my supervisor, Professor Amund Bruland, for providing me the possibility to do this thesis in real conditions, and all his invested time, patience and encouragement for reaching my goal.

I am grateful to the Norwegian Public Road Administration (Statens vegvesen) for allowing me to participate in the detonators test from which I was able to gather the necessary data for the thesis. And special thanks to Arild Neby, Karen Klemetsrud, Ola Hennum, Lovisa König, Eirik Jansson Haverstad and Marcin Kosakowski who shared their knowledge, supported and helped me during my stay in Sandvika.

SUMMARY

The drill and blast excavation method is the most commonly used method for tunnel construction in Norway. In D&B the results from blasting can be evaluated through several factors, such as pull percentage, vibration level and contour quality.

The main goal of the thesis was to analyze excavation with a special focus on the quality of the achieved contour and the influence of the applied initiation system. The analysis was performed based on results from the Bjørnegård tunnel, which was a part of the E16 Sandvika-Wøyen, Norwegian infrastructural project. Tunnel excavation analysis was done by an estimation of the drilling accuracy and measurement results from scanning. Data for the thesis was collected from one tunnel tube from twelve rounds in total: seven of which used standard non-electric detonators and five used electronic detonators. The assumption was that the use of the electronic detonators as an initiation system has the potential for better contour quality. Special accuracy of the drilling was required for the test.

The analysis was divided into two parts. The first part was focused on the analysis of drilling accuracy. For the evaluation of the results, MWD data from the drilling jumbo was used. Local coordinates from the drilling rig were used for the estimation of the spacing and length of the drilling holes, while global coordinates were used for the start and end position of the holes in comparison to the theoretical contour.

The second part focused on the analysis of the results from the tunnel scanning, which provided information about theoretical and actual contour length, theoretical and overblast area and distances from the theoretical to the actually blasted contour. Scanning analysis was based on an evaluation of the ratio of actual contour length to planned contour length (RCL), ratio of actual blasted to planned area (RBA), overbreak and Tunnel Contour Quality Index (TCI).

Analysis of the drilling results showed no significant difference between the accuracy of the drilling in the non-electric rounds compared to the test rounds. Estimation of the spacing and length of the contour holes presented a difference of 1% and 3% respectively. Results of the calculation of the starting position of the holes indicated a decrease of the accuracy of the placement of the hole in accordance to the theoretical profile. The special requirement of a maximum 10 cm distance from the theoretical contour of the starting position of the holes was fulfilled for 13% of the holes drilled in the test rounds.

Evaluation of the scanning results showed that results from non-electric and electronic detonators rounds were similar, and no improvement of the tunnel quality was calculated. Tunnel Contour Quality Index (TCI) for both data sets was similar and estimated as average.

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1 INTRODUCTION

1.1 BACKGROUND

Since prehistoric times, people have been strongly bound with construction. The development of new technologies, materials and engineering knowledge have allowed the construction industry to grow and evolve. Nowadays, every year engineers design and construct projects, which blaze past set limits.

One of the major branches of the construction industry is tunneling. Tunnels are used for many practical purposes: from transportation such as cross passaging for people or traffic and rail tunnels, to utility tunnels for electric power and telecommunication cables, to tunnels used in hydropower plants and military purposes. Technologies for underground structures are continuously developing, and there is a constant need for development of the techniques and methods for improving the efficiency, safety and quality of the underground works.

There are various methods of tunnel construction, the selection of which depends on many factors including ground conditions, ground water level, and the length and diameter of the tunnel. The process of choosing the best method is highly complex and must be preceded by the appropriate research.

Methods most commonly used for hard rock tunnel excavations are drill and blast (D&B) and mechanized TBM. In Norway, which is a front runner in underground excavation and tunneling, according to the Norwegian Tunnelling Society Publication no. 23 (2014), the D&B method has a great advantage over TBM in terms of dealing with and handling changing ground conditions, and the need for rock support and grouting to secure safe tunneling conditions.

Tunneling technology is developing rapidly with the ultimate goal of reducing associated time and costs. Construction entrepreneurs offer a wide range of services underlining the value of the quality of their works. However, the latest trends have shown that speed and efficiency have become the most important factors in the decision-making process for construction companies, with the quality of the excavated tunnel falling in second place.

The results from blasting using the D&B method can, in general, be estimated through the ratio of actual pull length to drilled length per round, vibration and noise level, and the quality of the excavated contour characterized by overbreak, underbreak and contour roughness

(Kim, 2009). It is desirable for all the mentioned constituents to be as low as possible, to achieve good results from excavation.

Figure 1.1 Drill and blast method - drilling jumbo at the face

Reduction of overbreak, underbreak and contour roughness, in general – improvement of the contour quality, could result in a decrease in construction time and cost in terms of the utilization of explosives, rock support application and muckpile removal. The constant development of excavation technologies means that there are continuously being solutions proposed to achieve this goal. Researches (Innaurato et al.,1998, Zare, 2007) emphasize the importance of accurate drilling. Also, the type of ignition system could influence the tunnel contour quality (König, 2000).

This thesis is based on the study of the results from the E16 Sandvika-Wøyen project, where in the Bjørnegård tunnel, which was excavated with the D&B method, electronic detonators were tested as an initiation system for the blasting. It relies on data from seven blasting rounds with application of normal non-electric detonators, and five test rounds of electronic detonators. Data for the thesis was collected from one tunnel tube.

1.2 OBJECTIVES AND ORGANIZATION OF THE THESIS

The main focus of this thesis is based on an analysis of the excavation of the Bjørnegård tunnel, part of the E16 Sandvika-Wøyen project. From aspects defining the drill and blast method used in the tunnel, drilling accuracy and contour quality were analyzed. The main objectives of the study are following:

- To analyze the accuracy of the drilling performed in the tunnel
- To analyze the results from scanning of the tunnel contour performed after blasting
- To evaluate the effect of the use of electronic detonators on the analyzed result

The thesis is organized in six chapters:

Chapter 1 consists of a description of the background for the thesis, providing a short introduction to the subject and objectives and organization of the thesis, and presenting the main research goals. Limitations of the thesis and general approach are also dealt in this chapter.

Chapter 2 is concentrated on the relevant theory. This chapter presents a description of the drill and blast excavation method, drilling and drilling accuracy and contour blasting techniques. Contour quality and scanning technology is also presented in this section. The last part is focused on the initiation systems with the description of non-electric and electronic detonators, which were used in the tunnel.

Chapter 3 describes site overview with the summary of the basic operations in the tunnel.

In **Chapter 4** after short description of the assumptions for the calculations, the accuracy of the drilling is analyzed. Results from the MWD data are used for estimation of spacing of the holes, drilling length and start and end position of the hole in relation to theoretical contour. Analysis and discussion of the results are done both for non-electric and electronic detonators rounds. Achieved results are compared. The section is completed with the summary of the drilling.

Chapter 5 consists of short description of the assumption for the calculation. In this section is presented analysis of the ratio between the theoretical and actual contour (RCL), ratio between actually blasted and theoretical blasting area (RBA), overbreak and Tunnel Contour Quality Index (TCI). Results are analyzed and discussed both for non-electric and electronic detonators rounds. The section is completed with the summary of the scanning.

Chapter 6 contains conclusions and recommendation for further work.

In Chapter 5 and Chapter 6, subchapters entitled “Results” consist of presentation of the results and preliminary discussion. Results are analyzed and discussed in subchapters titled “Analysis and discussion”.

1.3 LIMITATION OF THE THEIS

The thesis was primary limited by the access to the data what disallowed complex analysis of the tunnel excavation. Thesis is focused on limited number of factors. There are others aspects that influence the results of blasting as pull percentage or inducted noise level, which were not measured. The idea of comparison the rounds with non-electric and electronic detonators for the parallel stretches in neighboring tunnels had to be changed, due to the fact that for the rounds in parallel tunnel, analyzed measurements were not performed.

Another limitation of the thesis was amount of reliable research data. According to the constantly appearing unfortunate circumstances, objectives of the thesis had to be reduced and modified several times. The assumption of the electronic detonators test in the Bjørnegård tunnel was that there will be performed 20 rounds (100 m) with changed initiation system, which could have provided more reliable results than only five test rounds. Delays at the construction site made it impossible to continue detonators test after five rounds, because of changed cross section (niche).

Furthermore, scanning which is significant for the tunnel excavation and contour quality analysis was executed in total for twelve rounds. The distance between the last scanned round with use of non-electric and the first round of electronic detonators was around 26 m, which result also with e.g. change of the geological conditions.

Some of the data was impossible to analyze using the tools available during work on this thesis. No explicit answer to the correctness of the global coordinates sets, which were not corresponding to each other, precluded complex analysis of the drilling accuracy.

Access to additional data connected with the test could make results more reliable. Also increased number of analyzed rounds could reduce variation caused by e.g. changing rock mass condition.

1.4 GENERAL APPROACH

In general, this thesis can be divided into three major parts. Scheme of the work is presented on the diagram below.

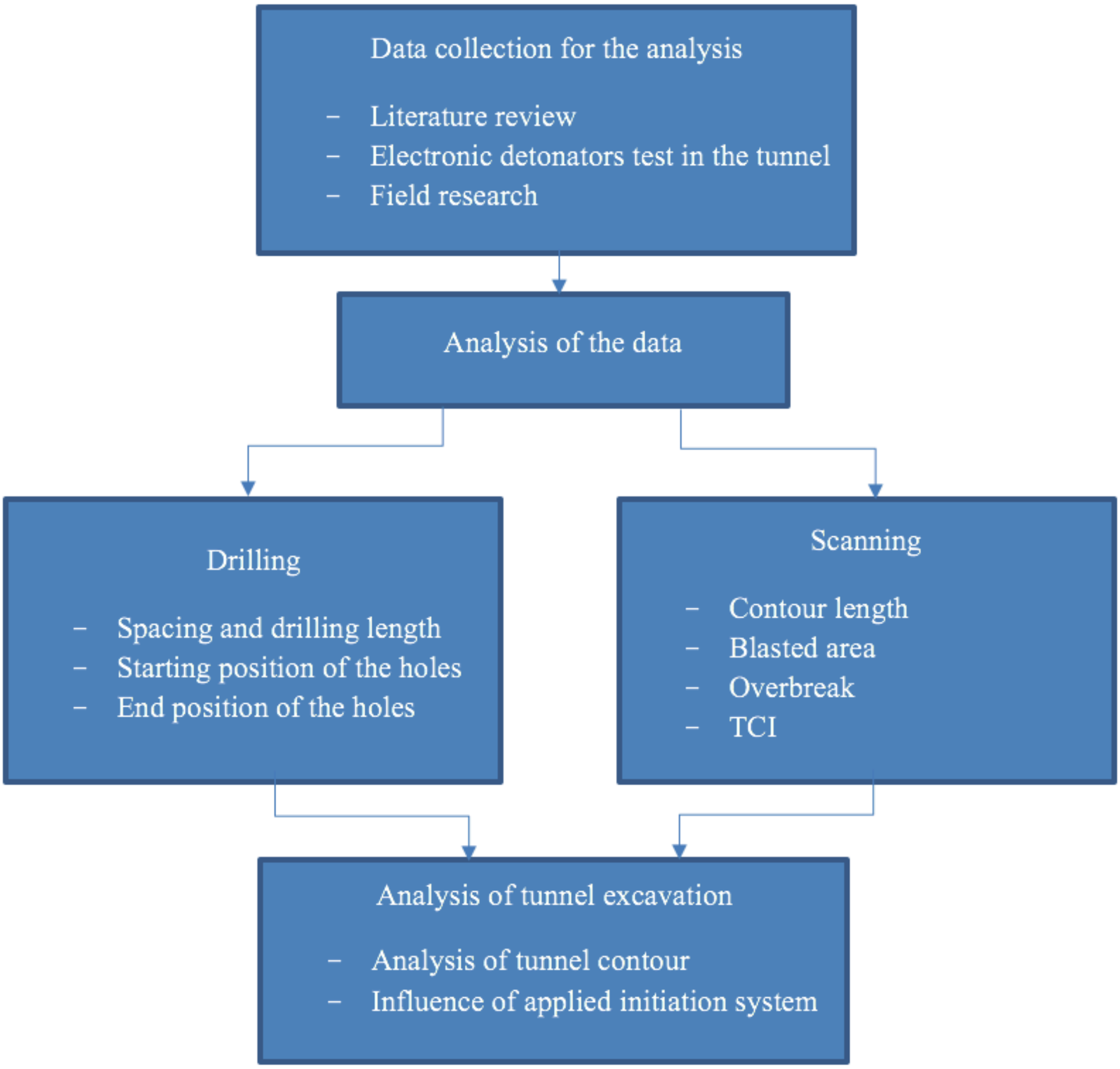


Figure 1.2 General structure for approach

The first part of the thesis was connected with collection of the data for the analysis. Choice of the data for the analysis was made based on the literature study and actual availability of the data. In this part field study was executed during both non-electric and electronic detonators rounds.

The second part of the thesis is concentrated on the analysis of the collected data. Analysis was divided into two groups: drilling and scanning. Both groups were analyzed in terms of use non-electric and electronic detonators. In the drilling section special focus was put on the spacing, drilling length, starting position and end position of the holes. In scanning section contour length, blasted area, overbreak and TCI was analyzed. In both section in the end was made the summary and comparison of the results in terms of applied initiation system.

The third part of the thesis consists of summary of all the results achieved from rounds with standard non-electric initiation system and results from test stretch with the use of electronic detonators. This part contains attempt to evaluate influence of choice of initiation system on tunnel excavation and contour quality.

2 RELEVANT THEORY

2.1 DRILL AND BLAST EXCAVATION METHOD

Drill and blast (D&B) is the most common excavation method in Norway. Due to the fact, that it can be adjusted to the changing ground conditions, it is widely applied in mining, quarrying and civil engineering. In tunnel excavation, D&B method is divided in to sequence of cycles. Standard cycle contains following operations:

- Drilling
- Charging
- Blasting
- Ventilation
- Loading
- Hauling
- Scaling
- Rock support

Excavation is not continuous and cycles are repeated until desired length of the tunnel is achieved.

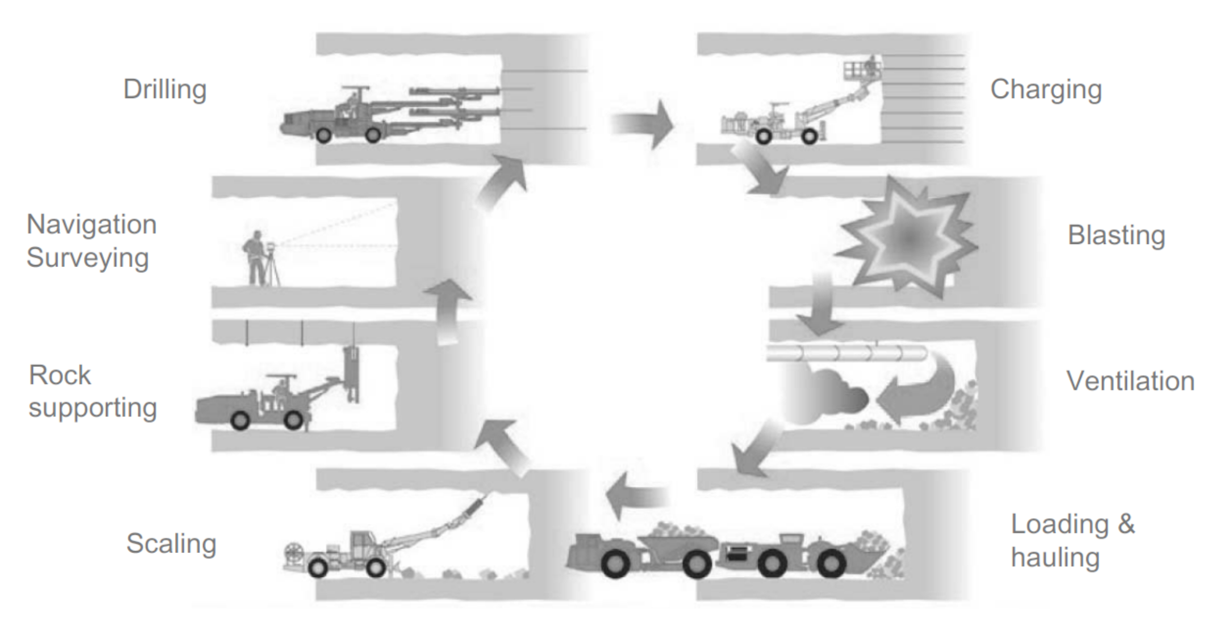


Figure 2.1 D&B tunneling cycle (Zare, 2007)

Even though the design process of the drilling, charging and firing patterns are prepared carefully, the first trail blast is usually used for adjustments to the actual ground conditions.

Nowadays, drilling is performed by computerized drilling jumbos. The operator of the jumbo can choose between manual drilling or an automatized option. The drill plan is prepared separately for each round with precise coordinates, which are stored in the drilling jumbo computer. Drilling time depends mostly on the length, diameter and number of holes in the drilling pattern, equipment used and rock mass conditions (Zare, 2007).

(a) View from the drilling jumbo

(b) Charging

Figure 2.2 Drill and blast method

The next operation in D&B is charging of the drilled holes. This is performed according to the charging plan prepared for given tunnel construction. Explosives used for blasting in tunneling operations are bulk emulsions. They have been in use since mid the 1990's (Olsen et al., 2014) and have almost completely replaced cartridge explosives and ANFO. There are many advantages of emulsions over other types of explosives, e.g. water resistance or less fumes and smoke production. They are also not classified as explosives until they are combined with the chemical sensitization compound, which increases safety (Zare, 2007, Olsen et al 2014). The emulsion is transported to the tunnel face by a separate charging unit, and with the use of computer programed system, it is pumped into drilled holes. The amount of charge is pre-programed and differs for different hole types. Even though it is possible to use the automatic charging option, it is still more common for charging to be performed manually.

The standard initiation system used in Norwegian tunneling is a non-electric system. Due to the potential improvement of blasting results, there are attempts to introduce an electronic initiation system for common use.

Ventilation is necessary part of the excavation process, which is performed after blasting of the rock. To enable the continuation of the works, harmful gases and dust particles must be removed from the tunnel face. A proper ventilation system reduces the cycle time.

Blasted rock mass has to be removed after every blast. Loading and hauling of the material can be executed by track or trackless transport. The first option can be used only in tunnels with small cross sections. In tunnels with trackless transport, muckpile removal is performed with the combination of wheel loader and dump truck. In well-organized tunnels, loading is continuous, which means that the loader does not have to wait for the hauling unit.

Scaling is the process of removing loose rock from the walls and roof of the blasted area. It is done before rock support application. After scaling and before shotcreting, mapping of the face is performed. During this operation, the condition of the rock mass is checked. Experienced workers map all the major joints, and discontinue and estimate the Q-value, which is the most commonly used system for rock support selections.

Following execution of all of the mentioned above operations, the cycle starts from the beginning and repeats until the designed tunnel length has been achieved. In case of unfavorable ground conditions or water problems, there are some additional actions taken, like grouting or spilling bolts installation, before starting new round.

2.2 DRILLING AND DRILLING ACCURACY

There are four main types of holes in the D&B method:

- Cut holes
- Easers
- Invert holes
- Contour holes

The most important elements for the blasting operation are cut and contour holes, which are placed first when designing the drilling pattern. The cut design has an influence on the fragmentation, consumption of explosives, the shape of the muckpile and loadability. Additionally, proper design and execution of contour holes affect the quality of the finished opening and the drilling of the next round. (Zare, 2007). To avoid a “saw-toothed” contour, holes should be drilled with the smallest eccentricity as possible.

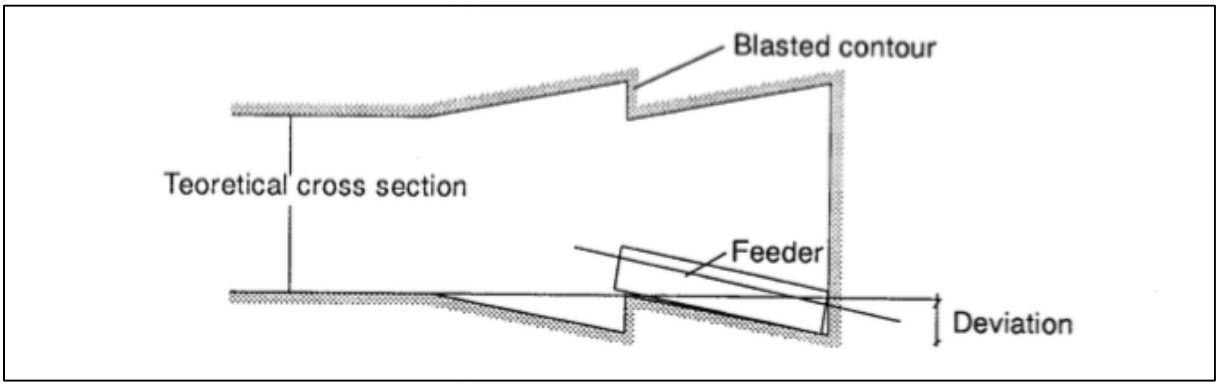


Figure 2.3 Results of drilling contour holes with a "saw-toothed" contour (Zare, 2007)

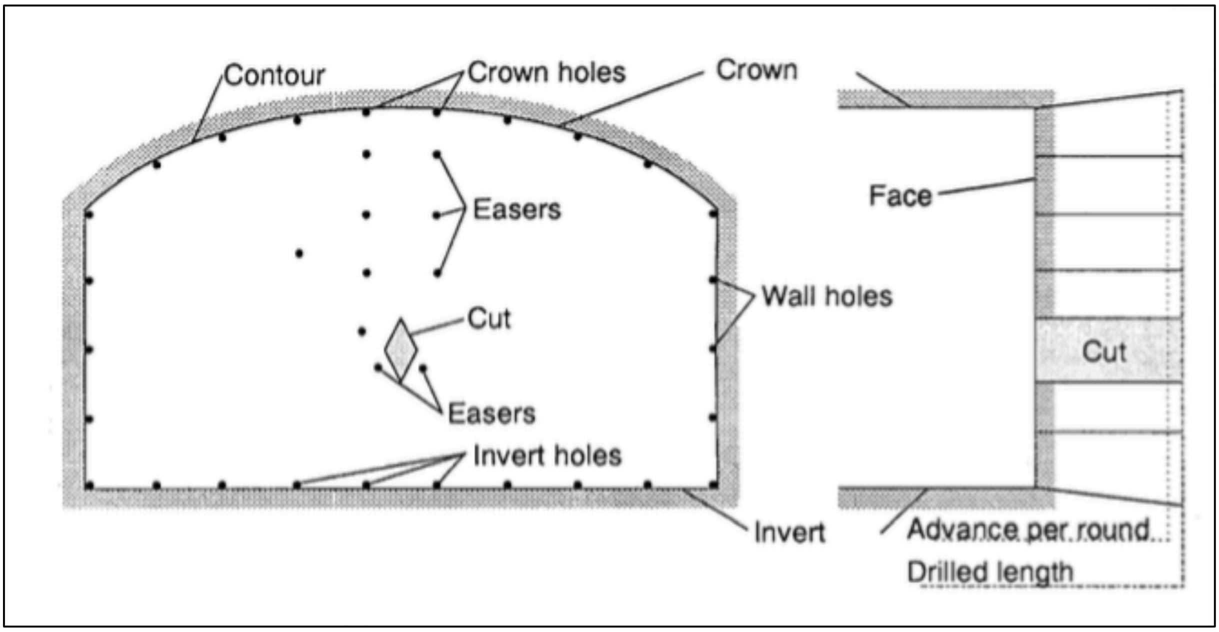


Figure 2.4 The most important notations when blasting in tunnel (Zare, 2007)

Requirements for the accuracy of the contour hole drilling in Norway are defined by Handbook R7561 and are presented in the Figure 2.5. The starting position of the holes should be placed in the area covered by radius of the 100 mm from the line offset from the theoretical contour of the tunnel.

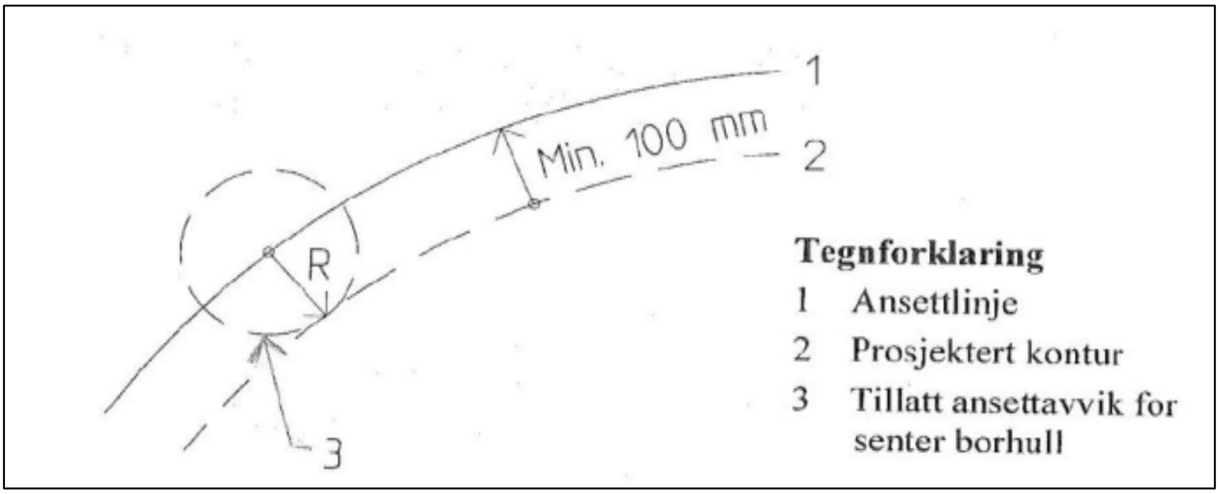


Figure 2.5 Norwegian regulation for starting position of the contour holes (Handbook R7561, 2015)

The importance of accurate drilling in order to achieve the desired excavation results has been underlined many times in literature. Accurate drilling has been mentioned as significant aspect of reduction of underbreak and overbreak. It is also suggested that careful drilling with special attention put on the starting position and look-out of the drillholes could dramatically improve tunnel contour quality. As Innaurato et al. (1998) stated, by placing boreholes correctly and as close as possible to the project profile, it is possible to improve pull and overbreak. Also Olofsson (1990) mentioned the need for accurate blasting in tunnels where the overbreak has to be replaced with expensive concrete and significance of accurate drilling to achieve that.

According to Kaltenegger (2016), accurate drilling is, next to delay design and explosive types, one of the best practices for optimization of the blasting operation regarding vibration reduction.

Ibarra et al. (1996) proposed that cause of overbreak and underbreak can be divided into two groups: geological conditions (as joint orientation and spacing, clay fillings, alteration, rock strength and ground stress effect) and blasting factors (as explosive type, powder factor, charge concentration, delay timing, perimeter blasthole pattern, drilling deviation, blasthole length and diameter, large hole cut). Both overbreak and underbreak are undesirable and are causing additional costs. In linear tunnels underbreak has to be removed, what is connected with e.g. re-blasting or increased scaling. On the other hand, overbreak which is usually connected with rock damage and loosening, requires extra concrete to replace missing rock, which increases rock support costs and time. Due to the fact that geological conditions cannot be changed, only blasting factors can be adjusted to reduce either underbreak or overbreak, resulting with more precise profile and reduction in the damage to the tunnel walls and therefore reduction of the rock support.

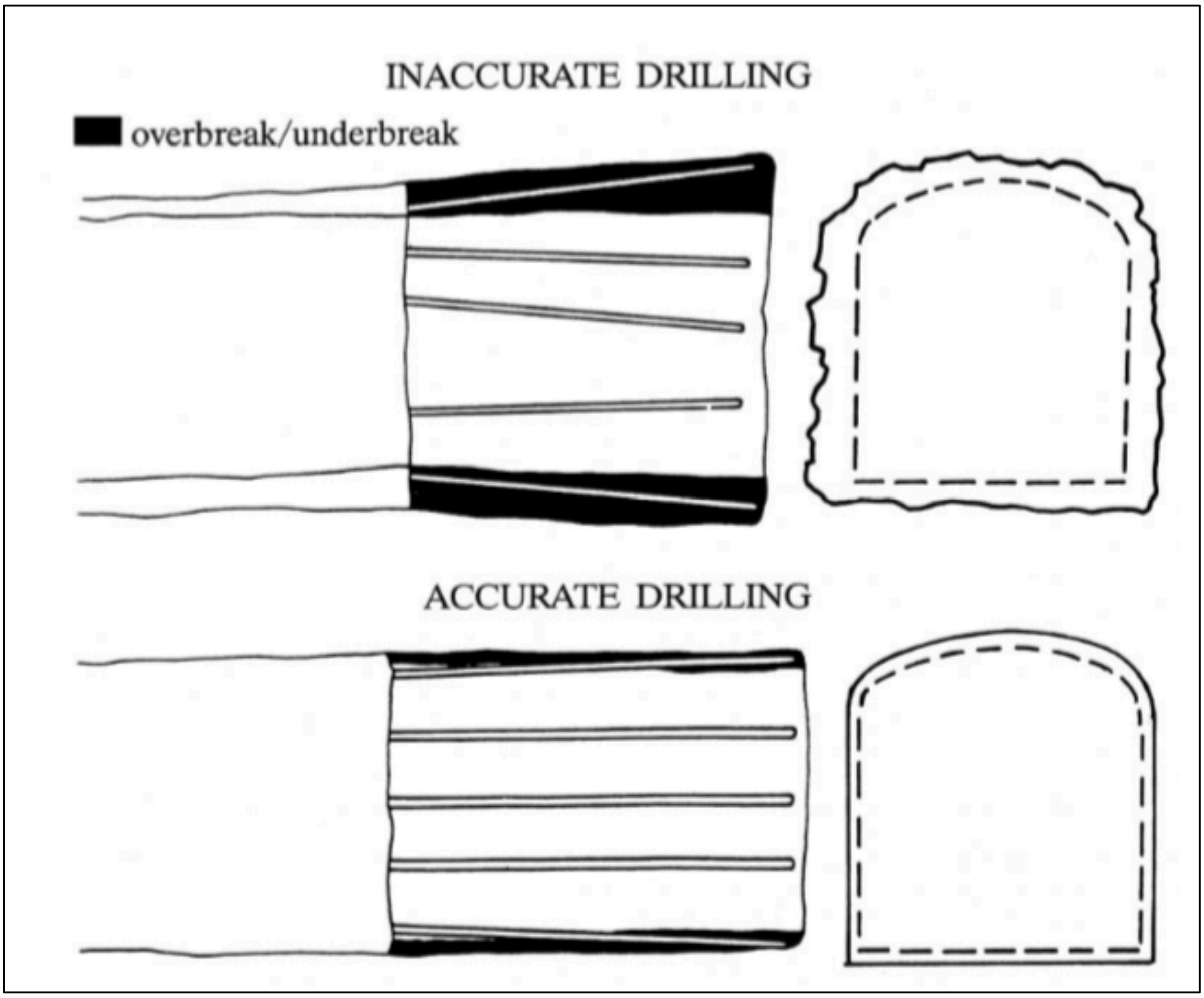


Figure 2.6 Cumulative drilling errors in drifting and tunneling (Sandvik Tamrock Corp., 1999)

2.3 CONTOUR CONTROL BLASTING TECHNIQUES

Special attention in the blasting operation should be put on the contour. The main advantage of control contour blasting is a good contour quality. Additionally, the following benefits can be achieved:

- Reduction of loading and hauling cost and time for muckpile,
- Reduction of rock support cost and time,
- Improvement of tunnel stability and safety.

Smooth blasting is a technique used for controlled contour blasting in which closely spaced drill holes are loaded with decoupled charges and fired simultaneously. According to Sandvik Tamrock Corp. Rock Excavation Handbook (1999), in smooth blasting, contour holes are drilled closer to each other and are specially charged. Spacing is typically from 0.5 m to 0.7 m and burden varies between 1 and 1.25 times the space. Blasting of contour holes should be performed last with a detonating cord or with the same detonating number.

As suggested by Innaurato et al. (1998), the objective of controlled blasting is to reduce the over-profile (which means deviation beyond the theoretical profile) to a minimum. It can reduce the costs of rock support and fracturing of the rock around the tunnel.

When using electronic detonators, it is possible to plan the delay interval, which, according to the type of round, permits to obtain an optimal fragmentation of the blasted material and to substantially reduce the vibration inducted by blasting. Moreover, firing groups of shots simultaneously improves the excavation profile, which is particularly appreciated in tunneling, where the narrow limits imposed for the overbreak together with the relevant costly penalties make it compulsory to change radically the blasting techniques normally adopted (König, 2000)

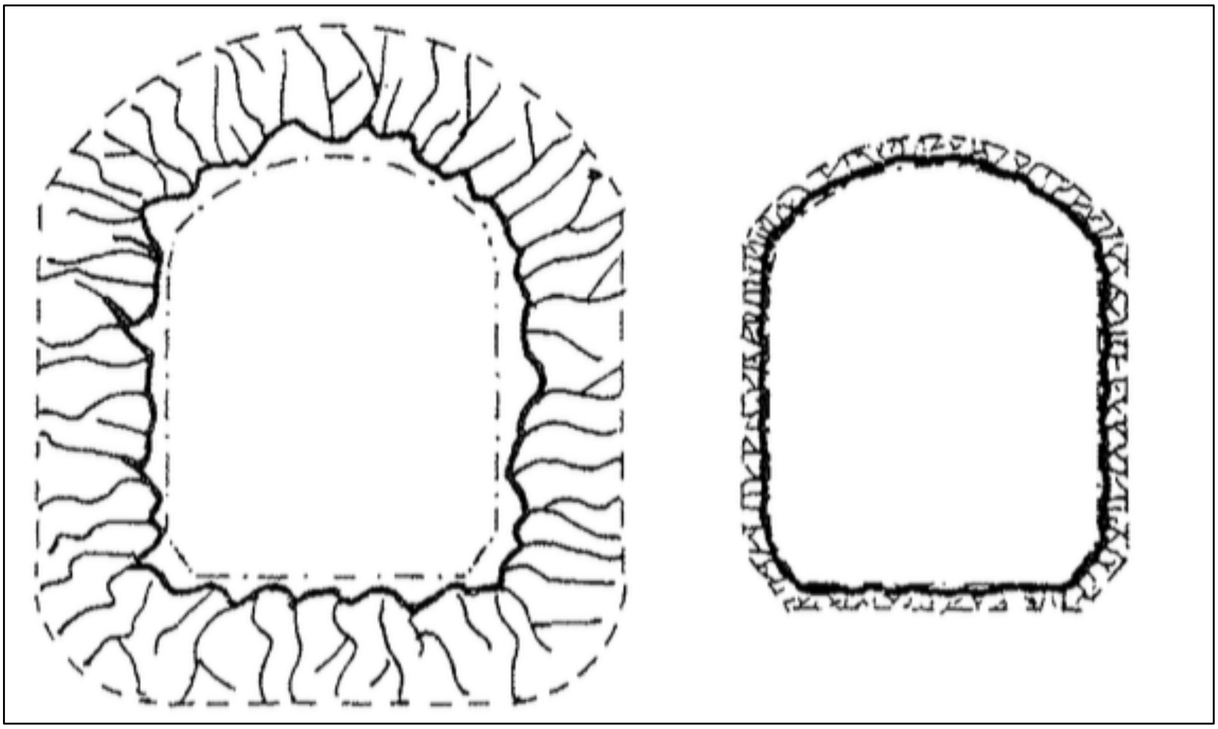


Figure 2.7 Left: crack zone from blasting with conventional explosives. Right: crack zone from smooth blasting (Olofsson, 1990)

2.4 CONTOUR QUALITY AND SCANNING TECHNOLOGY

The quality of tunnel contour is a very important part of tunnel excavation. Innaurato et al. (1998) suggested that for tunnels destined for civil purposes, it is of the utmost importance to keep the cross-profile of the tunnel as close as possible to that of the project.

The positive influence on construction time and cost can be achieved by controlling and reducing the over- and underbreak (Kim, 2009, Ibarra et al. 1996). Nowadays, scanning technology is so well-developed that it is possible to check the tunnel contour in a very precise way. Scanning can be performed using a scanner installed on the drilling jumbo, shotcrete machine or from the ground by surveyors. There are many possibilities to use scan results: not only they can give information about effectiveness of technology of blasting, but also constant scanning can be used to control thickness of the applied shotcrete.

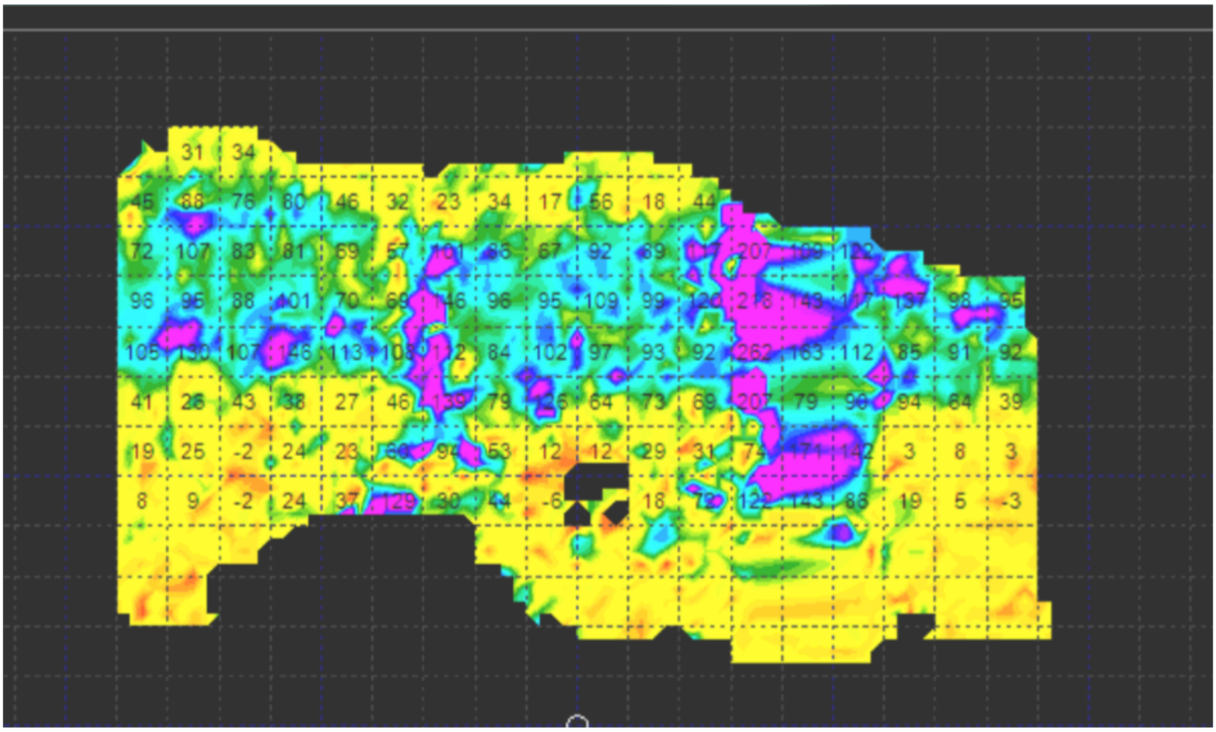


Figure 2.8 Surface plot showing thickness of applied shotcrete (Bever Control)

Factors described by Innaurato et al. (1998) that can be used to verify the quality of blasting are following:

- The ratio between the real and the theoretical pull of the round
- The geometry of the contour of the cross-profile
- The powder factor of the explosive
- The size distribution of the rock fragments produced by the round and the muck pile profile

The adequacy of the profile geometry after blasting to the theoretical one can be evaluated from two parameters:

- The value of the overbreak (OB) or the extra-profile (OB: the ratio of the difference of the theoretical and real areas of the cross sections to the perimeter of the tunnel cross section, excluding floor)
- The ratio between the length of the half-cast holes in the contour after blasting and the total length of the contour boreholes (HCF)

Kim (2009) suggested that results from blasting in drill and blast tunnels are generally evaluated through pull percentage (the ratio of actual pull length to drilled length per round), the level of induced vibration and noise, and the quality of the excavated contour. In his research, he focused on contour quality and characterized it by overbreak and underbreak, and contour roughness. He based the importance of good contour quality on the statement that poorer contour quality normally results in greater construction cost and time, as well as lower safety. In his study, he came to the conclusion that overbreak is affected by the surrounding conditions and any operation related to the blasting.

In his doctoral thesis, he proposed an index for contour quality (Tunnel Contour Quality Index TCI), which could be used to:

- Quantify easily the contour quality produced after blasting
- Compare it effectively with other cases
- Analyze more systematically the effect of any factor affecting the contour quality

TCI could be defined for the evaluation of an entire tunnel or more than five blasting rounds (TCI_T) and of only one or each blasting round (TCI_R).

$$TCI_L = \frac{C_r}{W_1E_A + W_2E_L + W_3E_V}$$

$$TCI_R = \frac{C_r}{W_1E_A + W_2E_L}$$

Where:

C_r - Constant for range adjustment

$E_A = C_1 \cdot \hat{O}_v$ - Overbreak area element

$E_L = C_2 \cdot RCL$ - Contour length element

$E_V = C_3 \cdot V_o$ - Longitudinal overbreak variation element

W_1, W_2, W_3 – Weights

C_1, C_2, C_3 - Correction factors

$\hat{O}_v$ - Average of total overbreak for each round

RCL - The ratio of actual contour length to planned contour length

V_o - Longitudinal overbreak variation

On the basis of his research, he recommended that the constant for range adjustment should be equal to 300, weights W_1:W_2:W_3 - 4.5:4.5:1 and three correction factors C_1, C_2, C_3 respectively 0.006, 0.8, 0.02.

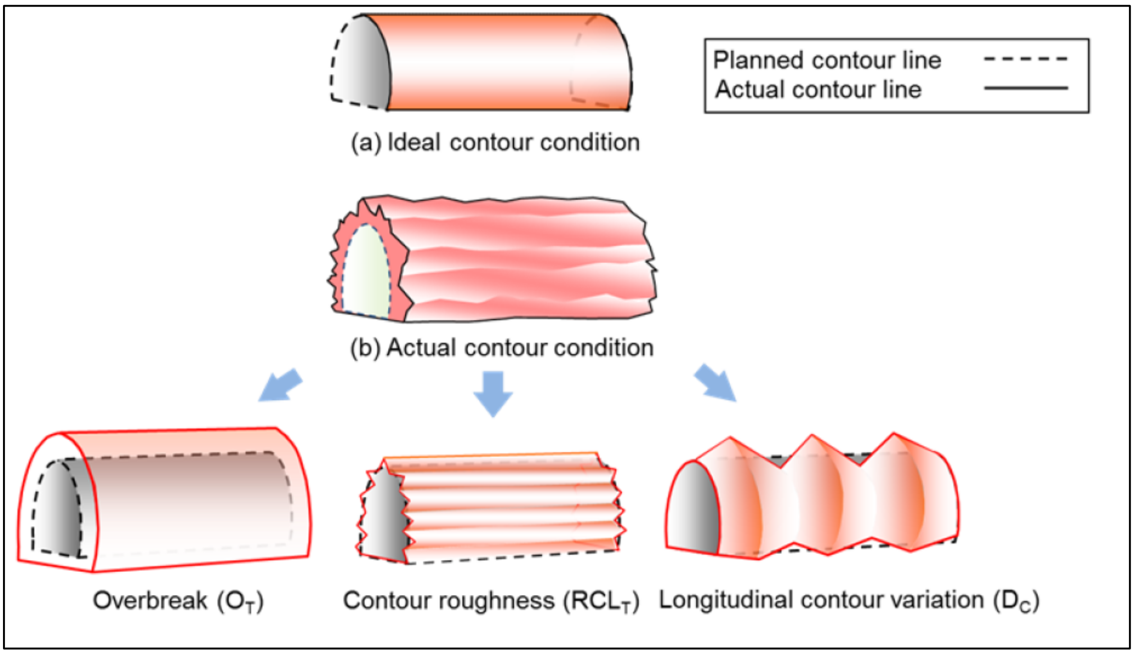


Figure 2.9 Actual contour conditions for TCI calculation (Kim, 2009)

2.5 DETONATORS

Explosives are used in many areas of application. For many years, with the drill and blast tunneling method, explosive materials have been used for breaking the rock for excavation. During this time, the development of technology and new solutions has been focused on achieving better blasting results and improving safety of use. Nowadays, a requirement of safety explosives is that they do not detonate easily and they should only do so intentionally (Chapman et al., 2010). Detonation of high explosive charges at the specified time and in the correct order requires an initiation system.

There are three main types of detonator systems:

- Electric detonator system
- Non-electric detonator system
- Electronic detonator system

Due to the fact that electric systems are susceptible to surrounding electric tension fields and there is risk of premature detonation caused by e.g. lightning, static stray currents or radio frequency energy, they are not normally used in tunneling, and in some countries, like Sweden, they are not even allowed (Chapman et al., 2010)

2.5.1 NON-ELECTRIC DETONATOR SYSTEM

Non-electric detonator system is the most common initiation system used in the drill and blast tunneling excavation method. Detonators are composed of a hollow plastic shock tube, which delivers the firing impulse to the firing impulse. That kind of initiation system makes it immune to stray electric currents. Three-layer plastic tube coated from inside with reactive explosive compound is part of small diameter shock tube. After initiation, the explosive coat propagates a low energy signal with approximately 2000 m/s along the length of the tubing, which fires a pyrotechnical initiating composition, then delay composition and at the end, primary and secondary explosives.

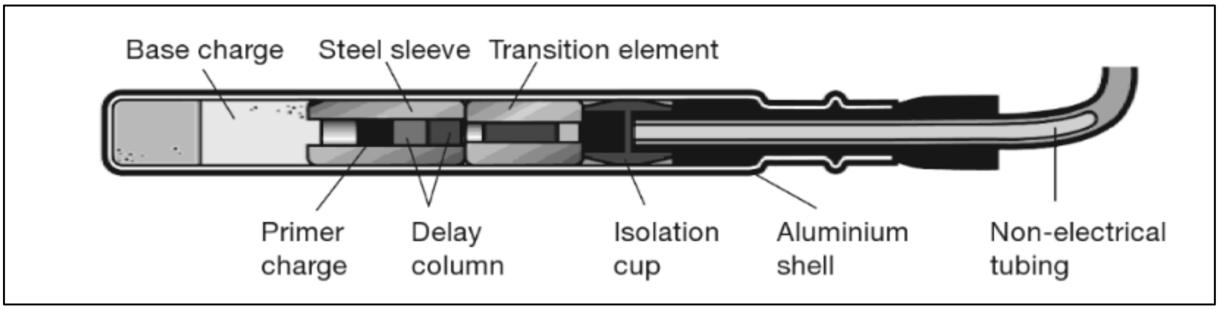


Figure 2.10 Details of non-electric detonators (Chapman et al., 2010)

2.5.2 ELECTRONIC DETONATOR SYSTEM

Electronic detonator system is the most advanced initiation system in which delay is achieved electronically and not pyrotechnically. Each detonator consists of a microprocessor chip, which controls the time of initiation. Each detonator can have unique delay time and can be programmed in 1-millisecond incensements from 1 to 10000 ms. (Austin Powder, 2016). Electronic detonators can be programmed either at the face or before assembly and are activated right before the explosion.

(c) Detonator

(d) Detonators connected to the branch line

Figure 2.11 Electronic detonators

2.5.3 NON-ELECTRIC VS ELECTRONIC

As stated by König (2000), when using electronic detonators, it is possible to plan the delay interval, which, according to the type of round, permits to obtain an optimal fragmentation of the blasted material and to substantially reduce the vibration inducted by blasting. Moreover, effective simultaneity in the firing of groups of shots allow to improve the excavation profile and this is particularly appreciated in tunneling, where the narrow limits imposed for the overbreak together with the relevant costly penalties make it compulsory to change radically the blasting techniques normally adopted.

Nowadays, the most common initiation system in tunneling is a non-electric detonator system. There are some attempts to introduce electronic detonators to the tunneling industry, but the very high cost of detonators and need for intensive user training have hindered its popularity. There are many advantages of use electronic detonators instead of non-electric, e.g. possible improvement of the tunnel contour and better control of overbreak. Very accurate delay times of electronic detonators can be adjusted to create “destructive interference” at frequencies that are favored by local geology, which could result in reduction of vibrations that excite structural elements in range of the underground blasting (Cradu et al., 2013). Even though electronic detonators are characterized by higher precision and reduction of air blast and ground vibration, around five times higher cost causes that they are not taken under consideration in the normal tunnel design process.

3 SITE OVERVIEW

In order to check the quality of the tunnel excavation and the influence of applied initiating systems, various type of data was collected from tunneling site Kjørbo-Mølla in Sandvika in Norway.

3.1 GENERAL

E16 is the main road between Oslo and Bergen. The E16 project is divided into three parts:

- Sandvika-Wøyen – which is currently under construction
- Wøyen-Bjørum – opened for traffic in 2009
- Bjørum-Skaret – regulation plan accepted in 2013

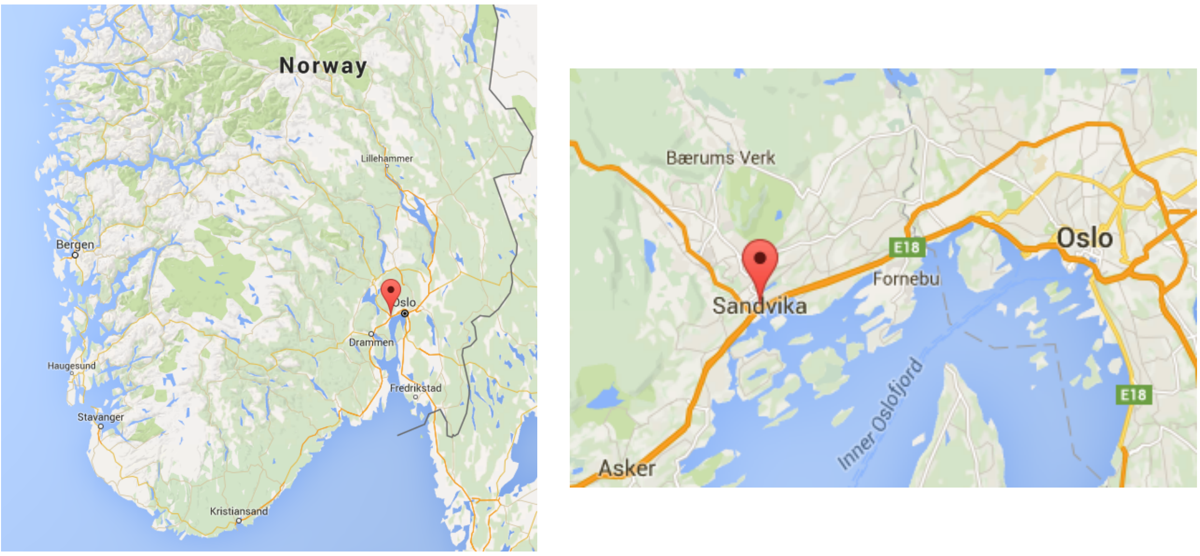


Figure 3.1 Location of Bjørnegård tunnel

The Sandvika-Wøyen project, with a budget of around 4 bln Norwegian Kroner, started in February 2015. Planned time of finishing the construction is in 2020.

In 2010, traffic on the E16 stretch between Kjørbo and Bærumsveien was estimated to be around 35,000 vehicles per day. The road currently has one lane in each direction and a speed limit of 70 km/h. It is assumed that rebuilding of the Sandvika-Wøyen road hub would decrease traffic to 12,000 vehicles per day in living areas (Statens vegvesen).

The major part of the E16 Sandvika-Wøyen stretch is Bjørnegård tunnel located in Sandvika, west of Oslo. Bjørnegård tunnel consist of two tubes (tunnel A and tunnel B) with two lanes in each tube. Total length of the tunnel is approximately 2260 m (tunnel A) and 2335 m (tunnel B). It is composed of four merged tunnels:

- Kjørbo-Mølla rock tunnel, length ca.1550 m (tunnel A)
- Mølla concrete tunnel, length ca. 105 m
- Mølla rock tunnel, length ca. 95 m
- Franzefoss concrete tunnel, ca. 510 m.

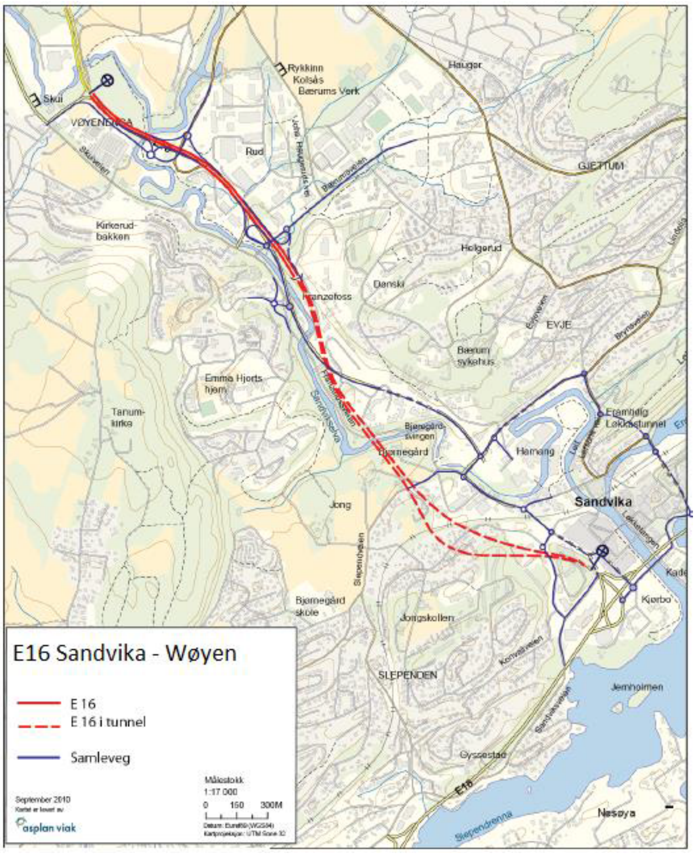


Figure 3.2 E16 Sandvika-Wøyen location

Both Kjørbo-Mølla and Mølla rock tunnel are excavated with drill and blast excavation method. Kjørbo-Mølla tunnel excavation started from an adit, the additional access tunnel to the main tunnel, with length around 290 m.

3.2 SITE OVERVIEW

Data for the thesis was collected from the Kjørbo-Molla rock tunnel, which is a part of the Bjørnegård tunnel. The tunnel consists of two tubes:

- Tunnel A, with approximate length 1550 m
- Tunnel B, with approximate length 1640 m.

Shale and Limestone are major rock types for the tunnel construction area.

3.2.1 DRILL AND BLAST METHOD

According to the "Manual 021, Road Tunnels", published by the Norwegian Public Road Administration (Nor. Statens vegvesen) in 2004, tunnel cross section designed for Kjørbo-Mølla tunnel can be classified into two major types:

- T9.5 regular cross section with tunnel width equal to 9.5 m
- T12.5 as an extended cross section for emergency lay-bys with width 12.5 m.

The drilling pattern consisted of 143 drilling holes for T9.5 profile and of 169 drilling holes for T12.5 profile.

The blasting was designed as full face blast round in normal conditions and with reduced round length or divided cross section in the demanding geological conditions. Basic round length is 5.2 m with the charging hole diameter of 48 mm. Drilling jumbo used for tunnel operations is three boom Atlas Copco Boomer XE3 C equipped with COP 3038 rock drills.

Information from the drilling is automatically recorded for every drilling operation. All the MWD data can be analyzed with GPM Rockma+ software. The information collected in the drilling logs includes the position of the holes, time of drilling, rock mass strength, fracturing and ground water level, among others.

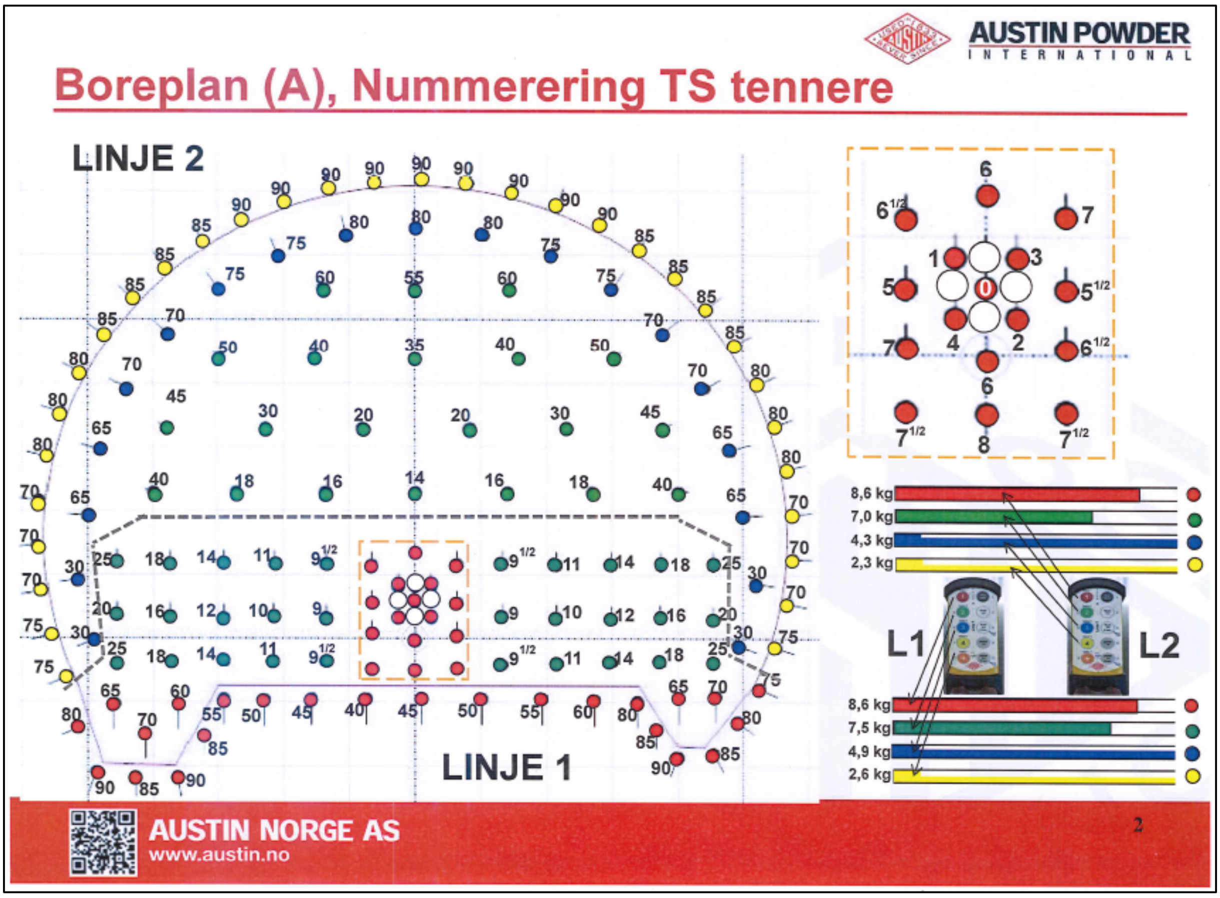


Figure 3.3 Typical drilling pattern with charging plan for non-electric detonators (Statens vegvesen)

Charging is performed from the ground and in higher sections from a boom basket of the drilling jumbo. Bulk explosives used in the tunnel are supplied by the charging truck. Charging of the face is divided into two sections with different charging of the easer holes. The designed charging weight was 8.5 kg for invert holes, 5.5 kg for row next to the contour and 2.3 kg for contour for both lines and 7.5 kg for easer holes in lower part of the cross section and 6.5 kg for upper holes. In the major part of the tunnel, non-electric detonators are used. For the need of FoU program for contour, five rounds were blasted with changed initiation system to the electronic detonators.

Scaling of the contour is performed before shotcrete application. After mechanical removal of loose rock and rock mass, which did not blast properly, the Contractor performed manual scaling from the platform. This was performed together with rock mass observation. In case of unsuccessful blasting where removal of the rock by scaling is not enough, additional blasting of the remaining rock mass was requested before scaling.

(e) Manual removal of the loose rock (f) Surface washing before shotcreting

Figure 3.4 Operation at the tunnel face

3.2.2 SCANNING OF THE TUNNEL

In the whole Kjørbo-Mølla tunnel scanning of the contour was performed by surveyors from the Client and the Contractor. Regular scanning by surveyors was done after shotcreting in order to check if there is no rock mass remaining in the planed profile area. For the FoU program in Bjørnegård tunnel, additional scanning after blasting and scaling and before shotcreting was requested. In total, there were seventeen additional scanning rounds divided into two parts performed: seven scans of the contour after blasting with non-electric detonators and ten scans of the contour after blasting with electronic detonators. For the test stretch scans were performed both before and after scaling. Due to the safety reasons, to avoid danger from loose rock, scanner had to be placed few meters in front of the recently blasted area without rock support.

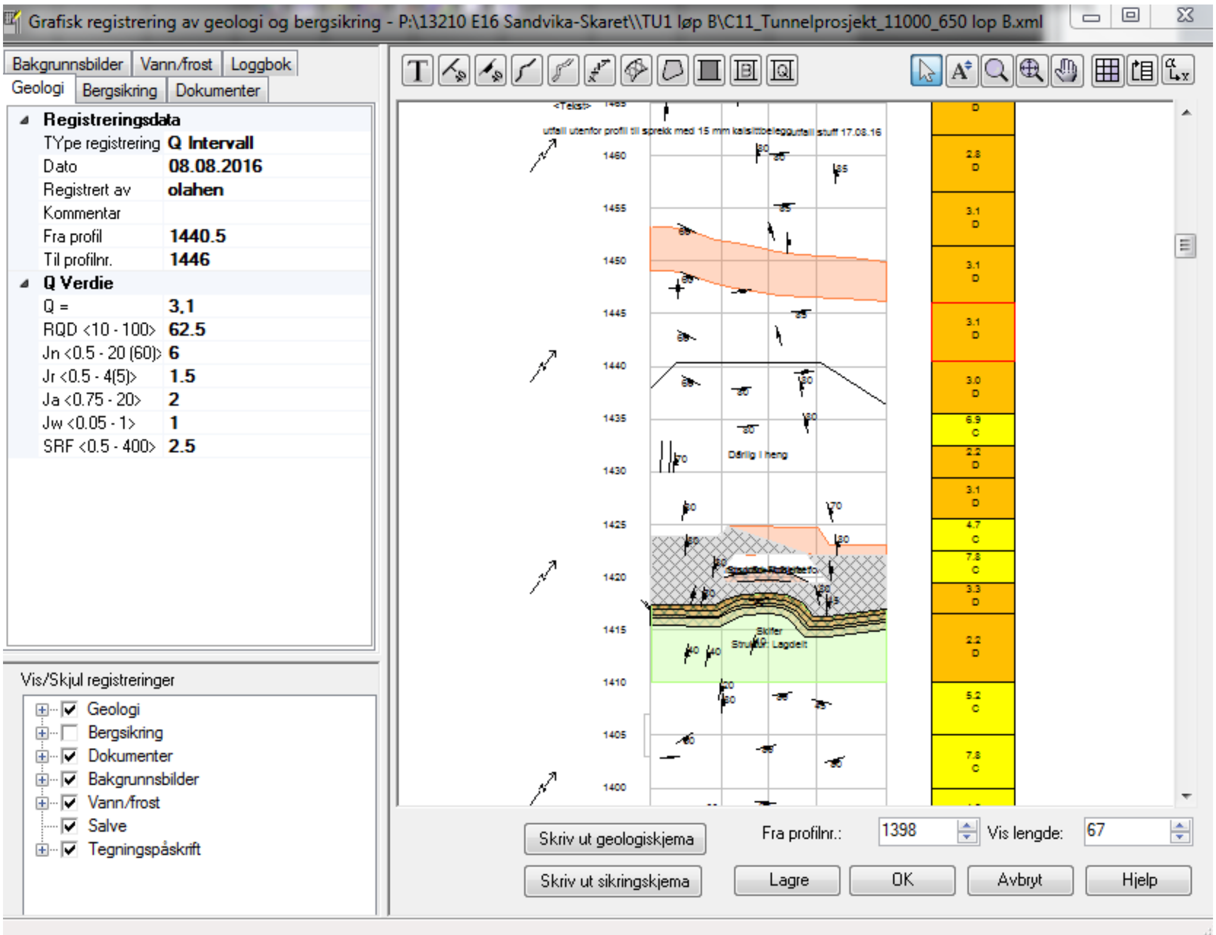
For the scanning, a Leica ScanStation C10 scanner was used. The Leica C10 is a high-accuracy long-range scanner. Scanning was performed with the use of a spinning mirror or mirror's oscillating mode. The scanner used in the Kjørbo-Mølla tunnel was fully operational between bright sunlight and complete darkness, therefore it was well adapted to the tunnel poor lightning conditions.

The reference of the point clouds from the scanner was done with the use of Leica Cyclone software. To produce the mesh, 3DReshaper was used. Contour lengths, blasted area and distances between actual and theoretical blasted profile were calculated in Powell Gemini 11 software. All the operations connected with scanning results preparation were performed by Statens vegvesen surveyors.

3.2.3 GEOLOGY

The terrain level along the tunnel varied between 10 to 50 m above the see level. In the construction site area, the dominating rock type is limestone and shale with limestone beds.

For every round, after scaling and washing the rock with the water, quality engineers performed face mapping. The Q-value was estimated after every blasting by performing visual observations and measurements of the rock mass and Q-value elements. During quality control of the rock surface, conditions and positions of the discontinuities as well as strike and dip of major joints sets were checked. The geological data from the tunnel face manual mapping was entered to the Novapoint software.



Grafisk registrering av geologi og bergsikring - P:\13210 E16 Sandvika-Skaret\\TU1 løp B\C11_Tunnelprosjekt_11000_650 lop B.xml

Registreringsdata

TYpe registrering	**Q Intervall**
Dato	**08.08.2016**
Registrert av	**olahen**
Kommentar	
Fra profil	**1440.5**
Til profilnr.	**1446**

Q Verdie

Q =	**3.1**
RQD <10 - 100>	**62.5**
Jn <0.5 - 20 (60)>	**6**
Jr <0.5 - 4(5)>	**1.5**
Ja <0.75 - 20>	**2**
Jw <0.05 - 1>	**1**
SRF <0.5 - 400>	**2.5**

Vis/Skjul registreringer

- ☑ Geologi
- ☐ Bergsikring
- ☑ Dokumenter
- ☑ Bakgrunnsbilder
- ☑ Vann/frost
- ☑ Salve
- ☑ Tegningspåskrift

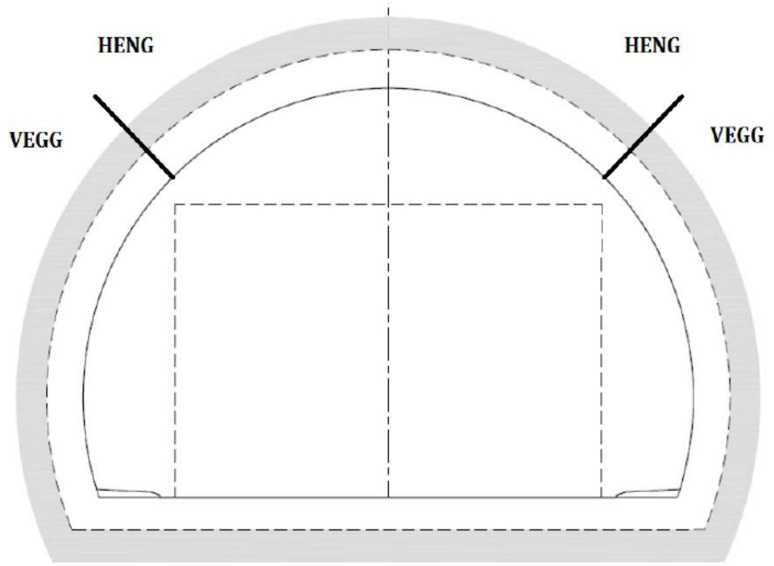
Fra profilnr.: 1398

Vis lengde: 67

Figure 3.5 Screen shot from Novapoint software

3.2.4 ROCK SUPPORT

Choice of rock support in the tunnel was executed based on the Q-value system. Guidelines used at the tunnel construction site for the amount and spacing of rock bolts and shotcrete thickness selection are presented in the Figure 3.6.



Profil 9,5 samt adkomsttunnel

Klasse	Q-verdi	Boltemønster	Boltelengder		Sprøytebetong		
			Heng	Vegg	Heng	Vegg	Type
I	> 10	3,5 m x 3,5 m	3 m	3 m	8 cm	8 cm	B35E700
II	4 – 10	2,0 m x 2,0 m	4 m	3 m	10 cm	8 cm	B35E700
III	1 – 4	1,5 m x 2,0 m	4 m	3 m	12 cm	10 cm	B35E700
IV	0,2 – 1	1,5 m x 1,5 m	4 m	4 m	15 cm	15 cm	B35E1000
V*	0,01 – 0,2	1,0 m x 1,0 m	4 m	4 m	20 cm	20 cm	B35E1000
VI	< 0,01	Stabilitetssikring vurderes spesielt					

*spiling og sprøytebetongbuer

Profil 12,5

Klasse	Q-verdi	Boltemønster	Boltelengder		Sprøytebetong		
			Heng	Vegg	Heng	Vegg	Type
I	> 10	–3,5 m x 2,5–3,	3 m	3 m	8 cm	8 cm	B35E700
II	4 – 10	2,0 m x 2,0 m	4 m	3 m	10 cm	8 cm	B35E700
III	1 – 4	1,5 m x 1,5 m	4 m	4 m	12 cm	10 cm	B35E1000
IV	0,2 – 1	1,5 m x 1,5 m	5 m	4 m	15 cm	15 cm	B35E1000
V*	0,01 – 0,2	1,0 m x 1,0 m	5 m	5 m	20 cm	20 cm	B35E1000
VI	< 0,01	Stabilitetssikring vurderes spesielt					

*spiling og sprøytebetongbuer

Figure 3.6 Guidelines for rock support for T9,5 and T12,5 tunnel profiles (Statens vegvesen)

3.2.5 VIBRATION MEASUREMENTS

During the entire construction time, the vibration level was constantly monitored. After an investigation of the construction influence zone, on structures that need to be under observation, sensors for measuring vibrations were installed. When inducted vibration reached a pre-programmed level, a text message with the number of sensor and reached value was sent. This way of monitoring allowed for immediate intervention in case of dangerous vibration levels.

To meet the needs of the FoU program, four additional geophones INFRA V12 were installed on the wall between tunnel A and tunnel B. Three (TU1, TU2, TU3) were assembled parallel to the tunnel axis, approximately 5m from each other and were moved with the progress of the excavation, and one (TU0) was installed perpendicular to the tunnel axis and its position was not changed. Geophones installed in the tunnel measured vibration levels in three dimensions.

(g) Geophone

(h) Master Unit

Figure 3.7 INFRA V12 Digital Triaxal Geophone

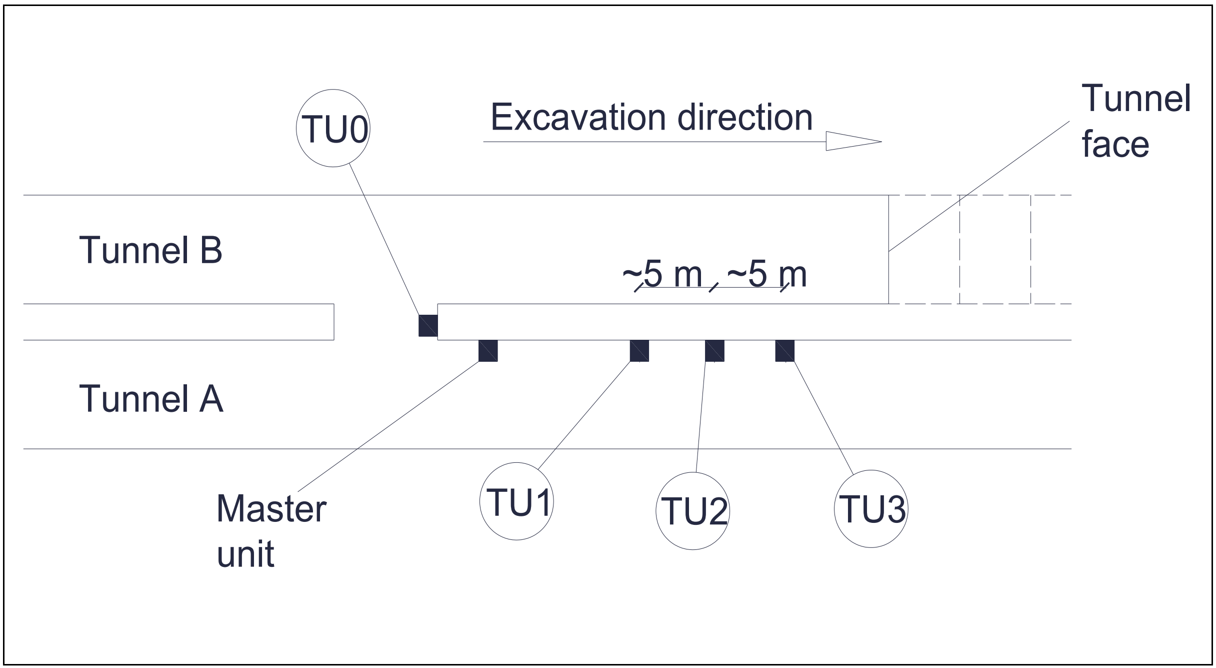


Figure 3.8 Location of geophones in the tunnel

3.3 FOU PROGRAM

FoU (Norwegian: Forskning- og utviklingsarbeidet) is a research and development program of Norwegian Public Roads Administration (Norwegian: Statens vegvesen). Research and development activities are to contribute to the development and maintenance of a safe, eco-friendly and efficient transport system (Statens vegvesen). The FoU program focuses on activities that are developing and securing the agency's specialist knowledge and skills and ensures that decisions are taken on the basis of professionalism, skill and knowledge. The results provide a basis for the revision of standards and guidelines, and benefits the entire transport sector.

The aim for FoU program for Bjørnegård tunnel was to test electronic detonators in terms of improvement of the contour quality and reduction of unreacted explosives and rock damage. It was planned to choose in cooperation with the Contractor, continuous stretch of approximately 100 m (around twenty blast rounds) to test influence of changed initiation system. During the test, electronic detonators were supposed to be used in all boreholes. Additionally, drilling jumbo operators should especially focus on the accuracy of drilling contour and row next to the contour holes. Charging of the contour and row next to the contour holes were supposed to be done using automatic pull in order to provide correct distribution of the explosives in the hole.

Due to some unpredicted circumstances, it was possible to perform five test rounds.

4 DRILLING

4.1 ASSUMPTIONS FOR THE DRILLING ANALYSIS

Data collected for the drilling analysis came from two sources: the Contractor and Rockma System AB. Types of data can be divided into MWD data and drilling plans. The Contractor provided drilling plans with global coordinates of the planned holes for first seven rounds. MWD data used in this thesis is divided into two types: local coordinates of the drilled holes coming from GPM+ software and global coordinates provided by Rockma System AB for special request.

Local coordinates from GPM+ were used to estimate spacing and length of the contour holes. For this calculation, longitudinal deviation of the holes start position was not taken under consideration, since it could be caused not necessarily by accuracy of the drilling, but by other factors like e.g. geological conditions of the rock mass.

The idea for use of global coordinates was to analyze the deviation of the actually drilled holes from planned starting position and deviation of the drillholes from theoretical tunnel contour.

As mentioned before, according to Handbook R761, the starting position of the contour holes had to be placed in the area covered by radius of the 100 mm from the line offset 100 mm from theoretical contour of the tunnel. It gave a maximum of 200 mm of acceptable deviation of the starting position of the hole from theoretical contour.

For the need of FoU program in Bjørnegård tunnel there was special, stricter requirement for the drilling accuracy presented on the Figure 4.1. According to those guidelines, starting position of the hole should be placed in the square area 100 mm x 100 mm from theoretical tunnel contour.

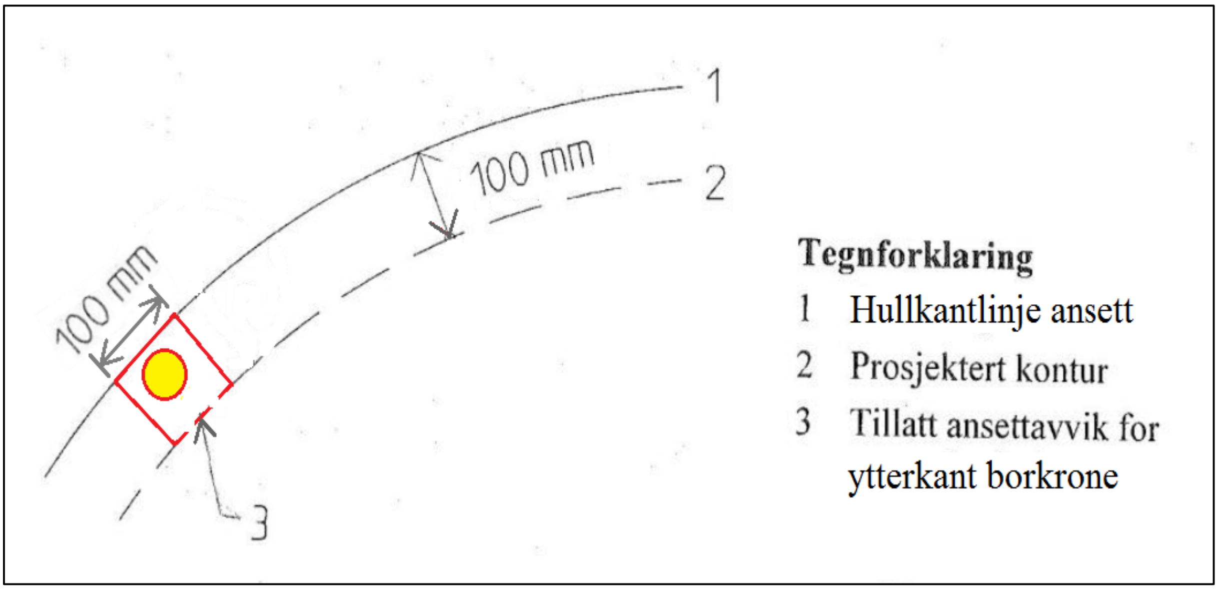


Figure 4.1 Regulation for starting position of the hole for FoU program (Statens vegvesen)

One of the assumptions for the drilling accuracy analysis was to compare coordinates of the planned holes from drilling pattern with the global coordinates of the actually drilled holes from MWD data. Calculations could show differences between actual starting position of the drilled holes and the designed drilling plan. Unfortunately, analysis of the deviation was impossible to be performed on account of the fact that data did not correspond to each other. For seven rounds before electronic detonators test, global coordinates of the drilling holes from MWD data and drilling patterns from the Contractor was collected to compare. To make the visual comparison, both sets of coordinates for each round were entered into AutoCad software. Lines corresponding to drilling holes from drilling pattern and MWD data were drawn in the same file and it appeared that the coordinates sets did not match. A comparison of the coordinates shown repeated rotation of the data with some constant value. Figure 4.2 presents the screen shot from AutoCad drawing with both MWD (green) and drilling pattern (purple) holes visualization. It seems impossible that for all seven rounds, which were checked, operators of the drilling jumbo drilled with the same level of deviation on the one side. Especially considering the fact that operators were working in the shift schedule and it was more than one person who was operating the drilling machine. It was difficult to find the source of the rotation, because even though calculation and logic of transformation of MWD data were checked, neither provider of the drilling pattern nor MWD data knew why global coordinates did not match. Due to that fact that the constant rotation value was not known, it was impossible to analyze the deviation of the starting position of the holes in this direction.

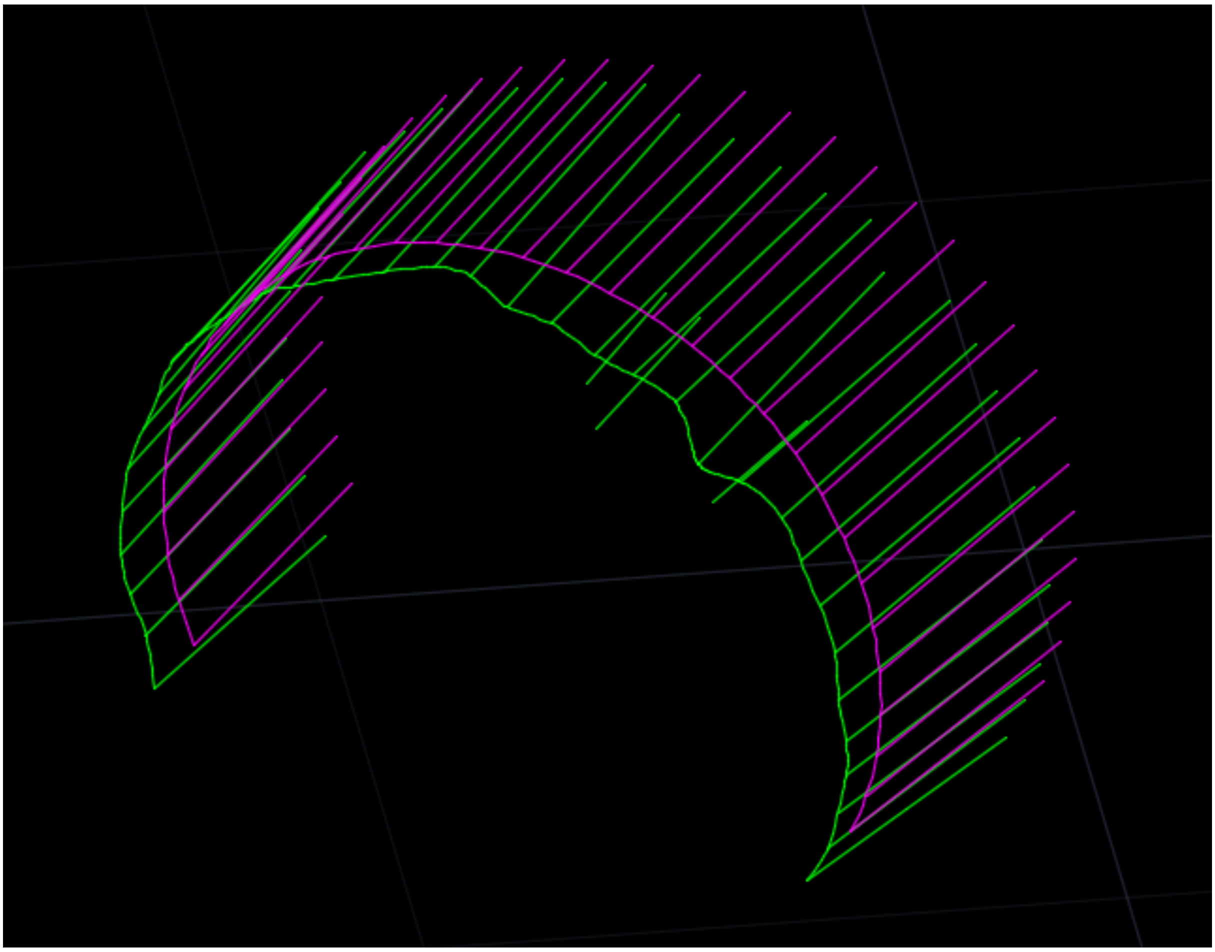


Figure 4.2 Drilling pattern and MWD data

Without any precise answer from the coordinate providers about the rotation of the coordination sets, it is hard to estimate which coordinate system is correct. For that reason, calculation of the drilling accuracy presented in this thesis, should only be considered in the informational way

Deviation of the drilling was calculated only in the direction normal to the theoretical contour. Deviation parallel to the contour was not taken under consideration, due to the fact that it was impossible to compare coordinates of the drilled holes with the planned starting position of each hole.

Spacing of the drilling holes in the contour was checked for seven rounds before test stretch and for the test rounds as well. Also distances from drilling holes in starting position, middle point and end of the hole to the theoretical tunnel contour were checked for all pre-test and test rounds of tunnel excavation. A comparison of the drilling pattern and MWD was checked for seven rounds with non-electric detonators and because the reason of the rotation of the coordinates sets was unknown and repeated in every checked round, it was not evaluated for the electronic detonators rounds.

For a few rounds, the deflection of the rod was also measured, but the results were not used in this thesis since there was not enough data and it was too complicated to apply the acquired results. Global coordinates of the drilled hole end from MWD data were calculated on the base of starting position, depth and angle of the drilling rod.

Due to the fact that MWD data registered all drilling operation it was necessary to choose right holes for the estimation. Only holes over 4 m were taken into consideration for the analysis. Contour holes with a length shorter than 4 m were rejected from all calculations.

Two last rounds of electronic detonators rounds were drilled with the 60 mm drillhole diameter.

4.2 SPACING AND LENGTH OF THE CONTOUR HOLES

4.2.1 RESULTS

Normal spacing of the contour holes in this project is 70 cm measured from center of the drill hole to center of the neighboring hole. For seven rounds with non-electric detonators and five rounds with electronic detonators, data from GPM+ software were collected and local coordinates and length of the holes were analyzed. Results are presented in the Table 4.1. For the calculation of the average length and spacing of the contour holes, arithmetic mean formula was used.

Round		Average per round		Average	
		Spacing [cm]	Length [m]	Spacing [cm]	Length [cm]
NO-TEST	1320	71	5.401	71	5.381
	1326	71	5.549		
	1331	70	5.239		
	1337	73	5.446		
	1342	72	4.745		
	1347	72	5.429		
	1410	71	5.855		
TEST	1442	72	5.277	71	5.349
	1447	71	5.342		
	1452	71	5.227		
	1457	70	5.632		
	1462	71	5.267		

Table 4.1 Spacing and length of the contour holes

The average spacing for seven rounds before electronic detonators test was equal to 69 cm. The highest average spacing between contour holes was observed in round 1337 and it was 73 cm. The shortest distances between centers of the neighboring holes were in round 1342, where average spacing was equal to 65 cm.

For rounds where electronic detonators were used, average spacing of all five test rounds was equal to 71 cm. Results from those rounds are very similar to each other. Three out of five have spacing equal to the average. Only one round, 1457, had average spacing exactly 70 cm. First test round had longest distances between contour holes with mean value equal to 72 cm.

Average distances for all analyzed rounds were equal to 71 cm for both non-electric detonators and electronic detonators rounds. Deviation from actual distances of the centers of holes to desired spacing equal to 70 cm for the contour is ±1%.

Calculation of the average length of the contour holes for non-electric detonators rounds shows that the shortest drillholes were executed in round 1331 with mean length of 5.239 m and the longest in round 1410 with length of 5.855 m. The average contour holes' length for those seven rounds was 5.381 m. For electronic detonators the shortest average length of the hole had round 1452 with 5.227 m and the longest round 1457 with length 5.632. The average drillhole length for test rounds was 5.349 m.

4.2.2 ANALYSIS AND DISCUSSION

As it is presented in Table 4.2 the percentage difference between average values of the spacing and 70 cm requirement vary from 0% to 4%, where in round 1337, where the difference is the biggest, actual spacing of the holes was only 3 cm different. Differences of the spacing both for non-electric and electronic detonators were similar and accuracy of the spacing can be considered as accurate.

Round		Average per round		Average		Difference	
		Spacing [cm]	Length [m]	Spacing [cm]	Length [cm]	Spacing	Length
NO-TEST	1320	71	5.401	71	5,381	1%	4%
	1326	71	5.549			1%	7%
	1331	70	5.239			0%	1%
	1337	73	5.446			4%	5%
	1342	72	4.745			3%	9%
	1347	72	5.429			3%	4%
	1410	71	5.855			1%	13%
TEST	1442	72	5.277	71	5.349	3%	1%
	1447	71	5.342			1%	3%
	1452	71	5.227			1%	1%
	1457	70	5.632			0%	8%
	1462	71	5.267			1%	1%

Table 4.2 Summary of the spacing and drilling length results

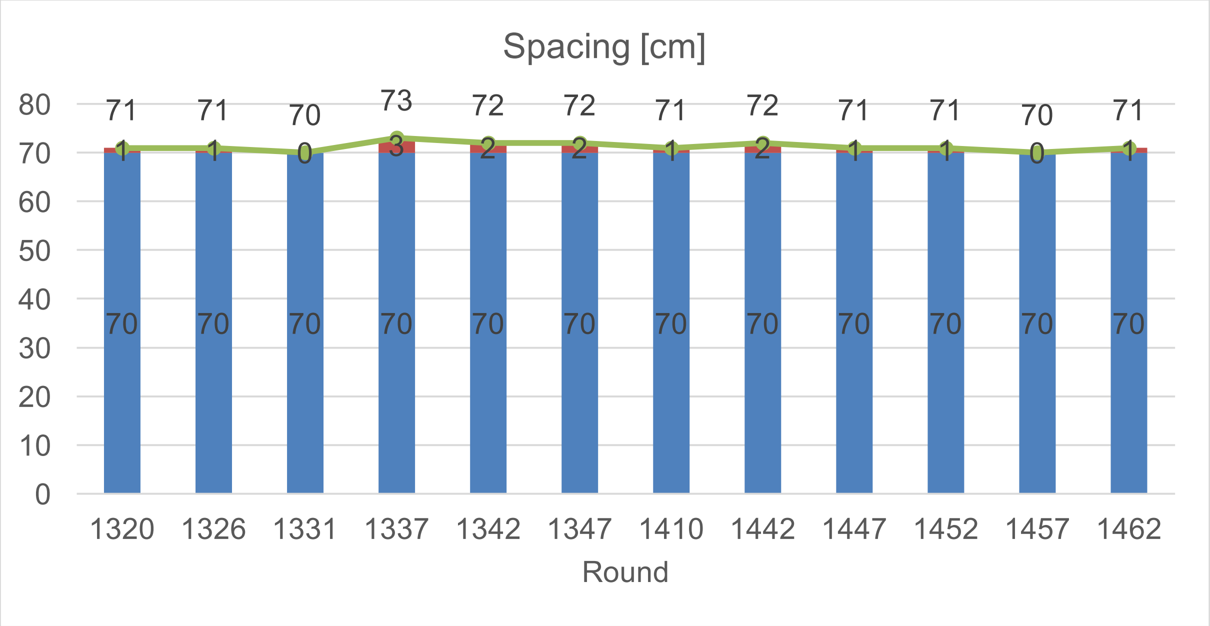


Figure 4.3 Graphical presentation of average spacing per round

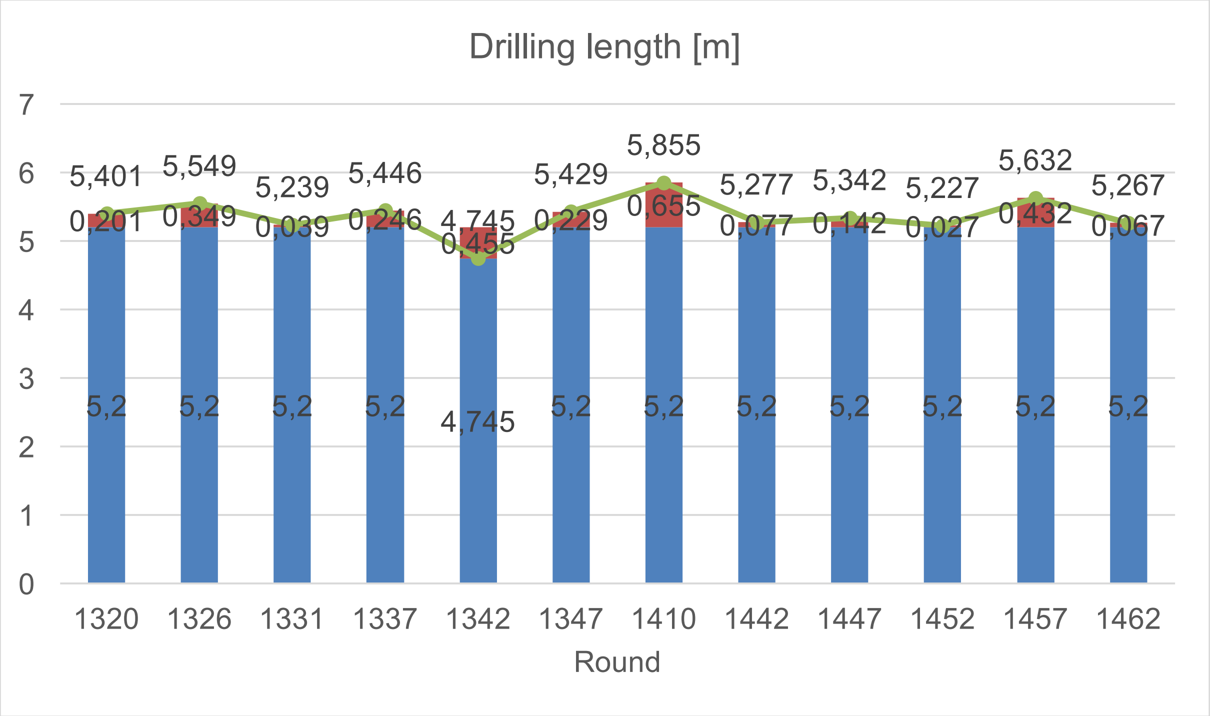


Figure 4.4 Graphical presentation of average drilling length per round

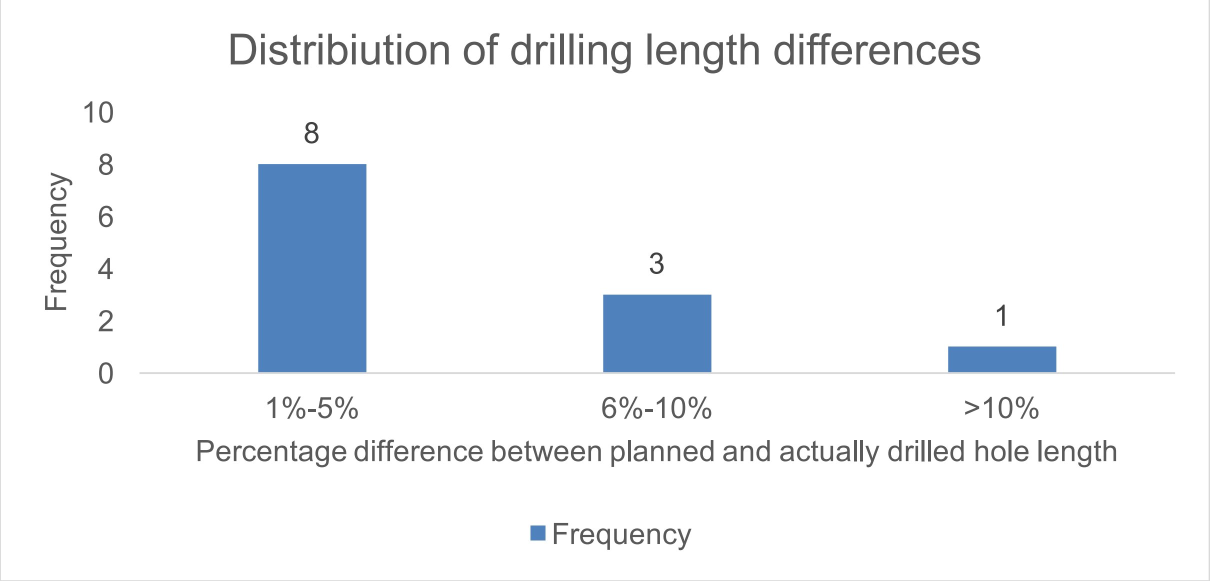


Figure 4.5 Distribution of drilling length differences

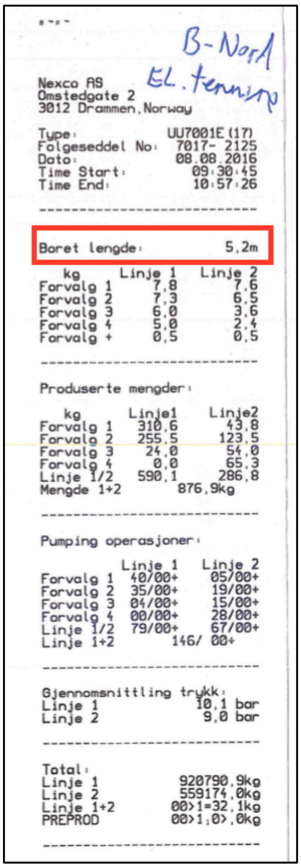
Results from average drilling length calculation showed more variations than results from spacing calculation. 11 out of 12 results from MWD data have greater length of the actually drilled holes than 5.2 meters, what was registered on the charging logs. As it is presented in the Table 4.2, difference between lengths vary from 1% to 13%. The biggest difference – 13%, corresponding to 65.5 cm was in the last non-electric round. That was the only one round with length difference over 10%. Most of the results (67%) had difference between 1%

to 5%. From electronic detonators rounds, where bigger accuracy was required, only one round had length 8% greater than assumed 5.2 m, rest of the results were within 1 to 3% difference. Only one round from the non-electric detonators rounds had average length shorter than assumed and difference from 5.2 m from logs was around 9%.

To assure the proper distribution of the explosive material in the hole the accuracy of the drilling length is necessary. It is caused by the fact that charging setting are preprogrammed and amount of explosives is calculated for specific length of the hole. When the hole length is bigger than assumed, there is a chance that material could be not distributed on the adequate length or the amount of explosives per meter would be lower than assumed. It might lead to underbreak and result in the need for re-blasting or increased scaling of the remaining rock mass.

In case of a too-short drilling length the effect could be opposite and accumulation of explosives in the hole could be bigger. It might lead to overbreak and decrease of tunnel contour quality. It is also connected with need for bigger amount of rock support.

Except for one round 1410 with 13% length difference from the charging logs drilling length, drilling in terms of the length accuracy could be assumed as satisfactory.



B-Nord
El. tenning

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Nexco AS
Omstedgate 2
3012 Drammen,Norway

Type:                UU7001E(17)
Folgeseddel No:   7017- 2125
Dato:               08.08.2016
Time Start:           09:30:45
Time End:             10:57:26

----------------------------

Boret lengde:             5,2m
    kg       Linje 1   Linje 2
Forvalg 1        7,8       7,6
Forvalg 2        7,3       6,5
Forvalg 3        6,0       3,6
Forvalg 4        5,0       2,4
Forvalg +        0,5       0,5

----------------------------

Produserte mengder:

    kg        Linje1    Linje2
Forvalg 1     310,6      43,8
Forvalg 2     255,5     123,5
Forvalg 3      24,0      54,0
Forvalg 4       0,0      65,3
Linje 1/2     590,1     286,8
Mengde 1+2        876,9kg

----------------------------

Pumping operasjoner:

             Linje 1   Linje 2
Forvalg 1   40/00+     05/00+
Forvalg 2   35/00+     19/00+
Forvalg 3   04/00+     15/00+
Forvalg 4   00/00+     28/00+
Linje 1/2   79/00+     67/00+
Linje 1+2        146/ 00+

----------------------------

Gjennomsnittling trykk:
Linje 1               10,1 bar
Linje 2                9,0 bar

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Total:
Linje 1            920790,9kg
Linje 2            559174,0kg
Linje 1+2          00>1=32,1kg
PREPROD            00>1;0>,0kg
----------------------------
```

Figure 4.6 Charging log

4.3 STARTING POSITION OF THE HOLES

4.3.1 RESULTS

In Table 4.3 are presented results from analysis of the global coordinates from MWD data. Calculations of the average distances from starting position of the hole to theoretical tunnel contour were divided into two groups. The first, average distance, is containing mean distance of only drilled holes which starting position was outside the tunnel contour. In the second group, named absolute average, distances from the holes inside the theoretical contour were also included in the calculation.

For all rounds with non-electric detonators for holes outside the contour, average distance from starting position was 15.7 cm. The absolute average, including holes with starting position inside the contour, was equal to 15.3 cm. From those seven rounds, drilling of round 1410 was executed with the highest precision of the holes positioning. The average distance was equal to 10.4 cm and absolute average to 9.6 cm. The highest average of the distances was calculated for rounds 1347 and it was equal to 20.3 cm. The value of absolute average was the same, due to the fact that all holes were drilled outside the theoretical contour. Similar results were achieved for round 1342 where both mean values were equal to 20.2 cm.

Considering requirements of maximum deviation of the starting position of the holes from the Handbook R761 and special request of FoU program, the most accurate drilling was performed in round 1410. 20 out of 32 contour holes were drilled in the distance not bigger than 10 cm from theoretical contour and all 32 holes were placed in the area 20 cm outside the contour. From the least accurate drilling rounds, both 1342 and 1347 can be considered as similarly inaccurate, with none or two holes drilled in the distance from the contour required by FoU program. For those rounds only 13 (1342) and 16 (1347) holes out of 32 were drilled in the distance described as acceptable by the Handbook R761.

In some cross sections, starting position of the holes was registered inside the contour. Considering fact, that holes supposed to be drilled outside the contour and usually distance from the theoretical contour to the center of those holes was not big, those values were not taken under consideration in the average distance. As it is showed in the Table 4.3 below, the absolute average distance is lower than average distance. In general, there were 20 holes drilled inside the theoretical contour: 12 for non-electric detonators rounds and 8 in test stretch. The highest distance for first 7 rounds was 13.5 cm and the shortest 0.8 cm. For the electronic detonators rounds the longest distance was 12 cm and the shortest 0.2 cm.

Round		Average distnace		Absolute average		Number of holes with starting position		
		per round	per set	per round	per set	≤ 10 cm	≤ 2 cm	inside
NO-TEST	1320	0.119	0.158	0.115	0.154	11	31	1
	1326	0.116		0.109		9	27	5
	1331	0.178		0.173		0	24	1
	1337	0.177		0.177		2	23	0
	1342	0.202		0.202		2	13	0
	1346	0.203		0.203		0	16	0
	1410	0.109		0.099		13	25	5
TEST	1442	0.208	0.174	0.208	0.169	0	12	0
	1447	0.193		0.193		2	19	0
	1452	0.158		0.158		6	24	0
	1457	0.142		0.125		9	21	5
	1463	0.170		0.161		5	22	3

Table 4.3 Starting position of the contour holes

The average distance of the starting position of the holes for the electronic detonators rounds was 17.4 cm. The absolute average, including 8 holes drilled in the theoretical contour was equal to 16.9 cm. From five test rounds, the most accurate drilling, with 9 holes drilled according to FoU program requirement, was observed for round 1457. Also for this round, average distances of placement of the holes is the lowest and it is equal to 14.2 cm. Round 1442 had the least accurate drilling from all test rounds. Due to the fact that none of the holes was drilled inside the contour the average distance and absolute average distance had the same value and were equal to 2.8 cm. In this round none of the hole was drilled in the FoU required maximum distance and only 12 out of 33 holes were drilled in the Handbook R761 requirement.

4.3.2 ANALYSIS AND DISCUSSION

In Table 4.4 and Table 4.5 below is presented distribution of drilling holes starting positions. Data was separated into three groups. The first group shows holes with a starting position placed in the distance of maximum 10 cm from theoretical contour. Second are holes with starting position distanced between 10 and 20 cm from theoretical contour. Third group represents holes drilled in distance bigger than 20 cm from theoretical contour. For this estimation, holes drilled inside the theoretical contour were not taken under consideration.

(RYSUNEK PODZIAŁU GRUP)

Round	Total number of holes	Number of holes:				
		inside	≤ 10 cm	10< ≤ 20 cm	≤ 20 cm	outside
1320	32	1	11	20	31	0
1326	32	5	9	18	27	0
1331	34	1	0	24	24	9
1337	32	0	2	21	23	9
1342	32	0	2	11	13	19
1347	32	0	0	16	16	16
1410	32	5	13	12	25	2
Sum:	226	12	37	122	159	55

Table 4.4 Distribution of starting position of the contour holes – non-electric detonators

Round	% inside	% ≤ 10 cm	% 10< ≤ 20 cm	% ≤ 20 cm	% outside
1320	3%	34%	63%	97%	0%
1326	16%	28%	56%	84%	0%
1331	3%	0%	75%	75%	26%
1337	0%	6%	66%	72%	28%
1342	0%	6%	34%	41%	59%
1347	0%	0%	50%	50%	50%
1410	16%	41%	38%	78%	6%
Sum:	5%	16%	54%	70%	24%

Table 4.5 Percentage distribution of the starting positions of the contour holes – non-electric detonators

In all seven rounds of non-electric detonators 12 holes were drilled inside the theoretical contour what is corresponding to 5% of all drilled holes. Calculation of starting position distances showed that most of the holes - 54%, were placed between 10 and 20 cm from the theoretical contour. Outside the area accepted by the Handbook R761 were placed 55 holes, what equals to 24% of all drilled holes. Only 16% of the holes was drilled in the distance not bigger than 10 cm from contour required by FoU program in Bjørnegård tunnel. Distribution of the distances of starting position of the holes drilled outside the contour is presented in Figure 4.7

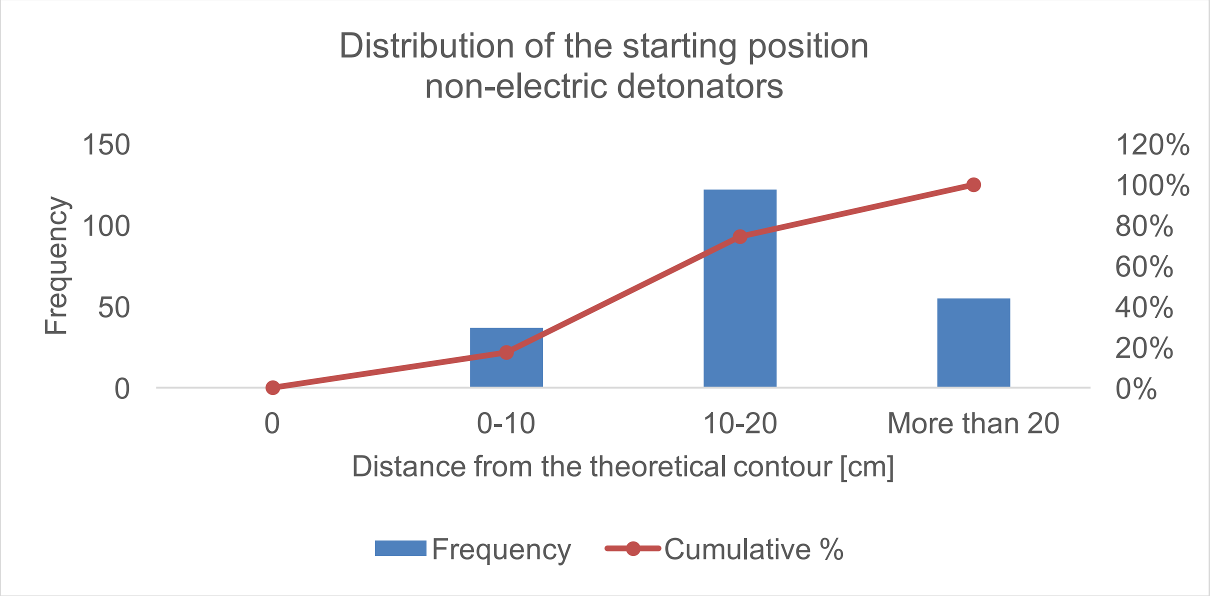


Figure 4.7 Distribution of the starting position of the contour holes – non-electric detonators

As mentioned before, for electronic detonators test special accuracy of drilling was requested. Results presented in the Table 4.7 shows that only 13% of all drilled holes met the requirements of 10 cm maximum distance from theoretical contour.

Round	Total number of holes	Number of holes:				
		inside	≤ 10 cm	10< ≤20 cm	≤ 20 cm	outside
1442	33	0	0	12	12	21
1447	33	0	2	17	19	14
1452	33	0	6	18	24	9
1457	33	5	9	12	21	7
1463	33	3	5	17	22	8
Sum:	165	8	22	76	98	59

Table 4.6 Distribution of starting position of the contour holes – electronic detonators

Round	% inside	% ≤ 10 cm	% 10< ≤ 20 cm	% ≤ 20 cm	% outside
1442	0%	0%	36%	36%	64%
1447	0%	6%	52%	58%	42%
1452	0%	18%	55%	73%	27%
1457	15%	27%	36%	64%	21%
1463	9%	15%	52%	67%	24%
Sum:	5%	13%	46%	59%	36%

Table 4.7 Percentage distribution of the starting positions of the contour holes – electronic detonators

Almost half of the holes drilled within the test stretch were drilled with starting position placed in distance from 10 to 20 cm from theoretical tunnel contour. 36% of all holes were drilled outside the 20 cm distance accepted by the Handbook R761.

Distribution of distances of starting position of the holes for actual test stretch is presented in Figure 4.8 below.

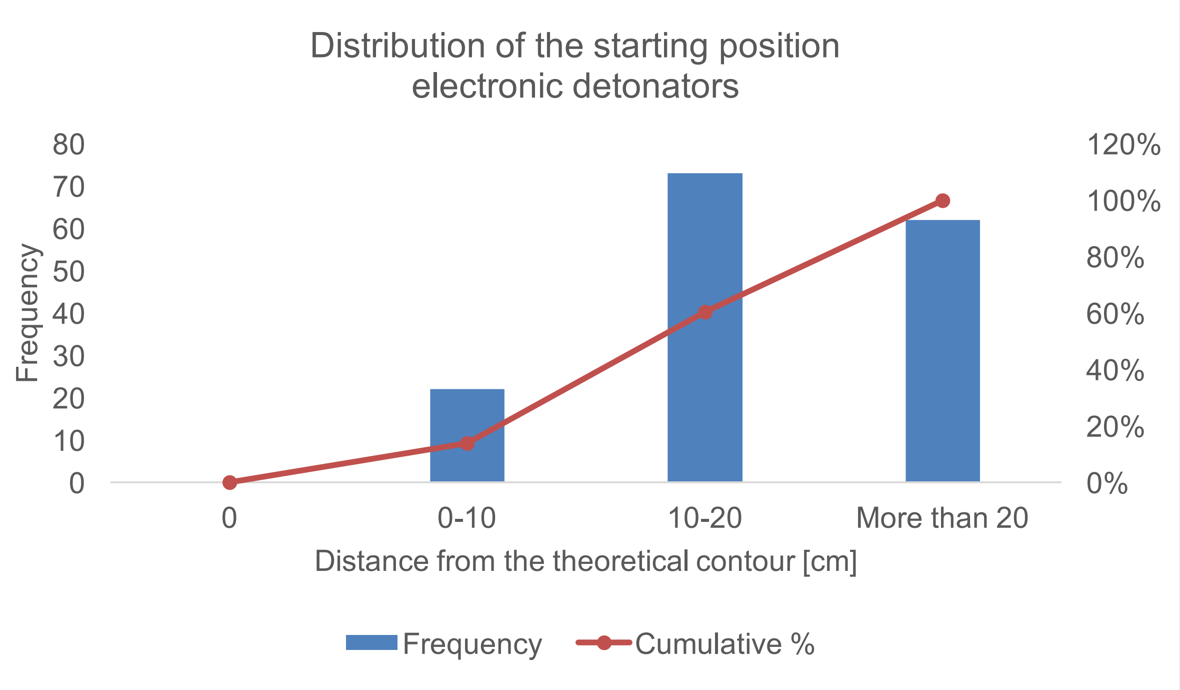


Figure 4.8 Distribution of the starting position of the contour holes – electronic detonators

Results from non-electric and electronic detonators rounds are presented on the Figure 4.9 below. As it is shown on the graphs, even though there was stricter accuracy requirement put on the electronic detonators rounds, drilling of the holes usually started in greater distance from the theoretical contour than it was requested. Electronic detonators rounds had 5 percentage points less holes drilled in the requested maximum 10 cm distance than it was registered for non-electric detonators rounds. At the same time, percentage of holes drilled outside the 20 cm distance accepted by the Handbook R761 was higher by 12 percentage points for test rounds.

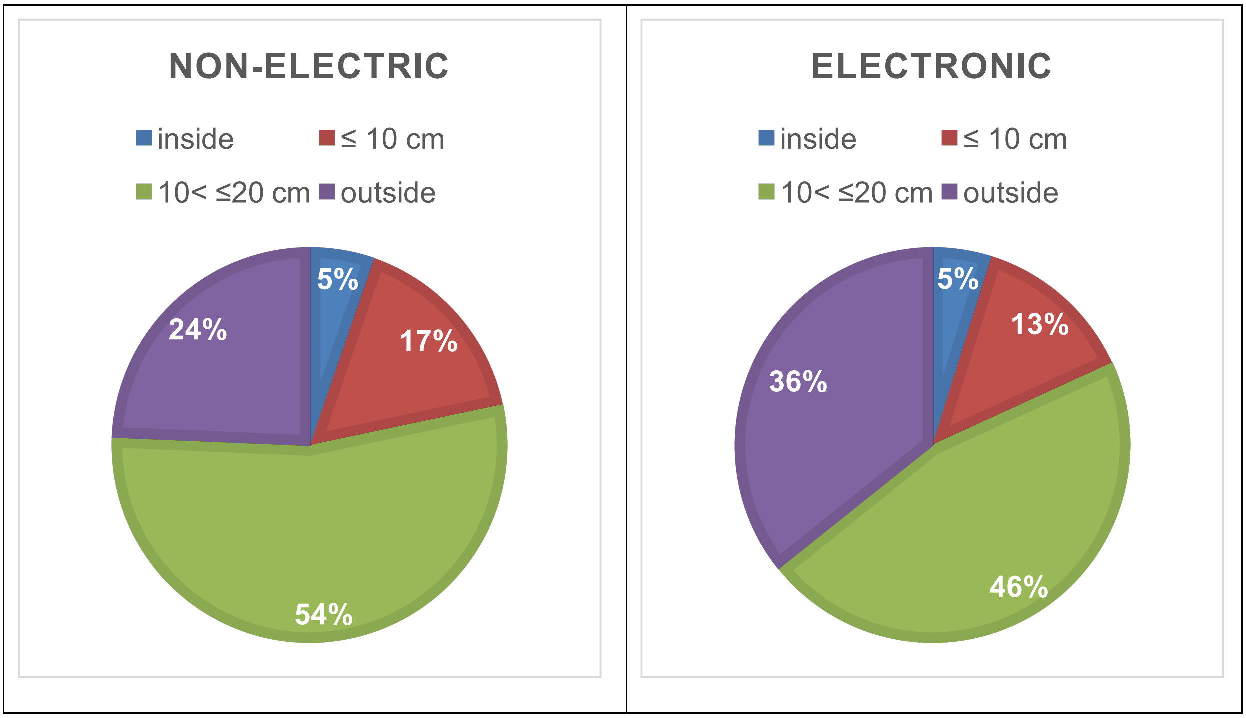


Figure 4.9 Proportion of the starting position of the contour holes

Considering fact that result for electronic detonators rounds shows lower percentage of holes drilled in the required distance and higher percentage of holes drilled outside the accepted distance, accuracy of the drilling can be rated as poor.

4.4 END POSITION OF THE HOLES

Due to the fact that in following chapter concerning scanning results only holes drilled outside the contour were taken under consideration for the analysis, the main focus was put on those type of holes. Although, the end position results both for average distances and absolute average including holes that have starting position inside the theoretical contour are presented in this chapter. End position is defined as the shortest distance from the end of the drilling hole to the theoretical contour. In this thesis look-out is defined as difference between distances of end and start position of the hole

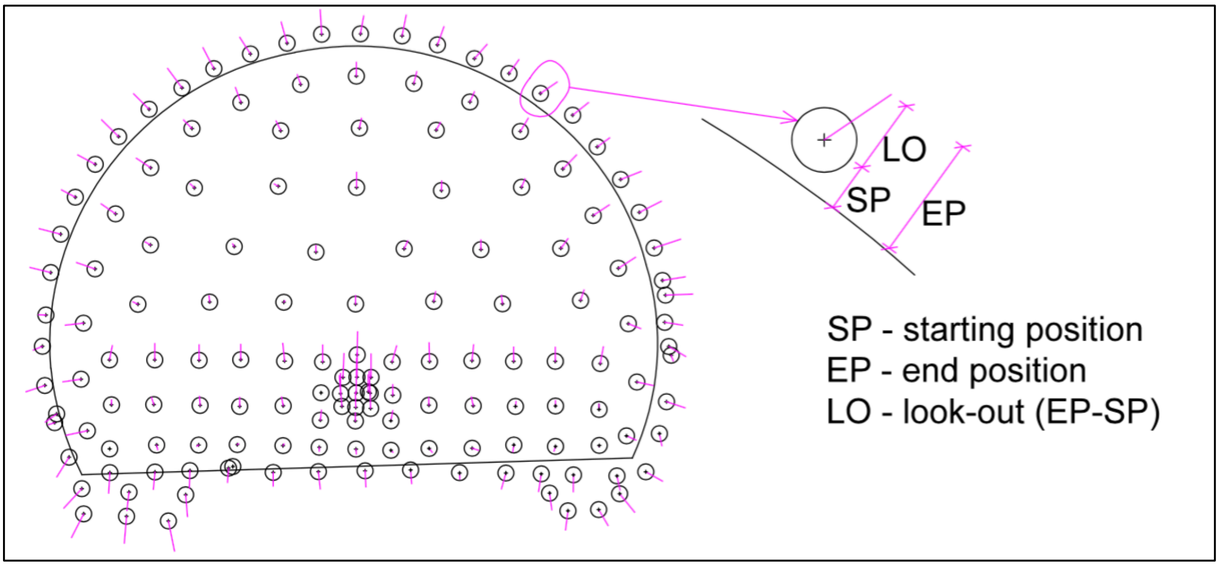


Figure 4.10 Definition of starting position, end position and look-out of the hole

4.4.1 RESULTS FROM NON-ELECTRIC DETONATORS ROUNDS

Below, in Table 4.8 are presented results from calculation of end position of the drilling holes. Even though for calculation of the average distance holes with the starting position inside the theoretical contour were not considered, both: average distance and absolute average from all non-electric detonators rounds, have the same value of 519 mm. Round with the biggest averages equal to 579 mm is round 1347. From non-electric detonators round, round 1326 had end of the drilled holes closest to the theoretical contour. The average distance in this round was equal to 445 mm and absolute average to 435 mm.

Considering starting position of the holes, average look-out for all seven rounds was 359 mm and absolute average – 365 mm. The biggest look-out was observed in round 1410 – 444 mm for average results and 463 mm for absolute average results. The smallest difference between end and start position was calculated for round 1337, where both averages were equal to 320 mm.

Round	Start position		End position		Look-out	
	average [cm]	absolute aveage [cm]	average [cm]	absolute aveage [cm]	average [cm]	absolute aveage [cm]
1320	0.119	0.115	0.472	0.473	0.353	0.357
1326	0.116	0.109	0.445	0.435	0.329	0.326
1331	0.178	0.173	0.524	0.528	0.346	0.355
1337	0.177	0.177	0.497	0.497	0.320	0.320
1342	0.202	0.202	0.558	0.558	0.357	0.357
1347	0.203	0.203	0.579	0.579	0.376	0.376
1410	0.109	0.099	0.552	0.562	0.444	0.463
Average:	0.158	0.154	0.519	0.519	0.359	0.365

Table 4.8 Start position, end position and look-out compilation – non-electric detonators

4.4.2 RESULTS FROM ELECTRONIC DETONATORS ROUNDS

For all five rounds of electronic detonators the average of end position of the hole is 495 mm. Absolute average including holes started inside the theoretical contour is 491 mm. From this data set, the biggest distances were observed for round 1462 with average equal to 601 mm and absolute average – 587 mm. Rounds 1452 and 1457 had similar results and the average distance was 447 mm and 446 mm respectively and absolute average 447 mm and 440 mm. Average difference between start and end position of the hole was between 431 mm (1462) and 289 mm (1447). The averages for all seven rounds were 319 mm and 322 mm.

Round	Start position		End position		Look-out	
	average [cm]	absolute aveage [cm]	average [cm]	absolute aveage [cm]	average [cm]	absolute aveage [cm]
1442	0.208	0.208	0.498	0.498	0.290	0.290
1447	0.193	0.193	0.482	0.482	0.289	0.289
1452	0.158	0.158	0.447	0.447	0.290	0.290
1457	0.142	0.125	0.446	0.440	0.304	0.315
1463	0.170	0.161	0.601	0.587	0.431	0.425
Average:	0.175	0.169	0.495	0.491	0.319	0.322

Table 4.9 Start position, end position and look-out compilation – electronic detonators

4.4.3 ANALYSIS AND DISCUSSION

There was no special requirement specified for the FoU program for the maximum distances of the end of the drilled holes from the theoretical contour. Neither there were none guidelines on that matter found in the literature.

Analysis of the averages from non-electric and electronic detonators rounds shows no big difference between achieved results. Comparing to non-electric detonators rounds, the averages of distances of the end position of the holes in electronic detonators rounds were only 5% shorter. Bigger results difference was observed for look-out, where deviations between test rounds and rounds before, were around 11%. Only the average distances of starting positions of the holes were 10% bigger in electronic detonators rounds than in non-electric.

Even though the percentage difference of distances varies from 5 to 12%, the numerical values are not bigger than 4.3 cm. It can be considered as an insignificant factor for accuracy estimation. Results presented in this section have informative character.

	Start position		End position		Look-out	
	average [cm]	absolute aveage [cm]	average [cm]	absolute aveage [cm]	average [cm]	absolute aveage [cm]
NO-TEST	0.158	0.154	0.519	0.519	0.359	0.365
TEST	0.175	0.169	0.495	0.491	0.319	0.322
Difference [cm]	-0.018	-0.015	0.025	0.028	0.040	0.043
Difference	-11%	-10%	5%	5%	11%	12%

Table 4.10 Compilation of the results: starting position, end position, look-out

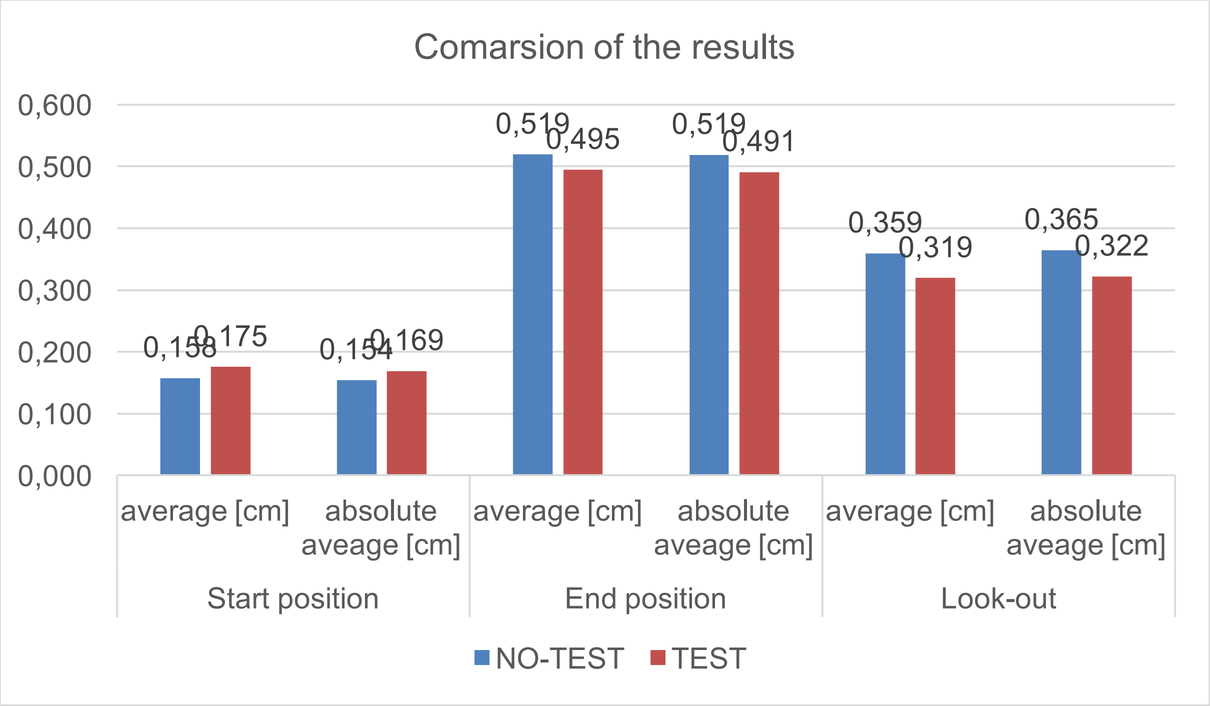


Figure 4.11 Graphical comparison of the results

4.5 SUMMARY OF THE DRILLING

Data analyzed in this chapter was divided into two groups: local coordinates used for the estimation of the spacing and length of the contour holes, and global coordinates used for the calculation of the start and end position of the holes. Both groups of data were MWD data and came from the same source.

The comparison of the deviation of the actual and planned starting position of the drilling holes was not possible, since the global coordinates from the drilling pattern and the MWD data did not correspond. Most likely the problem was with the reference of the coordinates systems; nevertheless, during the investigation of the source of the issue, no proper explanation was received.

From the received data average spacing of the contour holes was calculated. Results present only small variation of the calculated average spacing from the theoretical assumption both for electronic and for non-electric detonators rounds. Likewise, calculation of the average drilling length showed small variations from the designed holes length. Drilling accuracy in terms of spacing and drilling length could be assumed as satisfactory. Summary of the results from this section is presented in Table 4.11 below.

	Spacing		Length	
	[cm]	percentage	[cm]	percentage
NO-TEST	71	1%	5.381	3%
TEST	71	1%	5.349	3%

Table 4.11 Spacing and length summary

Calculation of the starting position of the holes showed that average distance of the holes drilled outside the contour length was 15.8 cm for non-electric and 17.4 cm for electronic detonators rounds. Even though for the test of the electronic detonators special accuracy of maximum 10 cm distance from the theoretical contour was requested, only 13% of all drilled holes met the requirement. Most of the holes were drilled with the starting position within 10 to 20 cm from the contour line. For rounds before test it was 54% of all drilled holes and for the actual test rounds – 74%. A relatively large amount of holes was drilled outside the 20 cm Handbook R761 requirement. 24% of holes drilled in rounds with non-electric detonators and 36% in test rounds were drilled in distance greater than 20 cm from theoretical contour. Based on the results from calculation of the starting position of the it can be stated that drilling accuracy did not meet the requirements.

The last part of the analysis was focused on the estimation of the end position and look-out of the drilled holes. Hence there was not any special requirements for the maximum distance of the end of the drilling holes to the theoretical contour, calculated averages could not be compared to any limit values. Achieved results have informative character and are shown in Table 4.12 both with the results from starting position calculation.

	Start position				End position	Look-out
	[m]	% ≤ 10 cm	% ≤ 20 cm	% outside		
NO-TEST	0,158	16%	54%	24%	0.519	0.359
TEST	0,174	13%	74%	36%	0.495	0.319

Table 4.12 Starting position, end position and look-out summary

5 SCANNING

5.1 ASSUMPTIONS FOR THE SCANNING ANALYSIS

Scanning performed in Bjørnegård tunnel can be considered as a high technology process. Precise scans give very accurate 3D model of the excavated tunnel which can be used for geometrical and visual estimation of the scanned tunnel surface.

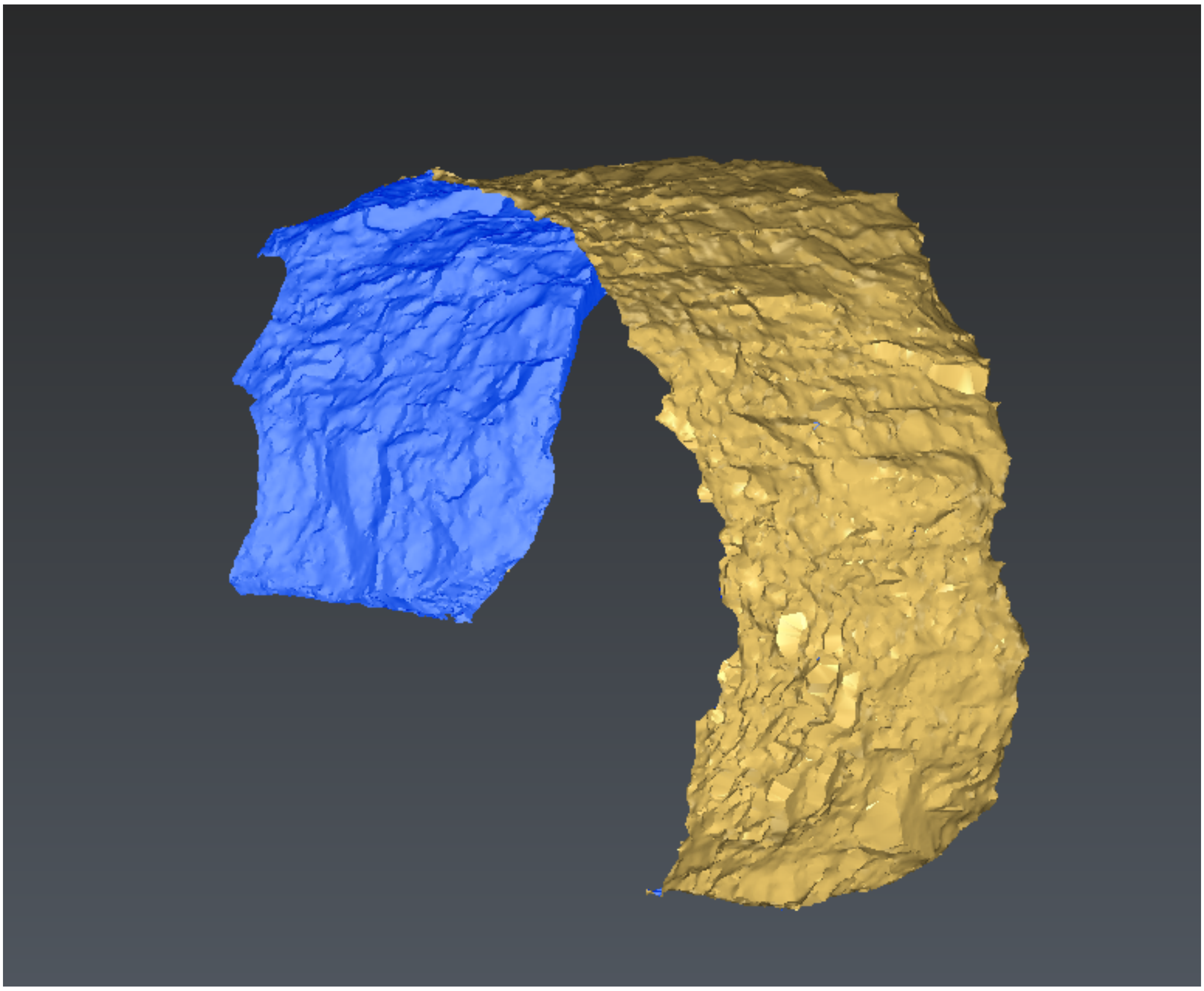
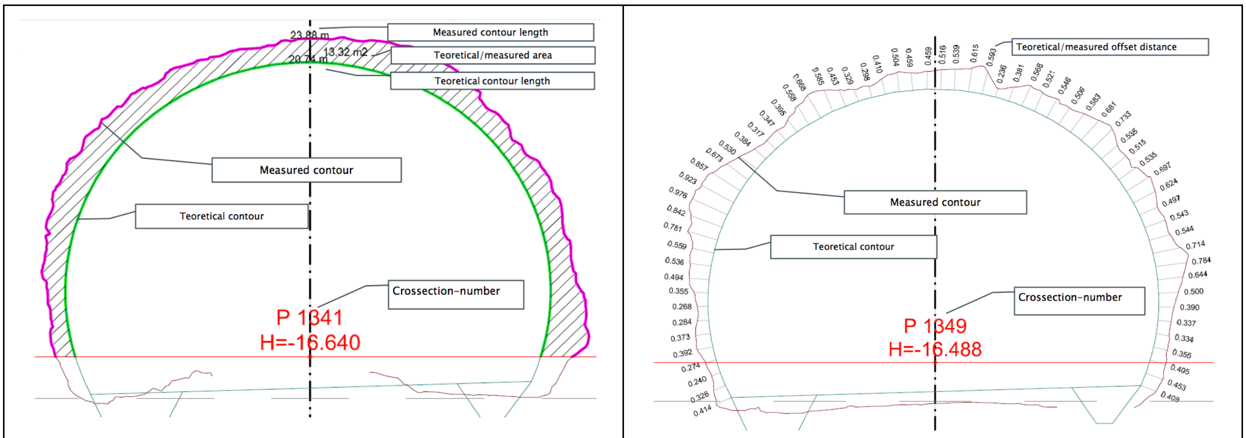


Figure 5.1 3D model from scanning

In this thesis calculation and tunnel contour analyses were executed for cross sections for every 0.5 m. Form of the results outcome is shown in the Figure 5.2



(i) Overblasted area and contour length

(j) Overbreak

Figure 5.2 Scanning outcome

To ensure uniform scanning results, a line 1 m above the center of the bottom of the tunnel profile was added. Only data above this line was considered for the analyses. This was caused by the fact that even though scanning was performed after removal of the blasted rock, in some places there were remains of the material left on the sides. Since the scanner is measuring distances to visible surfaces and mentioned above rock was not part of the tunnel contour, scanning data from the bottom of the profile could give incorrect results.

Some of the scanned cross sections had to be rejected from the calculation because data was damaged. This was due to the fact that the scanner was placed a few meters in front of the tunnel face under an already applied rock support. Scans of the contour surface after blasting had to be separated manually from the scans of the rest of the tunnel. Since the line of the shotcrete applied in the previous rounds is not regular, sometimes results from the beginning of the round were not complete. Also some scans form the end of the round had to be rejected by the reason of not regular tunnel face.

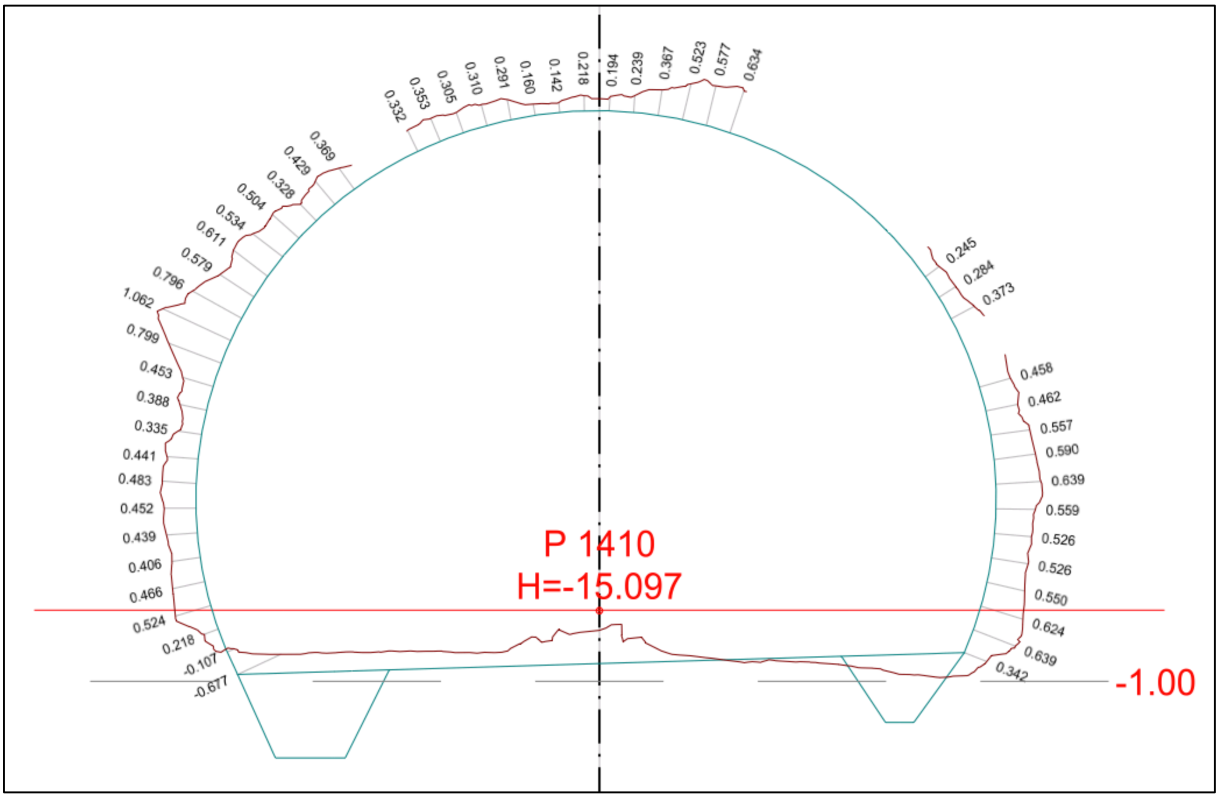


Figure 5.3 Example of rejected profile

Number of scanned cross sections with the results acceptable for calculation varies for most of the rounds as shown in Table 5.1 and Table 5.2

	Non-electric detonators						
Round	1320	1326	1331	1337	1342	1347	1410
Q-value	8,8	14	20	16	10	6,2	2,2
Number of profiles	10	11	11	11	7	8	10

Table 5.1 Number of scanned profiles – non-electric detonatros

	Electronic detonators				
Round	1441	1447	1452	1457	1462
Q-value	3,1	3,1	3,1	2,8	2,5
Number of profiles	11	9	9	10	7

Table 5.2 Number of scanned profiles – electronic detonators

Scanning of the tunnel for electronic detonators rounds was performed both before and after scaling, but in this thesis only results from scanning after scaling were used for unification of the results.

Separation of the profiles from scanning results into rounds sets was done based on the information from diaries of Statens vegvesen quality engineers.

5.2 CONTOUR LENGTH

5.2.1 RESULTS FROM NON-ELECTRIC DETONATORS ROUNDS

Contour length results analyzed in this thesis are the average of the results from each blasting round. The analysis was done separately for non-electric and electronic detonators rounds. Table 5.3 presents results from contour length analysis for non-electric detonators rounds.

The length of the theoretical tunnel contour calculated above the additional line was 20.74 m. Average length of all analyzed cross sections is 23.60 m, what gives average 2.86 m longer contour. The ratio of actual contour length to planned contour length (RCL) for all blasting rounds is equal to 1.14, meaning a 14% difference in contours lengths. The round with the smallest difference between both contours was the first scanned round, 1320, with RCL equal to 1.09 and average difference of 1.92 m. Round with the highest ratio of the lengths is the last round of non-electric rounds with RCL found to be 1.20. That gives 20% difference between the contours.

Round	Theoretical contour length [m]	Average contour length [m]	Average difference [m]	Average RCL	Average percentage difference
1320	20,74	22.66	1.92	1.09	9%
1326		22.76	2.02	1.10	10%
1331		23.31	2.57	1.12	12%
1337		23.74	3.01	1.14	14%
1342		23.89	3.16	1.15	15%
1347		24.20	3.47	1.17	17%
1410		24.92	4.19	1.20	20%

Table 5.3 Contour length – non-electric detonators

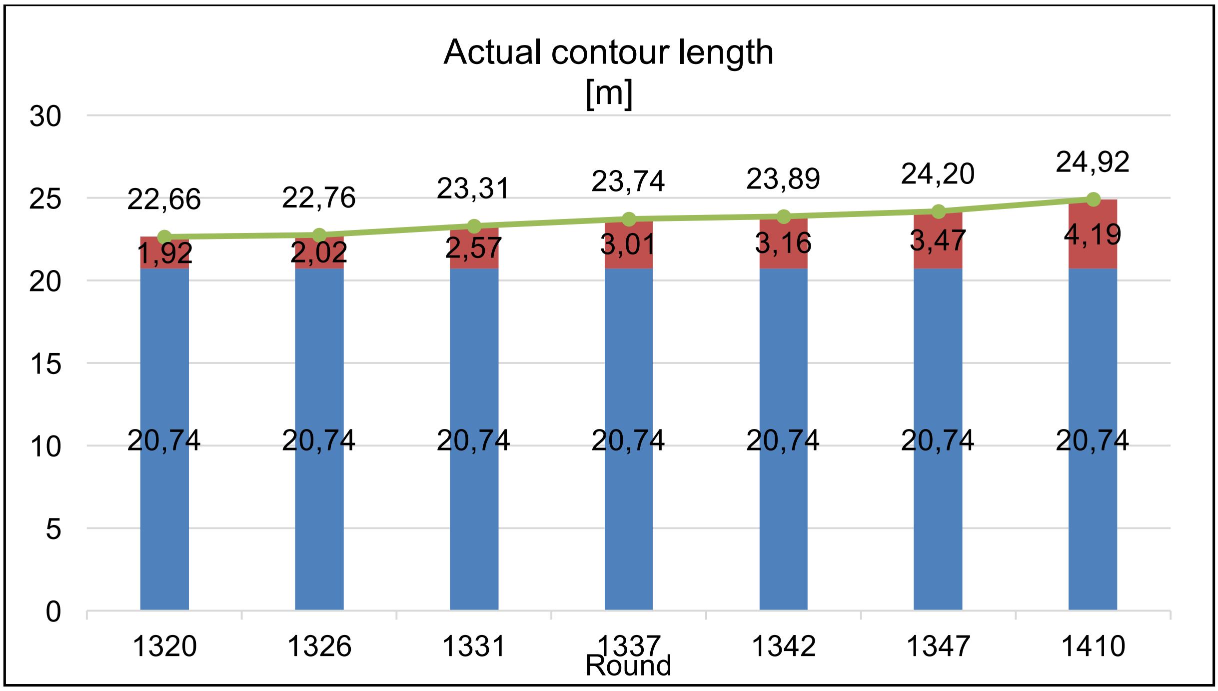


Figure 5.4 Graphical presentation of contour length – non-electric detonators

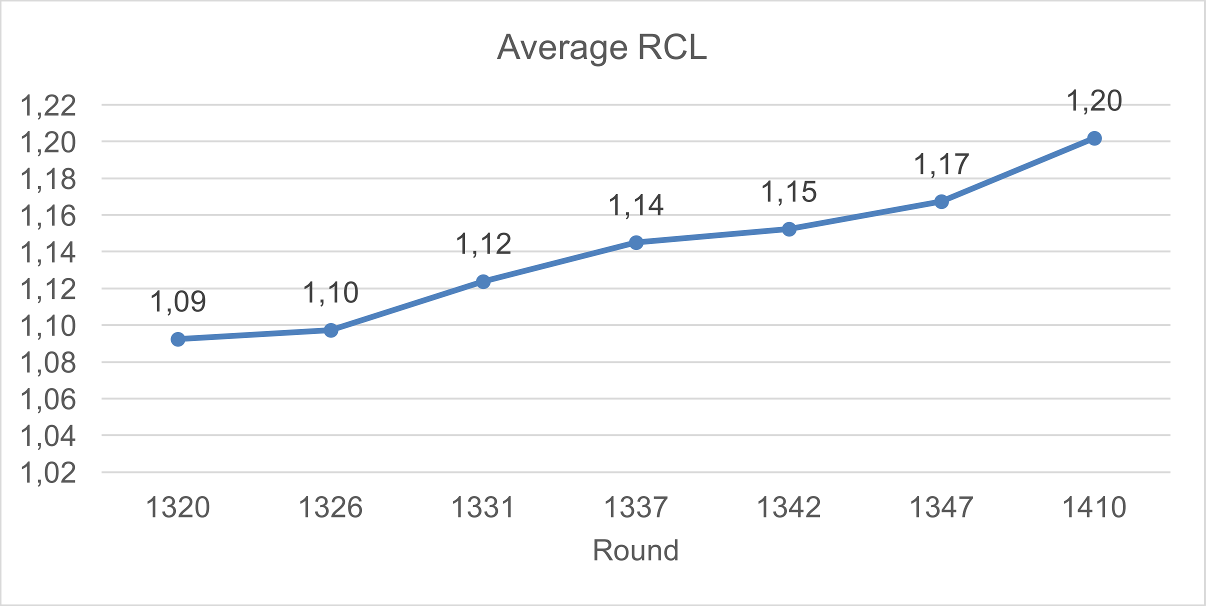


Figure 5.5 Average RCL – non-electric detonators

5.2.2 RESULTS FROM ELECTRONIC DETONATORS ROUNDS

Table 5.4 presents results from electronic detonators rounds. The average contour length for all five rounds was 24.19 m, which gives a 3.45 m difference from the theoretical contour length. Average RCL for the test stretch is 1.17. All rounds with electronic detonators had quite similar average contour length which varied from 23.66 m (RCL 1.14) in round 1462 to 2.43 m (RCL 1.18) in round 1457.

Round	Theoretical contour length [m]	Average contour length [m]	Average difference [m]	Average RCL	Average percentage difference
1442	20,74	24.37	3.63	1.17	17%
1447		24.01	3.27	1.16	16%
1452		24.28	3.54	1.17	17%
1457		24.43	3.69	1.18	18%
1462		23.66	2.92	1.14	14%

Table 5.4 Contour length – electronic detonators

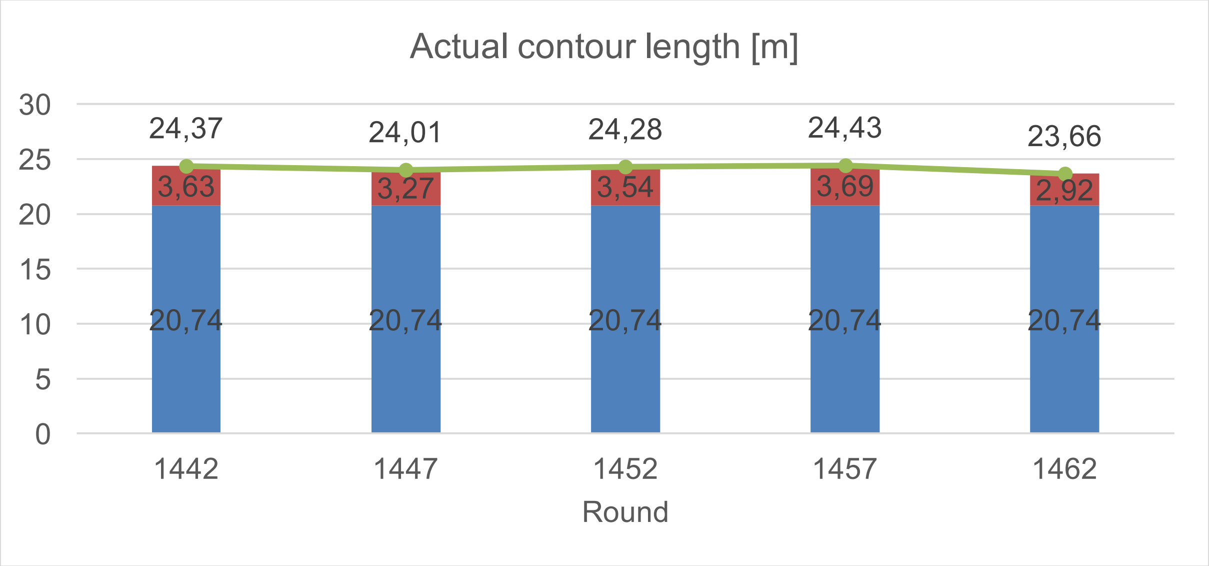


Figure 5.6 Graphical presentation of contour length – electronic detonators

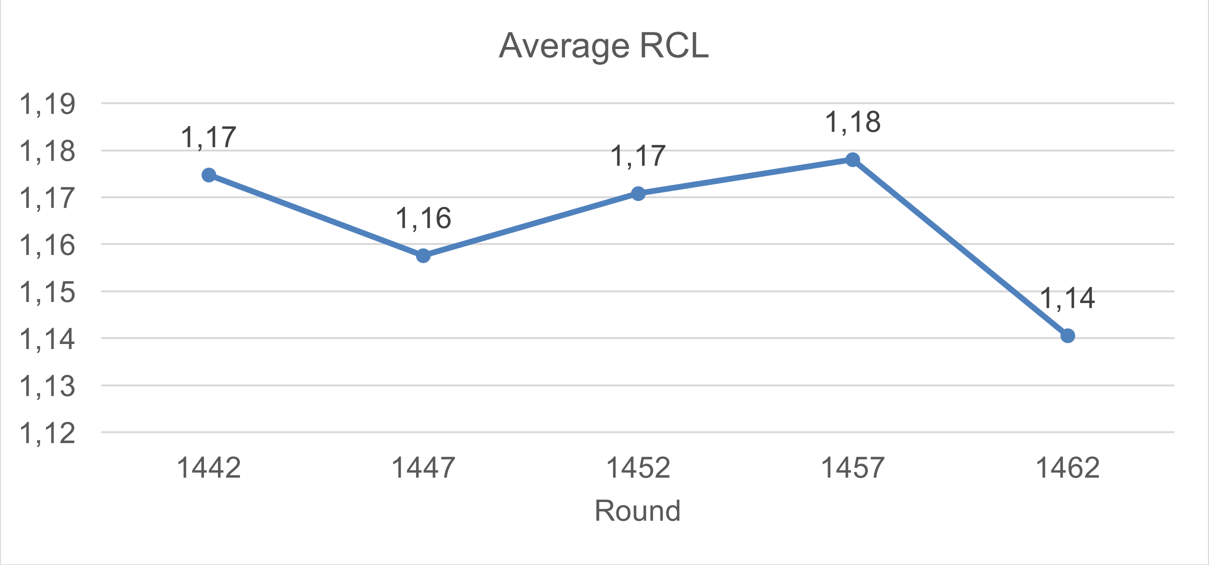


Figure 5.7 Average RCL – electronic detonators

5.2.3 ANALYSIS AND DISCUSSION

Compilation of the results from the contour length calculation from non-electric and electronic detonators are shown in Table 5.5. It was found that even though there was an assumption that test rounds should be characterized by the better quality of the contour, results of the contour length calculations were worse for the electronic detonators rounds. In general, the smaller the difference between the theoretical contour length and the actually blasted contour length, the better. Likewise, RCL value for the ideal case is equal to 1.0 and as its value becomes greater, it means the bigger difference of the contour.

	Average contour length [m]	Average difference [m]	Average RCL	Average percentage difference
NO-TEST	23.60	2.86	1.14	14%
TEST	24.19	3.45	1.17	17%

Table 5.5 Compilation of contour length results

As it is shown in the Table 5.5, the average difference between contour lengths from test rounds was 59 cm bigger than in non-electric detonators rounds. That implies the greater value of the RCL, which average value for non-electric detonators was equal to 1.14 and for electronic – 1.17. It was also found that in non-electric detonators rounds, both the highest and the lowest RCL value were registered. The difference between RCL values achieved in non-electric detonators varied from 1.09 to 1.20, corresponding to the length difference of 9% to 20%. In the test rounds, values differ from 1.14 to 1.18 (14% to 18%). This distribution of the RCL shows that electronic detonator rounds have more uniform distribution of the results.

Based on scanning results, it can be assumed that in terms of contour length, the achieved contour was better for non-electric detonators rounds than for the test rounds.

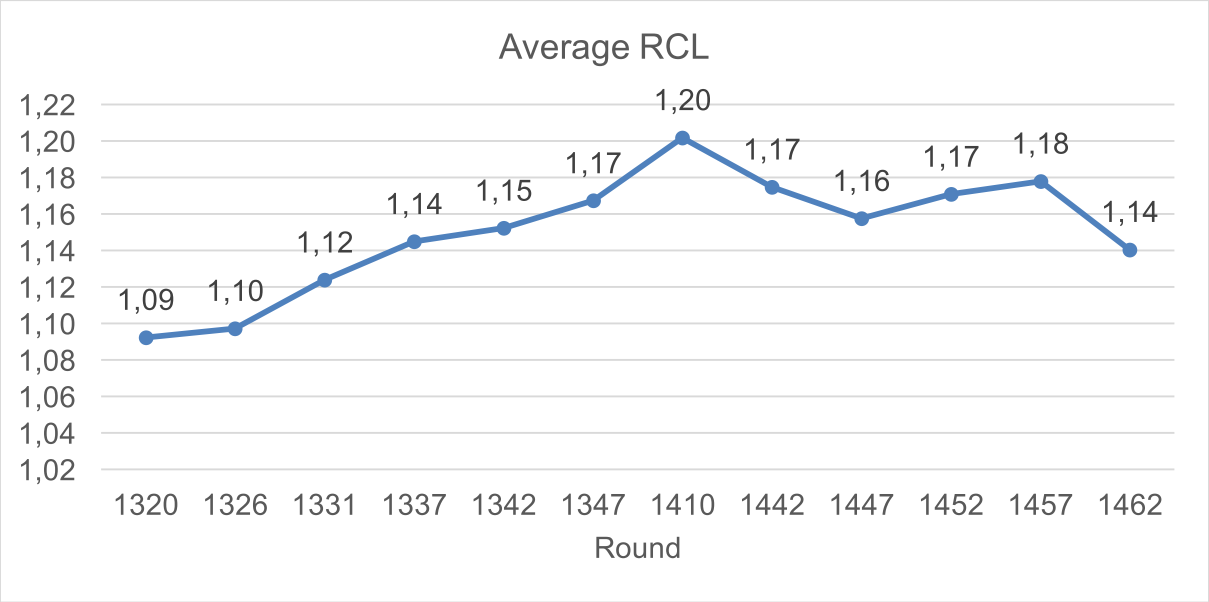


Figure 5.8 RCL results compilation

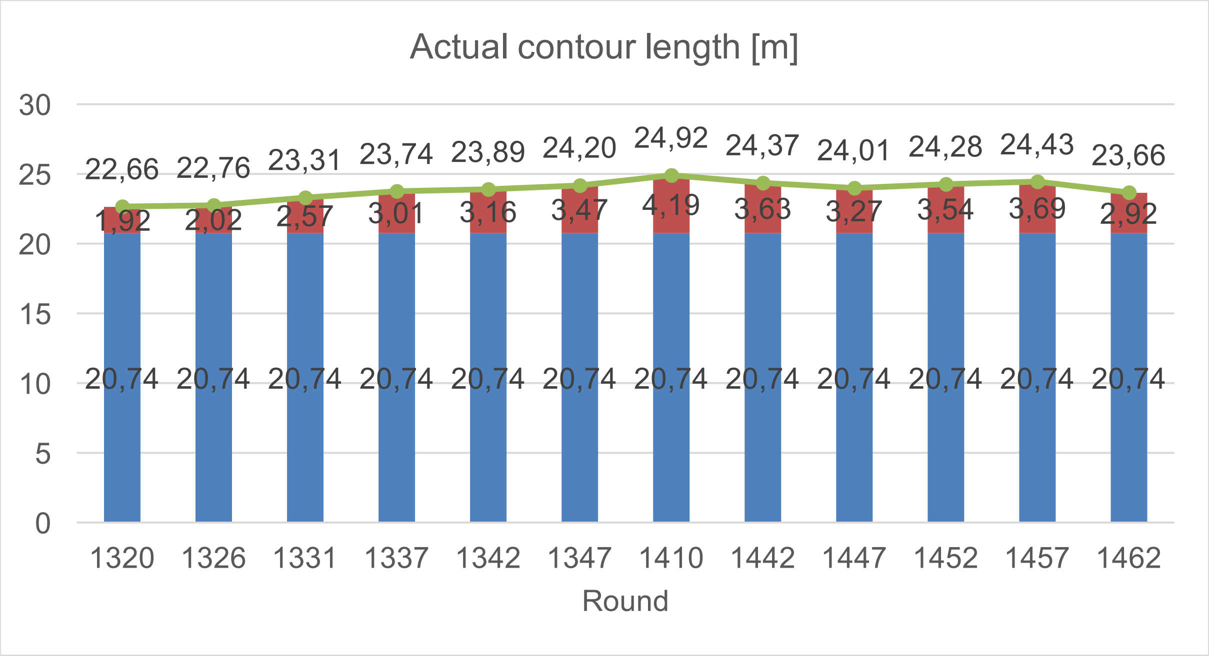


Figure 5.9 Graphical presentation of contour length

5.3 BLASTED AREA

5.3.1 RESULTS FROM NON-ELECTRIC DETONATORS ROUNDS

Results from blasted area calculation for non-electric detonators rounds are presented in the Table 5.6. The theoretical blasted area (above additional line 1 m above the bottom of the contour) was equal to 66.53 m^2. The average blasted area for all seven rounds was equal to 76.33 m^2, giving 9.80 m^2 of average overblast area. The ratio of the actually blasted to planned area (RBA) for all non-electric detonators rounds was 1.15, corresponding to a 15% difference. There were two rounds, 1320 and 1326, with similarly small overblast area equal to 6.53 m^2 and 6.63 m^2 respectively. For both rounds, difference between planed and achieved area was around 10%. Round with the biggest blasted area was round 1342 with 79.92 m^2 and 20 % difference between planned area and actually blasted one.

Round	Planned area [m^2]	Average overblast volume [m^2]	Average blasted area [m^2]	Ratio of blasted areas	Average percentage difference
1320	66.53	6.53	73.07	1.10	10%
1326		6.63	73.19	1.10	10%
1331		9.13	75.70	1.14	14%
1337		10.94	77.47	1.16	16%
1342		13.40	79.92	1.20	20%
1347		12.06	78.56	1.18	18%
1410		11.70	78.21	1.18	18%

Table 5.6 Blasted area – non-electric detonators

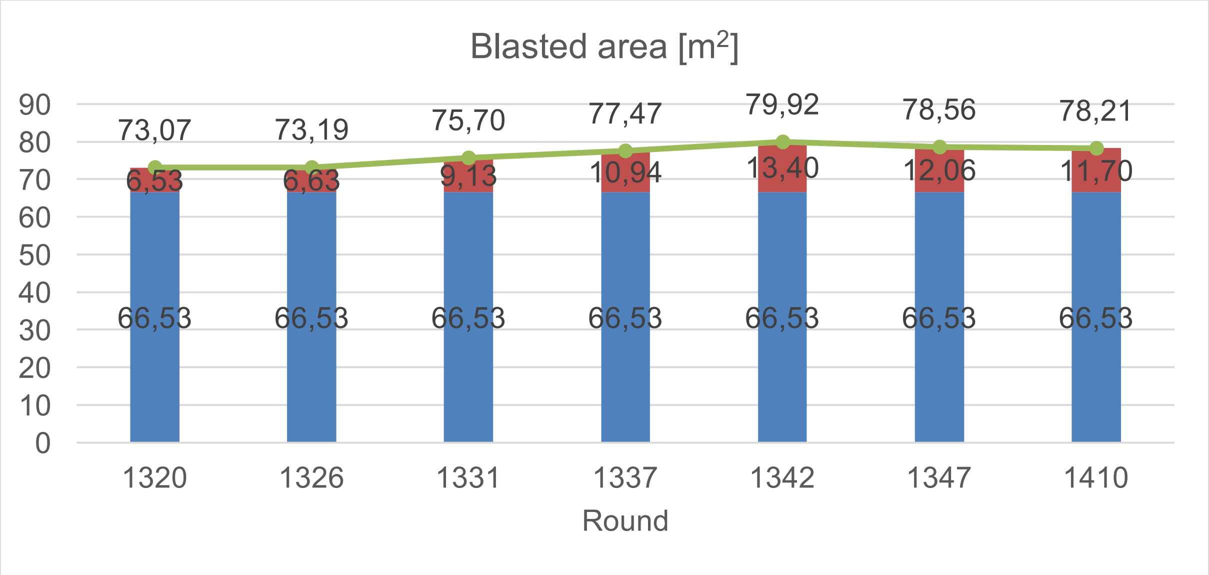


Figure 5.10 Graphical presentation of blasted area – non-electric detonators

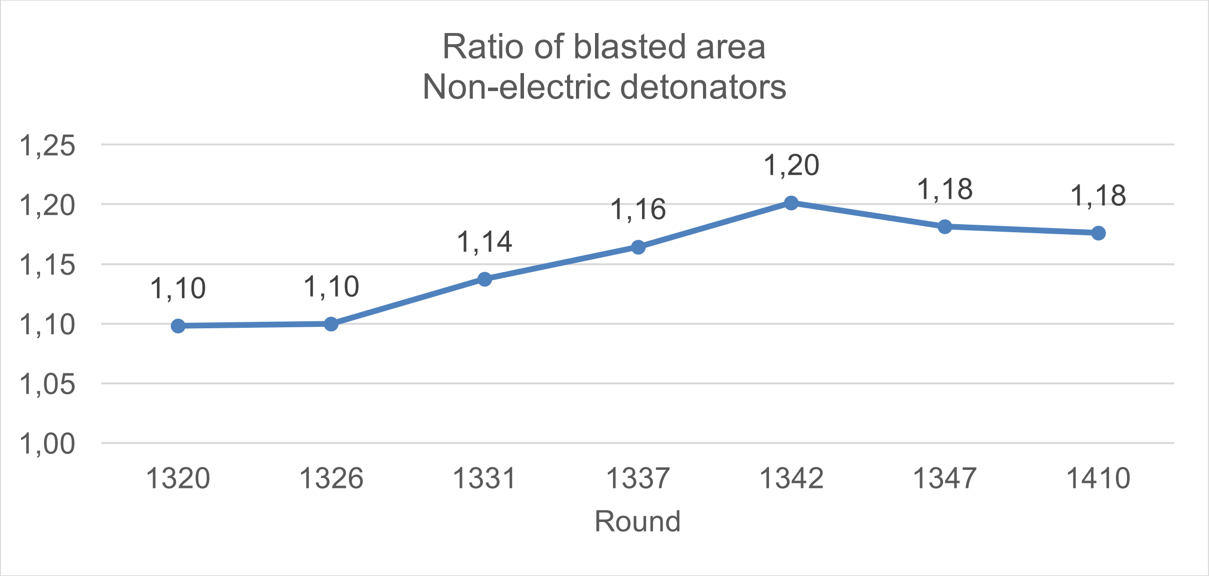


Figure 5.11 Ratio of blasted area – non-electric detonators

5.3.2 RESULTS FROM ELECTRONIC DETONATORS ROUNDS

The average blasted area for the electronic detonators rounds was 76.88 m^2. That result gives average 10.35 m^2 of overblast area and RBA equal to 1.16. For each rounds average percentage difference of the areas varies from 13 to 18%. Round with the smallest overblast area was round 1452 with 8.83 m^2 and 75.35 m^2 of actually blasted area. Round with the largest – 1442, had 12.07 m^2 of overblast area and 78.64 m^2 of actually blasted area.

Round	Planned area [m^2]	Average overblast volume [m^2]	Average blasted area [m^2]	Ratio of blasted areas	Average percentage difference
1442	66,53	12,07	78,64	1,18	18%
1447		9,89	76,44	1,15	15%
1452		8,83	75,35	1,13	13%
1457		9,82	76,33	1,15	15%
1462		10,94	77,47	1,16	16%

Table 5.7 Blasted area – electronic detonators

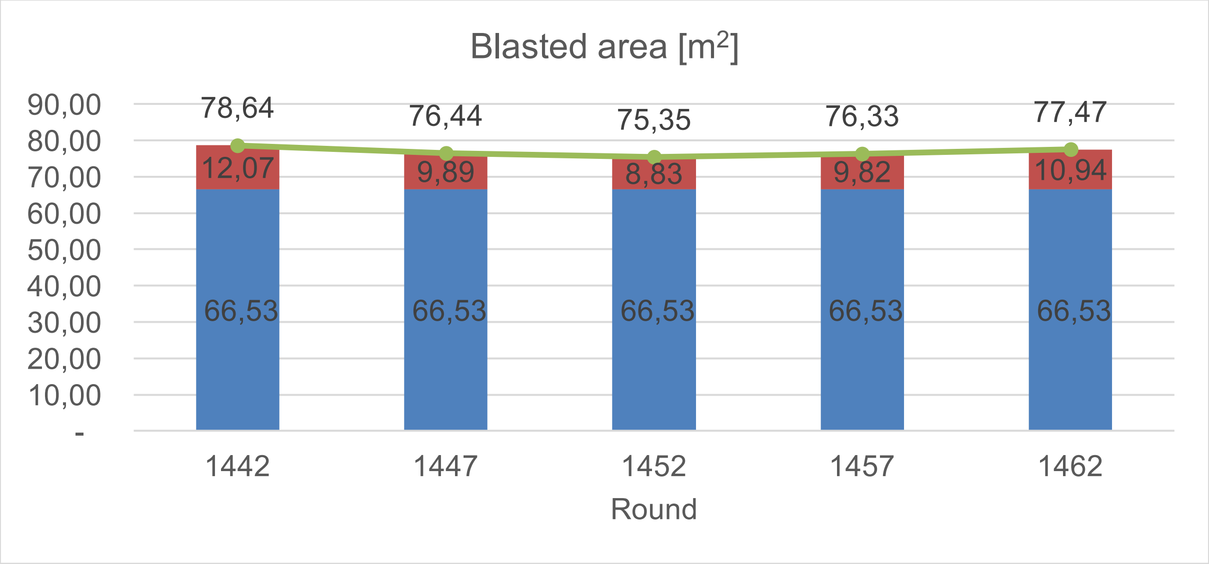


Figure 5.12 Graphical presentation of blasted area – electronic detonators

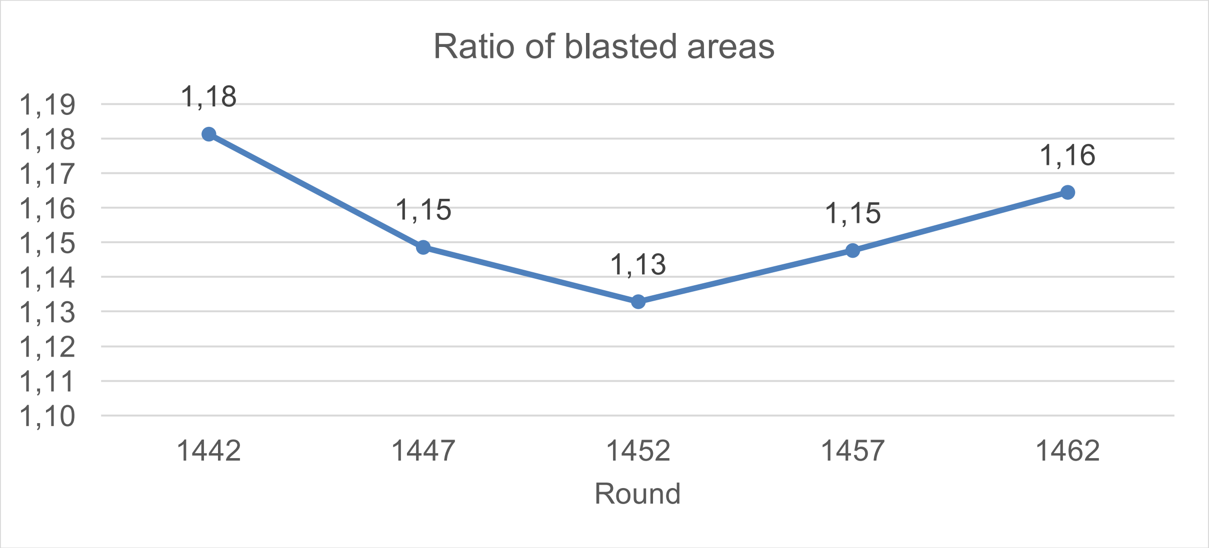


Figure 5.13 Ratio of blasted area – electronic detonators

5.3.3 ANALYSIS AND DISCUSSION

The analysis of the overblasted area is similar to the analysis of the contour length. In general, the smaller the overblasted area, the better. Additionally, the assumption for the ideal case, with RBA equal to 1.0, is analogic to the RCL estimation. A compilation of the results from blasted area calculation is presented in Table 5.8.

	Average overblast area [m^2]	Average blasted area [m^2]	Average ratio of blasted areas	Average percentage difference
NO-TEST	9.80	76.33	1.15	15%
TEST	10.35	76.88	1.16	16%

Table 5.8 Compilation of blasted area results

Results of the blasted area averages for non-electric and electronic detonators are relatively similar to each other. Average overbreak is found to be around 10 m2 for both sets of data, what is corresponding to RBA equal to 1.15-1.16 (15-16% of the difference from the theoretical area). RBA value for all 12 analyzed rounds are distributed between 1.10 and 1.20, and both, the highest and the lowest values are in the non-electric detonators data set. RCL just for test rounds, varies from 1.13 to 1.18. Based on the achieved results, no big improvement of the blasted area was observed.

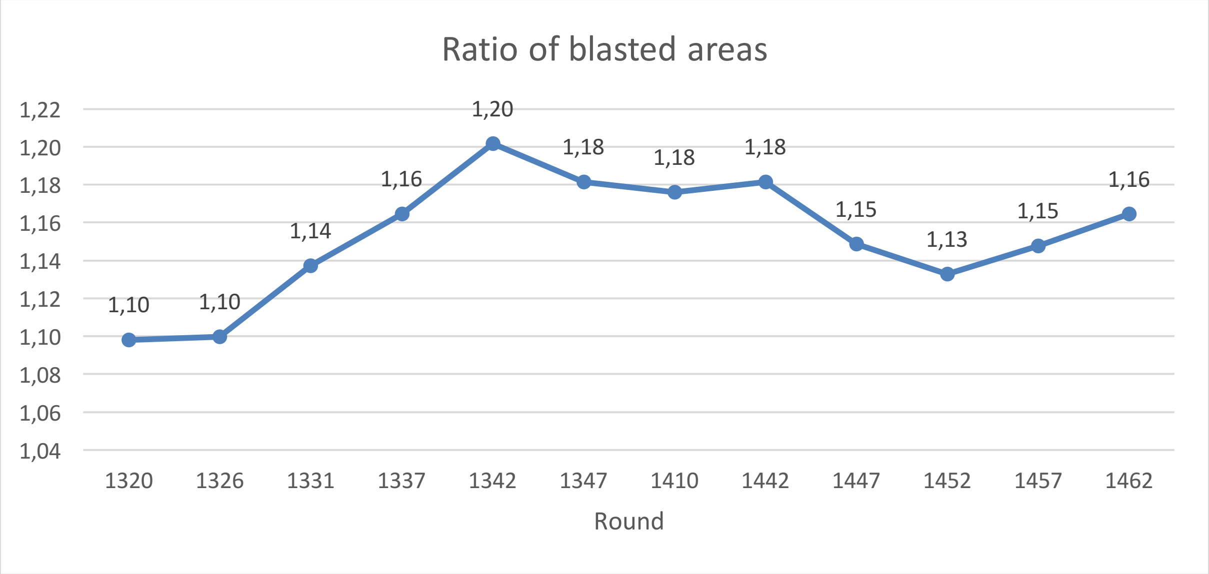


Figure 5.14 RBA results compilation

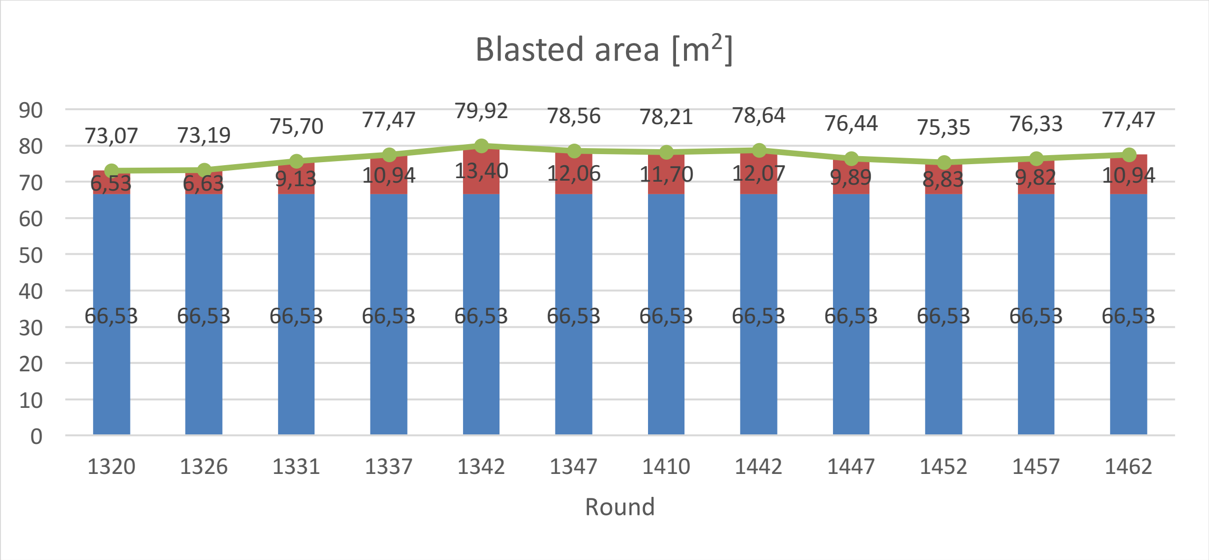


Figure 5.15 Graphical presentation of blasted area

5.4 OVERBREAK

Overbreak in this thesis is defined as the distance from planed contour line to the actually blasted contour line. For each round, the number of cross sections taken under consideration for the calculation are specified in Table 5.9. Only distances above the additional line were used for analysis of the overbreak.

Round	Number of scanned profiles
1320	10
1326	11
1342	11
1347	11
1352	7
1357	8
1410	10
1441	11
1447	9
1452	9
1457	10
1462	7

Table 5.9 Number of scanned profiles

5.4.1 RESULTS FROM NON-ELECTRIC DETONATORS ROUNDS

Figure 5.16 presents a graphical interpretation of average deviation of the overbreak.

Round	Min [mm]	Max [mm]	Average deviation per round [mm]
1320	258	352	308
1326	232	423	311
1331	319	525	425
1337	399	622	504
1342	557	689	615
1347	507	661	553
1410	414	674	538

Table 5.10 Overbreak results – non-electric detonators

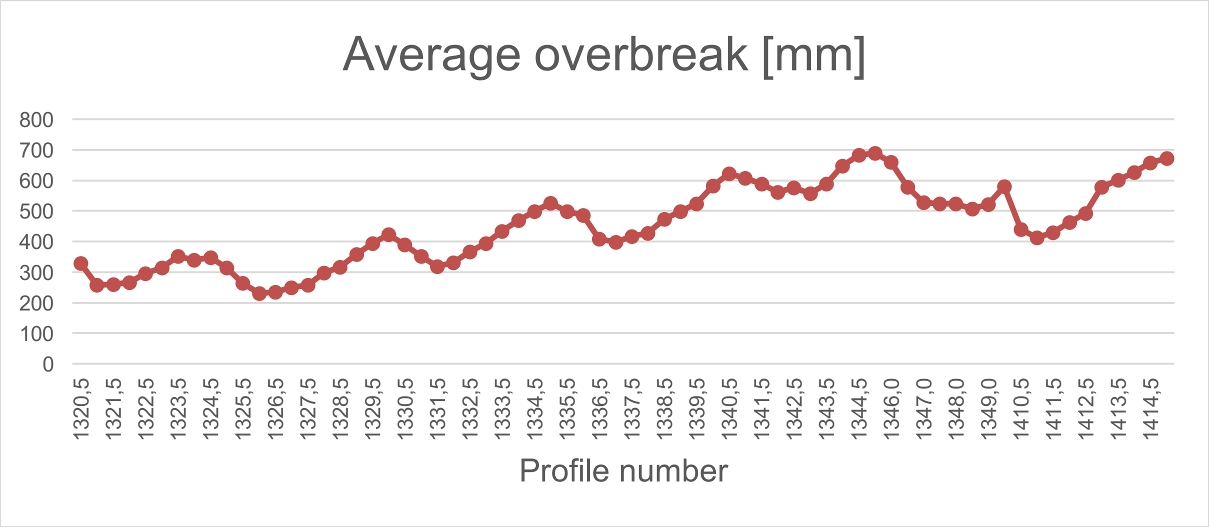


Figure 5.16 Graphical presentation of overbreak – non-electric detonators

The biggest overbreak was calculated for round 1342 where the highest value in profile 1347 was equal to 689 mm. In the same round, the average deviation per round had also the highest result with 615 mm. The first round of the scanning was characterized by the smallest average overbreak equal to 308 mm, but the smallest overbreak per profile was observed in round 1326 with 232 mm. Average overbreak for all seven rounds was 453 mm.

5.4.2 RESULTS FROM ELECTRONIC DETONATORS ROUNDS

For five electronic detonators rounds, the average value from all profiles was equal to 481 mm. The biggest average deviation per round was in round 1442 and it was 562 mm. In this round there was also profile with the highest calculated value from scanning equal to 656 mm. Round with the lowest average deviation was round 1452, but profile with the lowest value was 1463.5 in round 1462 with 338 mm of overbreak. Graphical interpretation and table with results are presented below.

Round	Min [mm]	Max [mm]	Average deviation per round [mm]
1442	470	656	562
1447	397	505	460
1452	360	483	413
1457	399	493	454
1462	338	629	506

Table 5.11 Overbreak results – electronic detonators

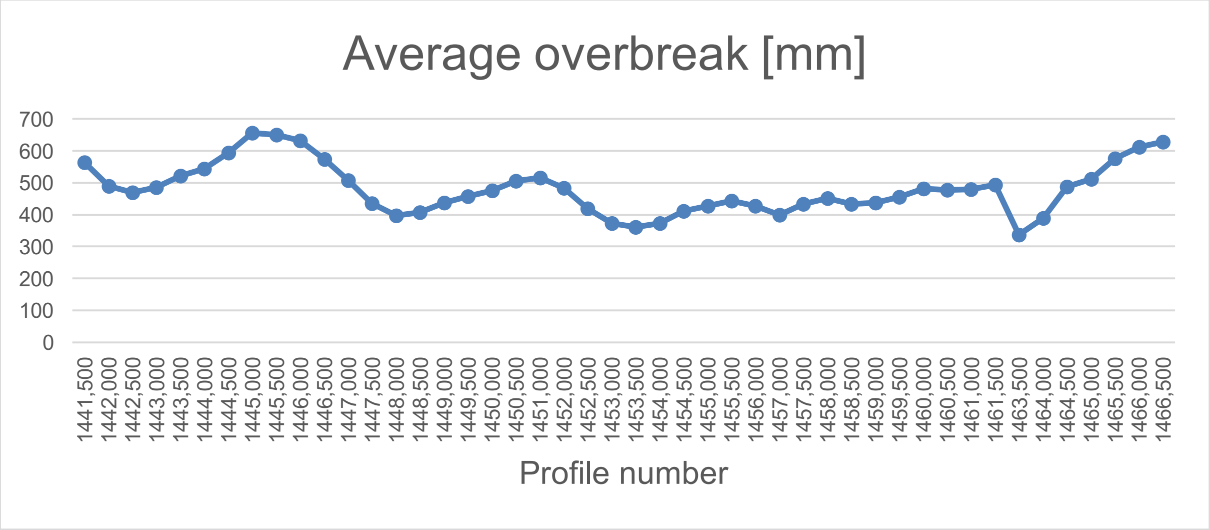


Figure 5.17 Graphical presentation of overbreak – electronic detonators

5.4.3 ANALYSIS AND DISCUSSION

Results from the overbreak calculation show that average overbreak for non-electric detonators was lower than for electronic detonators rounds. For rounds with normally used detonators, the average overbreak was 45.3 cm, what was 2.8 cm smaller than the value of the overbreak for test rounds.

	Average overbreak [mm]
NO-TEST	453
TEST	481

Table 5.12 Compilation of overbreak results

No special requirements for overbreak were stipulated for the electronic detonators test, so according to Stanens vegvesen Road Tunnel Strategy Study (2010), the boundary line of the overbreak can be calculated by the equation:

$$D = 0{,}07 \cdot \sqrt{A}$$

where:

D – distance between the theoretical excavation line and the boundary line

A – Theoretical excavated surface area

For the 78 m^2 theoretical area of the whole profile, D value is equal to 61.8 cm. None of the overbreak averages per round exceed this value, but in some averages of the profiles, the limit distance was surpassed. The overbreak limit distance was achieved in rounds 1337 (62.2 cm), 1342 (68.9 cm), 1347 (66.1 cm), 1410 (67.4 cm) from non-electric detonators rounds and in rounds 1442 (62.9 cm) and 1462 (65.6 cm) from test stretch.

Average overbreak per round for non-electric detonators varies from 30.8 cm to 61.5 cm, which gives around a 30 cm difference between minimum and maximum value. For electronic detonators the variation of the results was between 41.3 and 56.2 cm with a 15 cm difference between extreme values.

The assumption was that use of the electronic detonators would decrease the overbreak dimension, but instead of reduction, small increase of the overbreak average was observed. Although, test rounds comparing to non-electric detonators rounds are characterized with the more uniform distribution of the results. The difference between extreme values were twice smaller for electronic detonators. The difference between overbreak averages for both sets of data is slight, therefore it can be stated that the quality of the contour in terms of overbreak is similar for all rounds.

5.5 TUNNEL QUALITY INDEX

Tunnel Quality Index, TCI, proposed by Kim (2009) was used in this thesis for evaluation of the contour quality of a tunnel. TCI can be calculated for the one round, TCI_R, or for the entire tunnel (or more than 5 rounds) - TCI_T. Formula for TCI estimation proposed by Kim (2009) was slightly changed for the need of this thesis and it is determined by equation below. The difference is that the ratio of contour length element used in the contour length element of the formula. Because data from scanning provided very accurate contour lengths it was possible to evaluate the ratio using actual contour length and planned contour length, so there was no need for empirical estimation of the ratio like it was proposed by Kim.

$$TCI_T = \frac{300}{0.027 \cdot \overline{O_v} + 3.6 \cdot \overline{RCL} + 0.02 \cdot V_o}$$

$$TCI_R = \frac{300}{0.027 \cdot \overline{O_v} + 3.6 \cdot \overline{RCL}}$$

where:

$\overline{O_v}$ - Average of O_v for each round (cm)

V_o - Longitudinal overbreak variation (cm)

$\overline{RCL}$ - Ratio of actual contour length to planned contour length

5.5.1 RESULTS FROM NON-ELECTRIC DETONATORS ROUNDS

Results from Tunnel Quality Indexes calculation are presented below. TCI_R for non-electric detonators was distributed between 51.6 and 63. Round 1320 had the highest TCI_R value equal to 63. Round with the lowest TCI_R was round 1342 with 51.6. Calculated for all seven rounds, TCI_T, which included also longitudinal overbreak variation element, was equal to 54.1.

Round	Average contour length per round [m]	Average RCL	Average overbreak [cm]	TCI_R
1320	22.66	1.09	30.77	63.0
1326	22.76	1.10	31.10	62.6
1331	23.31	1.12	42.50	57.8
1337	23.74	1.14	50.43	54.7
1342	23.89	1.15	61.51	51.6
1347	24.20	1.17	55.30	52.7
1410	24.92	1.20	53.79	51.9
	MIN	1.09	30.8	51.6
	MAX	1.20	61.5	63.0

Table 5.13 TCI results – non-electric detonators

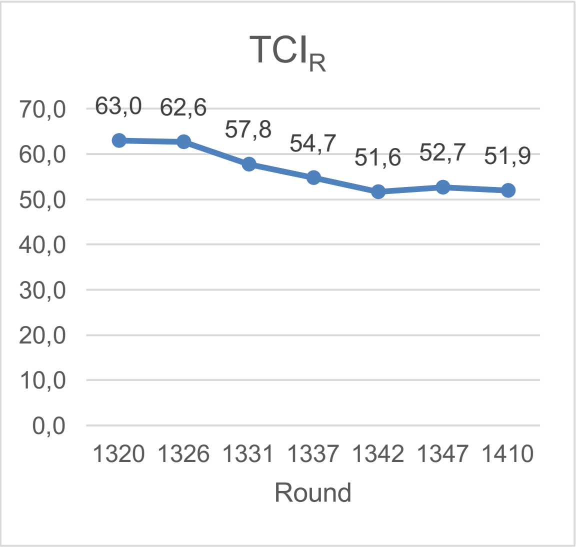


Figure 5.18 TCI_R results – non-electric detonators

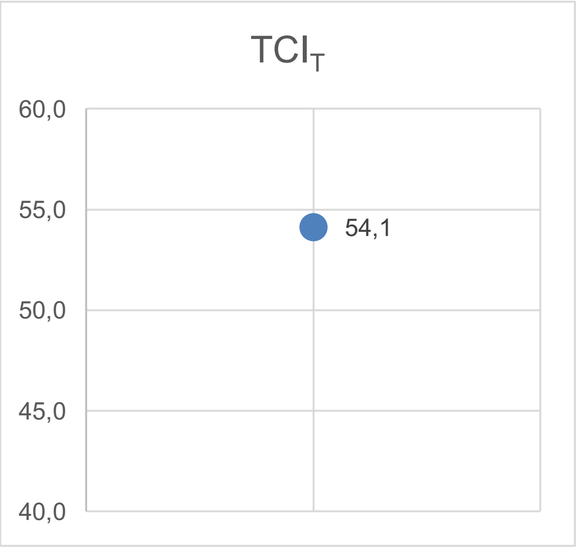


Figure 5.19 TCI_T result – non-electric detonators

5.5.2 RESULTS FROM ELECTRONIC DETONATORS ROUNDS

Table 5.14 shows the results from TCI_R calculation. It was found that TCI_R for electronic detonators rounds was distributed between 52.2 and 56.3. The most favorable contour quality had round 1452. Round with the lowest TCI_R equal to 52.2 was round 1442. The results of the TCI_L calculation showed that for all test rounds, taking into account the longitudinal overbreak variation element, contour quality was equal to 53.6.

Round	Average contour length per round [m]	Average RCL	Average Overbreak [cm]	TCI_R
1442	24.37	1.17	56.2	52.2
1447	24.01	1.16	46.0	55.5
1452	24.28	1.17	41.3	56.3
1457	24.43	1.18	45.4	54.9
1462	23.66	1.14	50.6	54.8
	Min	1.14	41.3	52.2
	Max	1.18	56.2	56.3

Table 5.14 TCI results – electronic detonators

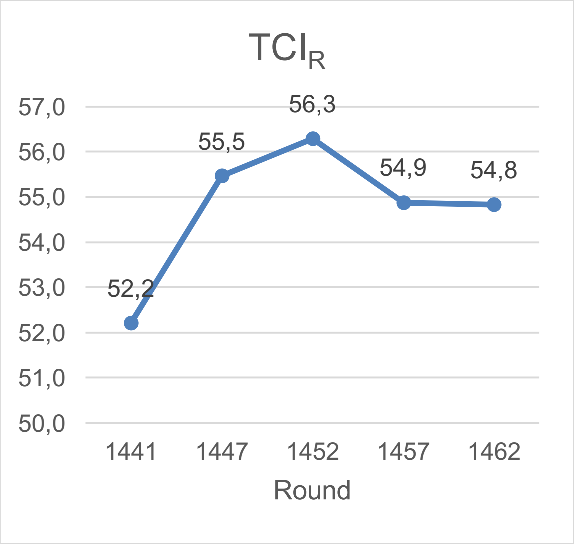


Figure 5.20 TCI_R results – electronic detonators

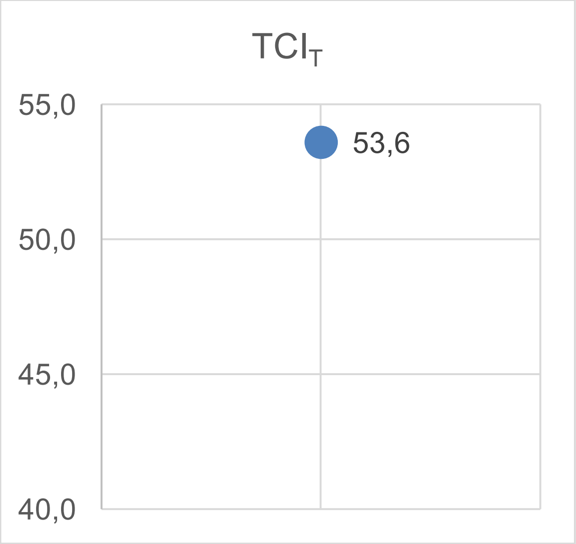


Figure 5.21 TCI_T result – electronic detonators

5.5.3 ANALYSIS AND DISCUSSION

Compilation of the results from TCI calculation is presented in Table 5.15, and Figures 5.22 and 5.23 below.

Round	TCI$_R$	TCI$_T$
1320	63.0	54.1
1326	62.6	
1331	57.8	
1337	54.7	
1342	51.6	
1347	52.7	
1410	51.9	
1442	52.2	53.6
1447	55.5	
1452	56.3	
1457	54.9	
1462	54.8	

Table 5.15 Compilation of TCI results

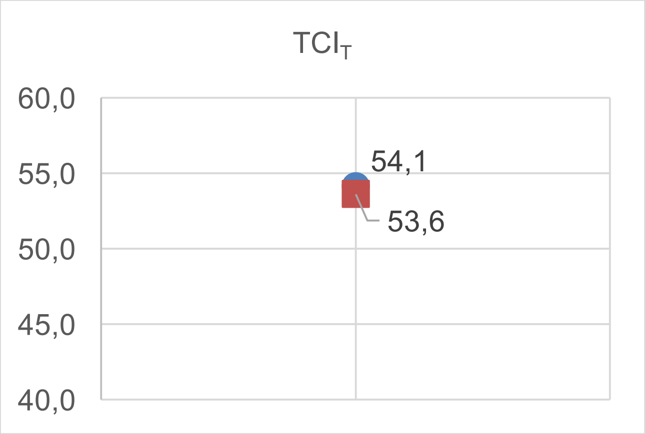


Figure 5.22 Compilation of TCI$_T$ results

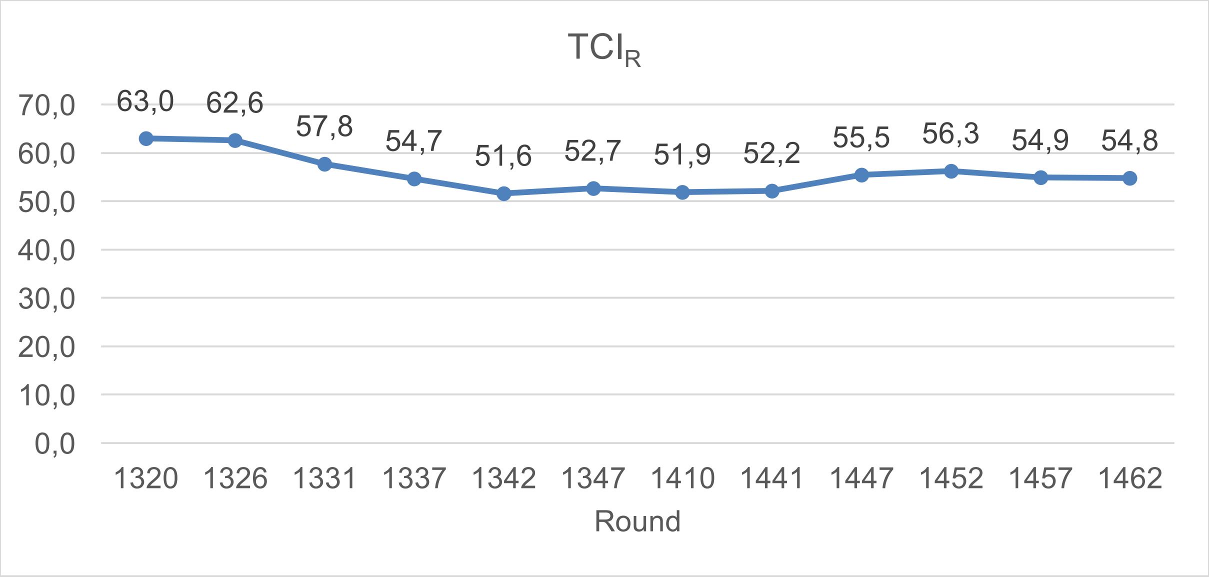


Figure 5.23 Compilation of TCI$_R$ results

In general, higher TCI values means better contour quality. Kim (2009) in his thesis estimated the extreme values for TCI_T: 29.8 for extremely bad case (overbreak – 155 cm, RCL – 1.34, longitudinal overbreak variation – 53 cm) and 81.5 for an ideal case (1 cm, 1.01, 1 cm – respectively). For normal cases, he evaluated the interval of TCI_T values from 38.6 to 61.6. For TCI_R there are none special boundaries estimated.

TCI_T results from Bjørnegård tunnel were similar for both type of detonators rounds. In non-electric detonators rounds, TCI_T of 54.1 was calculated. A slightly smaller value was achieved for electronic detonator rounds, where TCI_T was equal to 53.6. TCI_R in all calculated rounds varied from 51.6 to 63.0. Both extreme results were achieved in non-electric detonators rounds. Results from test rounds were in the range of 52.2 to 56.3.

TCI_T of 54 achieved for both detonators rounds was in the interval described by Kim for normal cases. Calculated value is more or less in the middle of the given interval and since there is no partition of the TCI_T into quality groups, the quality of 54 in this thesis will be estimated as average.

5.6 SUMMARY OF SCANNING

In the scanning chapter, data from laser scanning of the tunnel was analyzed. 103 profile scans were used for the analysis: 68 from non-electric detonators and 35 from electronic detonators rounds. The goal was to analyze achieved contour and evaluate the influence of change of the ignition system on the quality. The assumption was that the use of electronic detonators could have a positive impact on contour quality.

Scanning was performed with a high technology scanner, which provided very accurate 3D model of the tunnel surface and information about the geometry of the tunnel. Types of data from the scanning used in this thesis were following:

- Theoretical contour length,
- Actual contour length,
- Theoretical blasted area,
- Overblast area,
- Distances from the theoretical contour to actual contour.

Scanning was performed after removal of loose material (scaling) and scanner while measurements was placed few meres in front of tunnel face. Results from scanning were given for every 0.5 m of the scanned rounds, but in some cases data was damaged and those profiles were rejected from the calculation. Calculations were done for the cross sections above additional line 1m above the bottom of the contour.

Analysis was based on evaluation of following values:

- RCL – ratio of actual contour length to planned contour length,
- RBA – ratio of actual blasted area to planned blasting area,
- Overbreak – the average of the distances from the theoretical contour to actual contour,
- TCI – Tunnel Contour Quality Index.

Summary of the results from this section is presented in the Table 5.16 below:

	Average RCL	Average RBA	Average overbreak [mm]	TCI_T
NO-TEST	1.14	1.15	453	54.1
TEST	1.17	1.16	481	53.6

Table 5.16 Compilation of scanning results

Calculation of the mentioned above values, showed that there was no big improvement of the result in the rounds with electronic detonators. Furthermore, analysis of the scans indicated a slight deterioration of achieved results from the test stretch. However, the differences between results from both sets of data are rather similar with small deviations. Based on the outcomes from scanning results calculation, it can be assumed that the quality of the tunnel contour was very similar for non-electric and electronic detonators rounds.

In terms of overbreak calculation, according to Stanens vegvesen Road Tunnel Strategy Study, the limit value of the overbreak for the 78 m^2 tunnel cross section is equal to 61.8 cm. None of the overbreak averages exceeded this value, though in some profiles, the limit distance was surpassed. The overbreak limit distance was achieved in rounds 1337 (62.2 cm), 1342 (68.9 cm), 1347 (66.1 cm), 1410 (67.4 cm) from non-electric detonators rounds and in rounds 1442 (62.9 cm) and 1462 (65.6 cm) from test stretch.

Considering guidelines for TCI_T suggested by Kim (2009) it can be stated that achieved contour quality was average. TCI_T of 54 is more or less in the middle of Kim’s interval for normal cases. The average TCI_T is slightly different for non-electric and electronic detonators rounds and it is higher for the first set of data. Both averages for RCL, RBA and overbreak results are comparable for test rounds and for rounds before test.

Two last rounds of electronic detonator tests increased the drilling hole diameter from 48 mm to 60 mm. The change in the hole dimension did not influence the achieved results in a significant way.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The main idea of the thesis was to analyze the excavation of the E16 Sandvika-Wøyen Bjørnegård tunnel with special focus on the achieved contour quality and influence of applied initiation system. The analysis in the thesis is divided in the two major parts:

- Analysis of the drilling results
- Analysis of the scanning results

Discussion and analysis are included in conclusion section.

Drilling analysis was based on the MWD data from the drilling jumbo which was divided into two groups:

- Local coordinates – used for the estimation of the spacing and length of the contour holes
- Global coordinates – used for the calculation of the start and end position of the holes

Analysis of the local coordinates showed that there was a 1% variation in the calculated average spacing from the theoretical assumption for both non-electric and electronic rounds. Calculation of the average drilling length showed a 3% difference from the designed holes length. Drilling accuracy in terms of spacing and drilling length could be assumed as satisfactory.

Calculation of the starting position of the holes showed that average distance of the holes drilled outside the contour length was 15.8 cm for non-electric, and 17.4 cm for electronic detonator rounds. Even though a specific accuracy of a maximum of 10 cm distance from the theoretical contour was requested for the test of the electronic detonators, only 13% of all drilled holes met the requirements. The starting position of the most of the holes were placed within 10 to 20 cm from the contour line. This amounted to 54% of all drilled holes pre-test and 74% for the actual test rounds. A relatively large number of holes were drilled outside of the 20 cm Handbook R761 requirement. 24% of holes drilled in rounds with non-electric detonators and 36% in test rounds were drilled in distance greater than 20 cm from theoretical contour. Based on the results of the starting point calculations, it can be established that drilling accuracy did not meet the requirements.

The analysis of the end position and look-out of the drilled holes showed that for non-electric detonator rounds, the average end position of the holes was 51.9 cm and for electronic detonators rounds – 49.5 cm. Look-out results showed an average of 35.9 cm for non-electric and 31.9 cm for electronic detonator rounds. Calculated results were similar for non-electric and electronic detonator rounds. There were no special requirements for the maximum distance of those two values, therefore the achieved results have informative character.

An analysis of the laser scanning of the tunnel was done to evaluate achieved contour quality. Results from 103 profiles were taken under consideration: 68 from non-electric detonators rounds and 35 from electronic detonators. The scans provided following information:

- Theoretical contour length
- Actual contour length
- Theoretical blasted area
- Overblast area
- Distances from the theoretical contour to actual contour

Analysis of the scanning was based on the evaluation of the following values:

- RCL – ratio of actual contour length to planned contour length
- RBA – ratio of actual blasted area to planned blasting area
- Overbreak – the average of the distances from the theoretical contour to actual contour
- TCI – Tunnel Contour Quality Index

Calculation showed that the average RCL was equal to 1.14 for non-electric detonators rounds and 1.17 for electronic detonators. Estimation of the average RBA also showed similar results; for non-electric detonators it was 1.15 and for electronic – 1.16. There are no limit values for RCL and RBA, but results closer to 1.0 mean that the actual contour and blast area are closer to the theoretical assumption.

According to the Stanens vegvesen Road Tunnel Strategy Study, the limit value of the overbreak for the 78 m^2 tunnel cross section is equal to 61.8 cm. None of the overbreak averages exceed this value, but in some profiles, the limit distance was surpassed. The average overbreak for test rounds was 48.1 cm and 45.3 cm for non-electric detonators rounds.

The TCI_T calculated had similar values for both sets of rounds. Rounds with use of non-electric detonators were characterized by a TCI_T of 54.1. TCI_T for test rounds was 53.6. Considering the guidelines for TCI_T suggested by Kim (2009) it can be stated that the achieved contour quality was average. A TCI_T of 54 is more or less in the middle of Kim's interval for normal cases.

Considering guidelines for TCI_T suggested by Kim (2009) it can be established that achieved contour quality was average. A TCI_T of 54 is more or less in the middle of Kim's interval for normal cases. The average TCI_T is slightly different for non-electric and electronic detonator rounds, and it is higher for the first set of data. Both averages for RCL, RBA and overbreak results are comparable for test rounds and for rounds before test.

Despite the assumption of the improvement of the contour quality, calculations did not support this theory. According to Kim (2009), with the increase of the Q-value, TCI_R should also increase, but there was no relationship found with the TCI_T, therefore the lower Q-value which was registered in the test rounds should not have impact on the final results. However, he suggested that to dramatically improve the contour quality, more interest should be paid to the drilling conditions such as starting position of the hole or look-out. Considering results from the the drilling accuracy, where it has been founded that in the test stretch the accuracy of the drilling was actually worse than for the non-electric detonators, it can be assumed, that there is a connection between achieved results. There is a possibility that unfavorable drilling was recompensed by the positive influence of electronic detonators application.

In two last rounds of electronic detonators test drilling hole diameter was increased from 48 mm to 60 mm. Change of the hole dimension did not influence the achieved results in significant way.

6.2 RECOMMENDATIONS FOR FURTHER WORK

Analysis of the tunnel excavation is based on data from the construction site. Due to the fact that drill and blast tunnels are constructed in rock with variable characteristics, it would be recommended to eliminate the variation factor from the analysis. It could be achieved by e.g. extending the number of analyzed rounds.

In this thesis, tunnel excavation was analyzed on the basis of the quality of the achieved contour and drilling accuracy. For more extended evaluation, results of the ratio of actual pull length to drilled length per round and level of induced vibration and noise could be also taken into consideration for the analysis.

It would be also recommended to test the influence of the electronic detonators on the excavation results for more tunnels with varied excavation conditions.

Finally, the limitations of this research should be mitigated in order to achieve more reliable analysis of the tunnel excavation.

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