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Research paper

The influence of electronic detonators on the quality of the tunnel excavation

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Abstract: In drill and blast tunneling method (D&B), non-electric detonators are the most commonly used initiation system. The constant development of excavation technology provides advanced tools for achieving better results of excavation. The research presented in this paper was focused on the attempt to evaluate the influence of electronic detonators, which nowadays are unconventional in tunnelling engineering, on the quality of the excavated tunnel contour. Based on the data form Bjørnegård tunnel in Sandvika, where electronic detonators were tested in five blasting rounds, detailed analysis of drilling was performed. The analysis was made based on the data from laser scanning of the tunnel. 103 profile scans were used for the analysis: 68 from non-electric detonators and 35 from electronic detonators rounds. The results analyzed in terms of contour quality showed that comparing to the results from rounds blasted with non-electric detonators, there was not significant improvement of the contour quality in rounds with electronic detonators.

Keywords: Drill&blast method, contour quality, scanning, electronic detonators

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1. Introduction

One of the major branches of the construction industry is tunneling. 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.
Methods most commonly used for hard rock tunnel excavations are drill and blast (D&B) and mechanized TBM [1, 2]. In Norway, which, according to [3], is a front runner in underground excavation and tunneling, the D&B method has a great advantage over TBM in terms of dealing with changing ground conditions, and the need for rock support and grouting to secure safe tunneling conditions [4–6].
In general, the results from blasting using the D&B method can, be assessed through: 1) the ratio of actual pull length to drilled length per round, 2) vibration and noise level, and 3) the quality of the excavated contour characterized by overbreak, underbreak and contour roughness [7–14]. It is desirable for all the mentioned constituents to be as low as possible in order to achieve precise excavation.
Reduction of overbreak, underbreak and contour roughness, in general – improvement of the contour quality [15–16], 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 solutions continuously being proposed to achieve this goal [17–19]. Researches [20–21] emphasize the importance of accurate drilling and propose different approaches of prediction and control [22–29]. Also, the type, location of ignition system and timing could influence the tunnel contour quality [30–33]. The works [34–37] point out that there is a noticeable reduction of the overbreak due to the more prices blasting resulting from electronic detonators (ED). The work [38] reports that use of electronic detonators not only leads to a smaller extent of the excavation damaged zone (EDZ) but also a lower degree of rock breakage in the EDZ. [39] are underlining the variety of benefits of electronic detonators ignition system. Among advantages from using this technology, they listed wide range of delays, possible reduction of ground vibration and airblast, or limiting the amount of detonators per shot. But much higher cost in comparison to the non-electric detonator system and necessity of specialized user training, make it still a questionable choice. A review of the benefits of electronic detonators is given in [39].
By analyzing the results of in-situ test, the Authors attempt to verify whether the use of electronic detonators could have a positive impact on contour quality.

This assumption was evaluated based on the study of the results from the Sandvika-Wøyen project. In the Kjørbo-Mølla tunnel, part of the Bjørnegård tunnel excavated with the D&B method, electronic detonators were tested as an initiation system for the blasting. Analysis relies on data from seven blasting rounds with application of normal non-electric detonators, and five test rounds with application of electronic detonators.

Choice of the data for the analysis was based on the literature study and actual availability of the data. Field study was executed during both non-electric and electronic detonators rounds. Analysis is divided into two groups: drilling and scanning. Both groups were analyzed in terms of non-electric and electronic detonators use. 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_T (Tunnel Contour Quality Index) [7, 40] was analyzed.

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

2. Site overview

The major part of the Sandvika-Wøyen stretch is Bjørnegård tunnel located in Sandvika, west of Oslo (Fig. 1). The Bjornegard tunnel consist of two tubes (tunnel A and tunnel B) with two lanes in each tube. The Bjørnegård tunnel is composed of four merged tunnels, from which one is the Kjørbo-Mølla tunnel (tunnel A), excavated with drill and blast excavation method. Total length of the tunnel is approximately 2260 m (tunnel A) and 2335 m (tunnel B). Excavation started from an adit, the additional access tunnel to the main tunnel, with length around 290 m. Shale and limestone are major rock types for the tunnel construction area.

According to the "Manual 021, Road Tunnels", published by the Norwegian Public Road Administration (Nor. Statens vegvesen) in 2004 [41], 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.

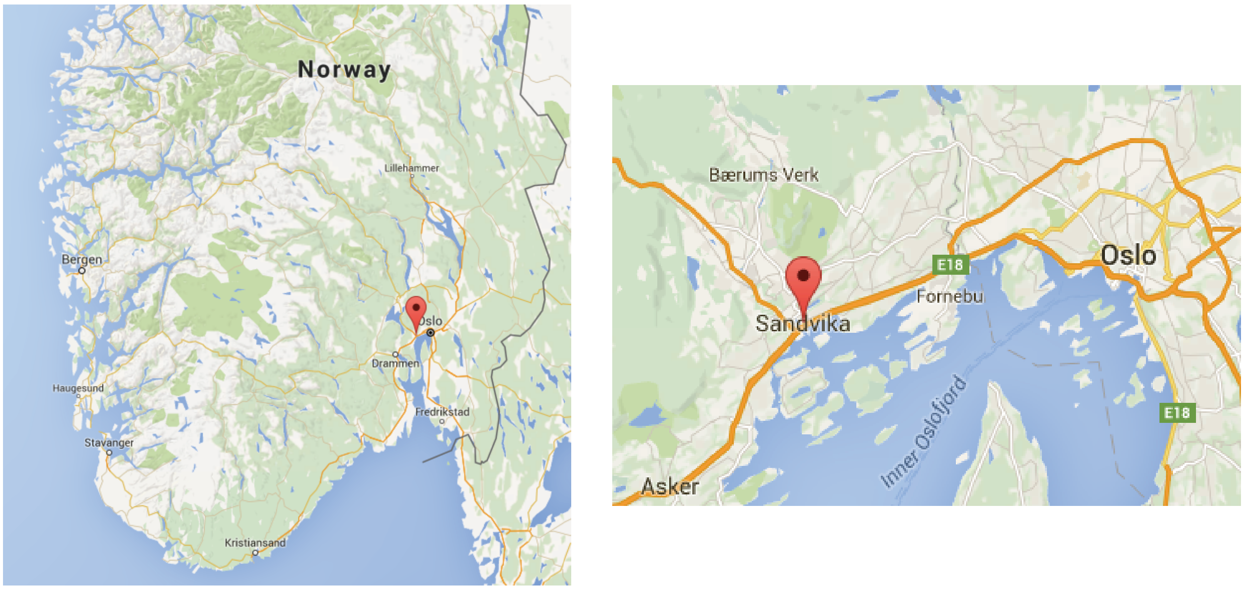


Fig. 1. Location of Bjørnegård tunnel

The drilling pattern consisted of 143 drilling holes for T9.5 profile (Fig. 2) and of 169 drilling holes for T12.5 profile.

In normal geological conditions, the blasting was designed as full-face blast round, and in the demanding geological conditions – with reduced round length or divided cross section. Basic round length was 5.2 m with the charging hole diameter of 48 mm. Charging of the face is divided into two sections with different charging of the easer holes (Fig. 2). 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.

Non-electric detonators were used in a major part of the tunnel. For the need of the presented study, five rounds were blasted with changed initiation system to the electronic detonators. Drilling jumbo used for tunnel operations was the three boom Atlas Copco Boomer XE3 C equipped with COP 3038 rock drills. Information from the drilling was automatically recorded for every drilling operation by Measurement-While-Drilling (MWD) [42-43]. All the MWD data was analyzed with GPM Rockma+ software. The information collected in the drilling logs included the position of the holes, time of drilling, rock mass strength, fracturing and ground water level, among others.

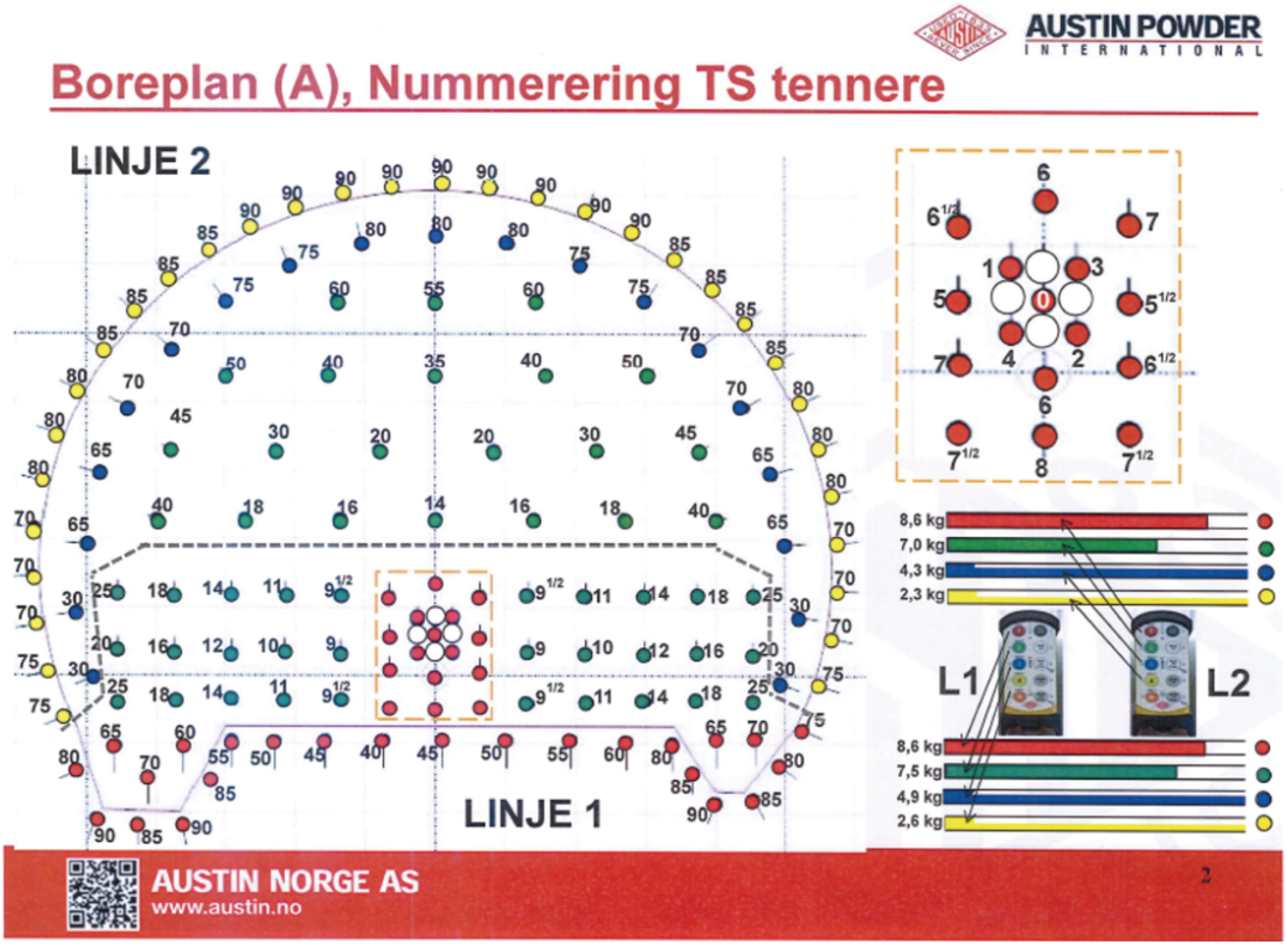


Fig. 2. Typical drilling pattern with charging plan for non-electric detonators (Statens vegvesen)

3. Assumptions for the drilling analysis

According to Handbook R761 [44], where the requirements for the accuracy of the contour hole drilling in Norway are defined, the starting position of the contour holes should be placed in the area covered by radius of the 100 mm from the line offset 100 mm from the theoretical contour of the tunnel. It gives a maximum of 200 mm of acceptable deviation of the starting position of the hole from theoretical contour.

For the need of electronic detonators test in Bjørnegård tunnel there was special, stricter requirement for the drilling accuracy presented in the Fig. 3. According to guidelines [44], starting position of the hole should be placed in the square area 100 × 100 mm from theoretical tunnel contour.

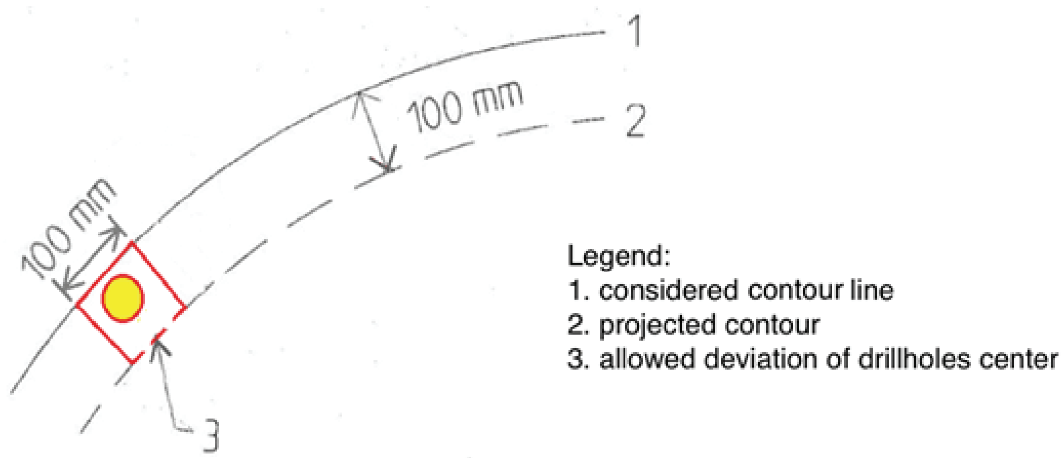


Fig. 3. Regulation for starting position of the hole for electronic detonators test [adapted from 44]

Spacing of the drilling holes in the contour was checked for seven rounds before test stretch and for all test rounds. Also, distances from drilling holes in starting position, middle point and end of the hole to the theoretical tunnel contour were checked for all considered rounds. A comparison of the drilling pattern and MWD was checked for seven rounds with non-electric detonators, but 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.

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. Designed spacing of the contour holes was 70 cm and drilling length – 5 m. The last two electronic detonators rounds were drilled with the 60 mm drillhole diameter.

4. Assumptions for the scanning analysis

In the blasting technique, verification (control) of the quality of the obtained contour of the excavation is a necessary element after the end of the technological cycle. Well-developed scanning technologies enable a very accurate assessment of the quality of the created contour (example – Fig. 4). Scanning can be done with a scanner placed on a drilling machine or can be done by surveyors using a portable scanning station. The obtained scans of the tunnel profile provide a lot of useful information for assessing the effectiveness of the blasting technique and estimating the thickness of the shotcrete layer. Limited lighting in the tunnel does not affect the scan quality. Scanning performed in Bjornegard tunnel was performed using Leica ScanStation C10, a high-accuracy long-range scanner, and can be considered as a high technology process. Precise scans gave very accurate 3D model of the excavated tunnel which can be used for geometrical and visual estimation of the scanned tunnel surface (Fig. 4).

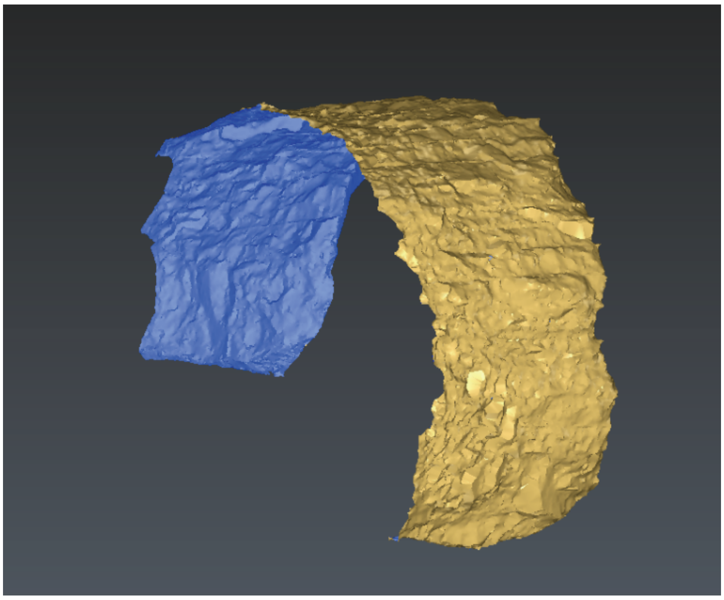
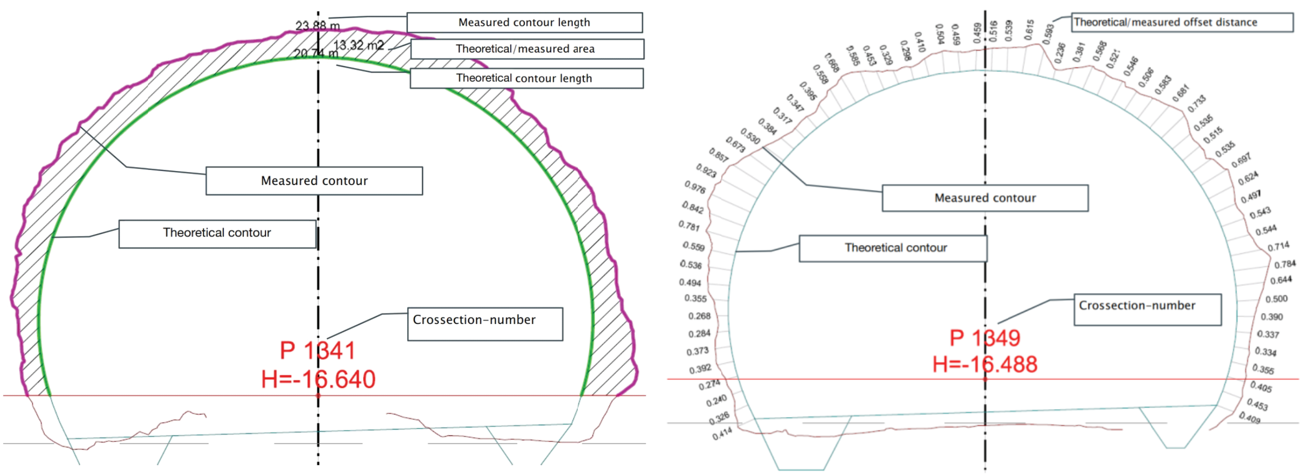


Fig. 4. Example of a 3D model of the scanned contour

Calculation and tunnel contour analyses were performed for cross sections every 0.5 m. Form of the results outcome is shown in the Fig. 5. Digital mapping was used for tunnel contour measuring [45–47], a method gaining popularity for contour quality estimation [48–50].



Overblasted area and contour length

Overbreak

Fig. 5. 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 assumption was justified 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.

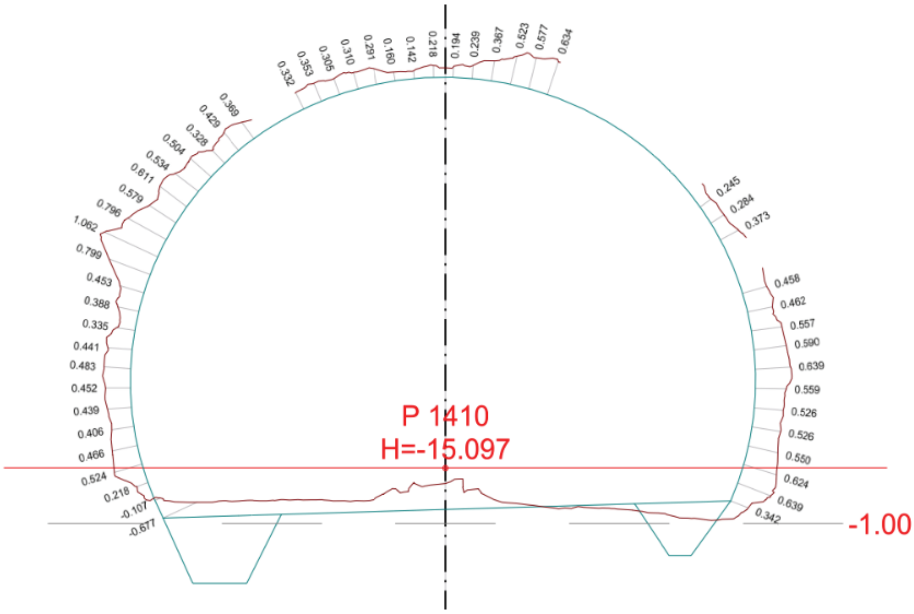


Fig. 6. Example of the rejected profile

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. The damaged scans of the cross sections were rejected from the calculation (example – Fig. 6). Additionally, some scans from the end of the round had to be rejected due to the irregular tunnel face.
After pre-selection of the cross section scans, the following data from the scanning was used for the analysis:

- theoretical contour length,
- actual contour length,
- theoretical blasted area,
- overblast area,
- distances from the theoretical contour to actual contour.

Number of scanned cross sections with the results acceptable for calculation varies for most of the rounds. Table 1 and 2 present the number of used scanned profiles and Q-values (the most commonly used system for rock support selections) for each considered round.

Table 1. Non-electric detonators: Q-values and number of scanned profiles for each blasting round

	Non-electric detonators						
Round number	1	2	3	4	5	6	7
Q-value	8,8	14	20	16	10	6,2	2,2
Number of profiles	10	11	11	11	7	8	10

Table 2. Electronic detonators: Q-values and number of scanned profiles for each blasting round.

	Electronic detonators				
Round number	8	9	10	11	12
Q-value	3.1	3.1	3.1	2.8	2.5
Number of profiles	11	9	9	10	7

Scanning of the tunnel for electronic detonators rounds was performed both before and after scaling (the process of removing loose rock from the walls and roof of the blasted area), but for the unification of the results, only results from scanning after scaling were used.

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,
- TCIT – Tunnel Contour Quality Index.

For the evaluation of an entire tunnel or more than five blasting rounds, TCI_T is calculated using following formula proposed by [40]:

(4.1) $$TCI_T = \frac{C_r}{W_1E_A+W_2E_L+W_3E_V}$$

where:

C_r – constant for range adjustment, $E_A = C_1 \cdot \hat{O}_v$ is an overbreak area element with $\hat{O}_v$ an average of total overbreak for each round, $E_L = C_2 \cdot$RCL - contour length element, $E_V = C_3 \cdot V_o$ – longitudinal overbreak variation element with V_o – the longitudinal overbreak variation. W_1, W_2, W_3 are weights and C_1, C_2, C_3 – correction factors.

5. Results and discussion

The main goal of the study is to analyze the excavation of the part of the Bjørnegård tunnel with special focus on the achieved contour quality and influence of applied initiation system. The analysis in the paper is divided in the two major parts:

- analysis of the drilling results,
- analysis of the scanning results.

5.1. Summary of the drilling results

High accuracy of the drilling length is necessary to assure the proper distribution of the explosive material in the hole. It is caused by the fact that charging settings are preprogrammed and the amount of explosives is calculated for a specific hole length. When the hole length is greater than assumed, there is a chance that the material could be distributed on an inadequate length, or the amount of explosives per meter would be less than assumed. It might lead to an underbreak and result in the need for re-blasting or an increased scaling of the remaining rock mass. In case of a too short drilling length, the effect could be opposite and the accumulation of explosives in the hole could be too large. It might lead to overbreak and decrease of the tunnel contour quality. This is also connected with a need for larger amount of rock support. The average spacing of the contour holes was calculated from the drilling data. Results present only small variation (1%) of the calculated average spacing from the theoretical assumption, both for the electronic and non-electric detonators rounds. Likewise, calculation of the average drilling length showed small variations (3%) 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 3 below.

Table 3. Drilling spacing and length summary

	Spacing		Length	
	[cm]	Misfit percentage	[cm]	Misfit percentage
Non-electric	71	1%	5.381	3%
Electronic	71	1%	5.349	3%

Calculation of the starting position of the holes (SP in Fig. 7) showed that the 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. Although 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: 54% for the rounds before the test, and 74% – for the actual test rounds. 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 holes 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 (Fig. 7).

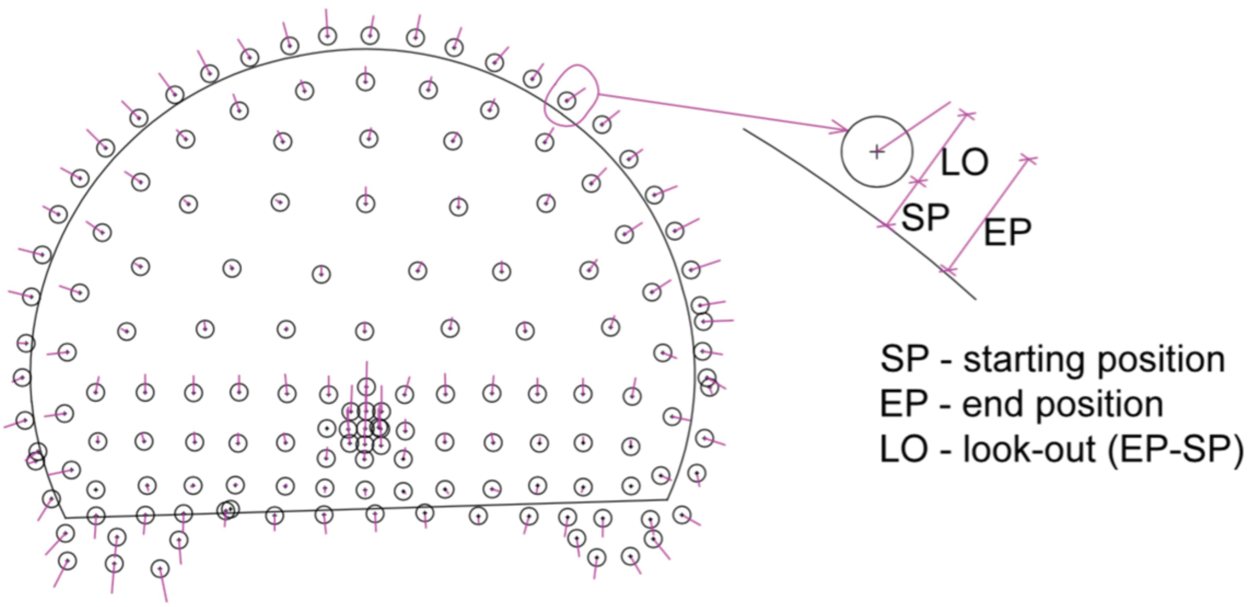


Fig. 7. Definition of starting position, end position and look-out of the hole

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 an informative character and are shown in Table 4, both with the results from starting position calculation.

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.

Table 4. Starting position, end position and look-out summary

	Start position				End position	Look-out
	[m]	% ≤ 10 cm	% ≤ 20 cm	% outside		
Non-electric	0,158	16%	54%	24%	0.519	0.359
Electronic	0,174	13%	74%	36%	0.495	0.319

5.2. Summary of scanning

In the scanning part, 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 to evaluate the influence of change of the ignition system on the quality of the contour. The assumption was, that the use of electronic detonators could have a positive impact on contour quality as reported before in literature [30–39].

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. The average blasted area for the electronic detonators rounds was 76.88 m^2. That result gives an average of 10.35 m^2 of the overblast area and RBA equal to 1.16. Summary of the results from this section is presented in the Table 5 below.

Table 5. Compilation of scanning results

	Average RCL	Average RBA	Average overbreak [mm]	TCI_T
Non-electric	1.14	1.15	453	54.1
Electronic	1.17	1.16	481	53.6

Calculation of the mentioned above values showed that there was no significant 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 outcome 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, contrary to previously published experiences [34–37]. 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 Stanens vegvesen Road Tunnel Strategy Study, in terms of overbreak calculation, 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 number 4 (62.2 cm), 5 (68.9 cm), 6 (66.1 cm), 7 (67.4 cm) from non-electric detonators rounds and in rounds number 8 (62.9 cm) and 12 (65.6 cm) from test stretch with electronic detonators. Considering guidelines for TCI_T suggested by [7] and [40] 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.

6. Conclusions

Despite the assumption of the improvement of the contour quality by the use of electronic detonators as an initiation system, as widely described by [39], and some previous studies, which suggested positive influence of the use of electronic detonators (e.g. [38]), the presented study did not support this theory. According to [7], with the increase of the Q-value, TCI_T 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, it should be stated, 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 drilling accuracy, where it has been found that in the test stretch (electronic detonators rounds) 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 a significant way.

In this paper, 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. Authors intend to test in future the influence of the electronic detonators on the excavation results for more tunnels with varied excavation conditions.

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List of notations

Symbol – Description
D&B – Drill and blast tunnelling method
ED – Electronic Detonators
EDZ – Excavation damage zone
TCI_T – Tunnel Contour Quality Index
MWD – Measurement-While-Drilling
RCL – Ratio of actual contour length to planned contour length
RBA – Ratio of actual blasted area to planned blasting area

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Analiza wpływu detonatorów elektronicznych na jakość konturu wyrobiska

Słowa kluczowe: technika strzałowa, kontur wyrobiska, skaning, detonatory elektroniczne

Streszczenie:

Obserwowany w dzisiejszych czasach rozwój metod tunelowania ukierunkowany jest przede wszystkim na redukcję czasu i kosztu budowy. Efektywność jest najważniejszym czynnikiem w procesie planowania i realizacji konstrukcji. W przypadku metod klasycznych budowy tuneli istotny wpływ na efektywność metody ma dobór sposobu urabiania masywu skalnego. W artykule do analizy wybrano technikę strzałową (drill and blast), w której efektywność można opisywać za pomocą wielu czynników, takich jak: stosunek rzeczywistej długości postępu przodka do długości wierconych otworów, poziom drgań i hałasu oraz jakość konturu tunelu, która może być scharakteryzowana poprzez przebranie, niedobranie oraz chropowatość konturu [7–14]. Minimalizacja wartości wszystkich wyżej wymienionych czynników pozwala na optymalizację procesu budowy. Jednym z istotniejszych czynników, przyczyniającym się do

redukcji czasu realizacji i kosztu obiektu w odniesieniu do użycia materiałów wybuchowych, stosowanych elementów zabezpieczenia masywu skalnego, czy ograniczenia wywozu ponadplanowego urobku, jest jakość konturu tunelu [15–16]. W literaturze, wielu autorów podkreśla znaczenie dokładności wiercenia [20–29] oraz zastosowanego sposobu inicjacji ładunków wybuchowych w odniesieniu do osiągniętej jakości konturu [30–39].

W artykule podjęto się analizy zagadnienia wpływu stosowania zapalników elektronicznych w miejsce nieelektrycznych na jakość konturu. Zagadnienie analizowano na podstawie wyników badań prowadzonych na projekcie Sandvika-Wøyen. W tunelu Kjørbo-Mølla, części tunelu Bjørnegård, który realizowany był metodą strzałową (D&B), testowano różne detonatory jako układ inicjujący wybuch. Analiza została wykonana na podstawie danych z badań terenowych, z siedmiu rund podstawowych z użyciem zwykłych zapalników nieelektrycznych i pięciu rund testowych z zapalnikami elektronicznymi.

Analiza została podzielona na dwa etapy: wiercenie i skanowanie. Obydwa etapy przeanalizowano pod kątem wykorzystania zapalników nieelektrycznych i elektronicznych. W części dotyczącej wiercenia szczególny nacisk położono na rozstaw, długość wiercenia, pozycję początkową i końcową otworów. W części dotyczącej skanowania analizowano długość konturu, powierzchnię odstrzału, przebranie i TCI_T (wskaźnik jakości konturu tunelu) [8]. Ostatnia część artykułu zawiera podsumowanie wszystkich wyników uzyskanych z rund strzałowych ze standardowym nieelektrycznym układem inicjującym oraz wyników z odcinka próbnego z użyciem zapalników elektronicznych.

W rozważaniach zakładano, że jakość konturu przy zastosowaniu zapalników elektronicznych jako układu inicjującego powinna ulec poprawie. Przeprowadzone analizy wyników badań nie potwierdziły tej teorii. Według [7], wraz ze wzrostem wartości Q, TCI_T również powinno wzrosnąć, jednak w badaniach testowych nie stwierdzono takiej zależności. Niższa wartość Q, która została zarejestrowana w rundach testowych, nie powinna mieć wobec tego wpływu na wyniki końcowe. Należy jednak stwierdzić, że aby radykalnie poprawić jakość konturu wyrobiska, należy zwrócić większą uwagę na dokładność wiercenia otworów strzałowych, tj. lokalizację początku i końca otworu. Biorąc pod uwagę wyniki z dokładności wiercenia, w których stwierdzono, że na odcinku próbnym (nabojami zapalników elektronicznych) dokładność wiercenia była faktycznie gorsza niż dla zapalników nieelektrycznych, można przyjąć, że istnieje związek pomiędzy uzyskanymi wynikami. Istnieje możliwość, że niedokładność wierceń została zrekompensowana pozytywnym wpływem zastosowania zapalników elektronicznych.

W ostatnich dwóch rundach z zastosowaniem zapalników elektronicznych średnicę otworu testowego zwiększono z 48 mm do 60 mm. Zmiana wymiaru otworu nie wpłynęła w znaczący sposób na osiągane wyniki.

W artykule dokonano analizy efektywności drążenia tunelu biorąc pod uwagę dwa wiodące parametry – jakość uzyskanego konturu i dokładność wiercenia. W celu przeprowadzenia bardziej rozbudowanej oceny, w analizie można również wziąć pod uwagę stosunek rzeczywistej długości odstrzału do długości wiercenia w danej rundzie oraz poziom indukowanych wibracji i hałasu. W dalszych badaniach przewiduje się analizę wpływu detonatorów elektronicznych na jakość konturu na podstawie większej liczby badań w tunelach realizowanych w różnych warunkach geologicznych.

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