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OPTIMAL PARAMETERS OF BLASTING IN TUNNELS USING PATRONED AND PUMPED EXPLOSIVES WITH ELECTRIC AND NON-ELECTRIC INITIATION

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Abstract: The parameters of drilling and blasting procedures during excavation of the "Grič" and "Mala Kapela" Tunnels are presented in this work. The tunnels are being constructed according to NATM (New Austrian Tunneling Method) in two parallel tubes.
By comparison of blasting with patroned and pumped explosives and electric and non-electric mode of initiation, optimal technological parameters have been defined concerning duration of blasting working cycle, progress, tunnel category and seismic effects of blasting on the tunnel support system of the parallel tunnel tube.

Ključne riječi: bušenje, miniranje, seizmički utjecaji, radni ciklus, NATM, primarna podgradni sustav tunela

Sažetak: U radu su prikazani parametri bušenja i miniranja tijekom iskopa tunela Grič i Mala Kapela. Tuneli se izvode Novom austrijskom tunelskom metodom u dvije paralelne cijevi. Uspoređujući miniranje s patroniranim i pumpanim eksplozivom i s električnim i neelektričnim načinom iniciranja, definiraju se optimalni tehnološki parametri s obzirom na vremensko trajanje radnog ciklusa miniranja, napredovanja, tunelske kategorije i seizmičkog utjecaja miniranja na tunelsku podgradu pralelne tunelske cijevi.

1. Introduction

Highway "Bregana – Zagreb – Dubrovnik", specifically its Section III "Bosiljevo – Sv. Rok", is a part of an international road route "Austria – Maribor – Zagreb – Bosiljevo – Split". The highway is classified as E-59 in the European road routes, linking northern and central parts of Europe with its south-eastern part and the Mediterranean. The "Mala Kapela" Tunnel is located at the end of Subsection IIIA2, and the "Grič" Tunnel is located on Subsection IIIB1 of the same Section.Excavation (drilling) of both tunnels is done by using NATM (New Austrian Tunneling Method), while drilling and blasting is done in similar geological surroundings – karst. Both tunnels are being constructed in two parallel tubes design, with 25m axis distance between the parallel tubes.

The left tunnel tube of the "Grič" Tunnel, (direction north- south), is 1210 meters long, while the right tube is 1235 meters long. The left tunnel tube of the "Mala Kapela" Tunnel, (direction north-south), is 5821 meters long, while the right tube is 5780 meters long. The surface of the cross section of both tunnels during excavation is identical and it amounts to app. 75 -78 m^2. Both tunnels are passing through mountain ranges with respective identical names.

Figure 1. Geographical position of "Mala Kapela" and "Grič" tunnels

Slika 1. Zemljopisni položaj tunela Mala Kapela i tunela Grič

2. Geology

The terrain where excavations for both tunnels are being done is predominantly of lower cretaceous sediments. Primary rock mass is limestone interchanging with post-sediment limestone breccia. In the rock mass of the "Grič" Tunnel, there are Jelar sediments, consisting of breccia and breccia-conglomerates, above cretaceous sediments. While the "Mala Kapela" Tunnel predominantly consists of limestone as well as dolomite and dolomite breccia. Regarding other sediments, there is presence of clay, most commonly of red and red-brown color, high-plastical and comprised ("terra rossa") – filling carstification widened discontinuities.

Tectonically, this is very complex area, with numerous faultes. The entire area is intensely carstificated, and there is presence of numerous karst sinkhole formations filled with clay material on surface. In the interior such formations are manifested as cavernous zones with tectonically intensely crushed rock material. Categorization, based on RMR classification, predicted categories II, III, IV and V of the rock mass, with predominant category III in the "Grič" Tunnel and category II in the "Mala Kapela" Tunnel.

3. Drilling and blasting

The construction of both tunnels is done by drilling and blasting, according to principles of NATM. In the areas where rock mass is favorable, construction is done entirely by drilling and blasting, whereas when less favorable categories are in question combination of drilling, blasting and machine excavation is applied, that is, only excavator, if the least favorable conditions are in question.

Excavation, according to principles of NATM, is based entirely on geotechnical characteristics of the rocks and the support element system consisting of spray concrete, armor-nets, steel arches, rock bolts and piercing support, and through the construction of which a support ring system is created. If needed, additional stabilization measures are undertaken to secure rock in top heading.

The choice of excavation technology in terms of drilling and blasting depends on the category of the rock mass. In accordance with that, different schemes of blasting have been chosen, as well as different steps of progress – depth of drilling – depending on the category of the rock mass. For the purpose of analyzing the duration of working cycle of drilling and blasting, as well as seismic effects, excavation in category II of the rock mass in both tunnels was observed.

3.1. Drilling and Blasting in the "Grič" Tunnel

The basic characteristic of drilling and blasting in the "Grič" Tunnel are the following: blasting is done by use of patroned explosives and electric initiation system, with 3.5 m maximum reach of drilling, while blast holes are 45 mm in diameter. Advance for category II of the rock mass is 3.0 meters., Tunnel drill "Atlas Copco 353 ES" with three drill hands and one hand with platform was used for drilling of blast holes. Double-wedge cut is used in all rock categories, while "Austrogel G1 Ø 30 mm" (gelatin-explosive) and "Lambrex 1 Ø 35 mm" (emulsion explosive) were used for charging cut (main) and auxiliary blast holes. Emulsion explosive "Lambrex 2 contour Ø 25 mm" was used for contour blast holes.
Current (optimal) scheme, (Figure 2), suitable for categories II and III of the rock mass, is the result obtained after monitoring the blasting parameters in the original scheme.

During inspection of the part where blasting had taken place, one can observe contour blast holes on more than 40% of the area of the rock, which demonstrates that parameters for contour blasting had been selected well.

Table 1. Detonation velocity of explosives and initiation devices used in "Grič" and "Mala Kapela" Tunnels
Tablica 1. Brzina detonacije eksploziva i inicijalna sredstva korištena u tunelima Grič i Mala Kapela

Explosive	Detonation Velocity (m/s)*
Lambrex 1	5600
Lambrex 2 contour	4200
Austrogel G1	6000
Goma II Eco	5300
Elmulex	5200
Elmulexal	5350
Elmulex P	3600
Electric detonators: Schaffler, Moment detonators: TED-BRWP 2x4 m; Millisecond detonators: 500MIZP 80 2x5 m/Cu	
Non-electric detonators: primadet sl,UEB, 100-6000 ms	

*manufactured data

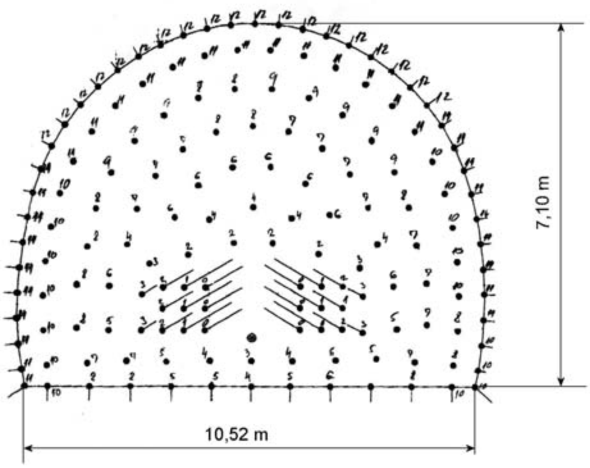

Figure 2. Drilling and blasting scheme on Tunnel "Grič"

Slika 2. Shema bušenja i miniranja- tunel Grič

3.2 Drilling and Blasting in the "Mala Kapela" Tunnel

Two blasting methods are used in the "Mala Kapela" Tunnel: pumped emulsion explosive "Elmulex P", prepared at the construction site in mobile production facility "EMOUNT 4" or patron gelatin-explosive "Goma II ECO" Ø 40 mm and emulsion explosive "Elmulex" and "Elmulexal" Ø 38 mm, for charges of cut and auxiliary blast drills. In both cases, contour "Elmulex" explosive was used for contour blast holes. Non-electric system was used for initiation of blast holes. Since booster is needed for initiation of "Elmulex P", emulsion booster was used in this case. Blast holes were 51 mm in diameter. Contour charges patrons were 25 mm in diameter, with initiator patron "Goma II Eco Ø 40 mm" or "Elmulex" Ø 38 mm. "Atlas Copco Rocket Boomer" drill with three drill hands was used for drilling of blast holes. Double-wedge cut is used for all categories of excavation.

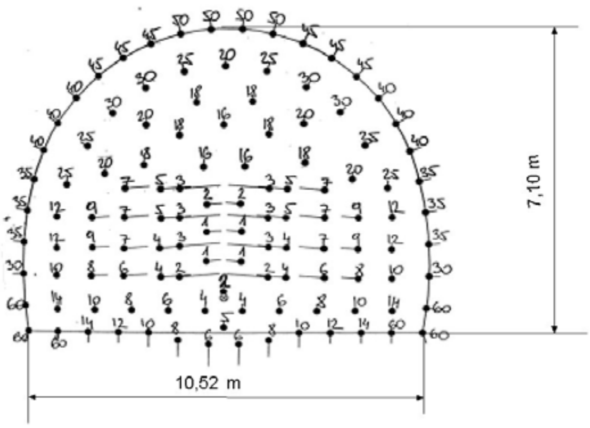

Figure 3 Drilling and blasting scheme – Tunnel "Mala Kapela"

Slika 3. Shema bušenja i miniranja- tunel Mala Kapela

4. Measurements

4.1 *Measurements of Working Cycle*

Duration of working cycle, the technological phase of drilling and blasting, was measured in both tunnels, during excavation of category II of the rock mass.
Tables 2. and 3. show working cycle duration in the "Grič" and "Mala Kapela" Tunnels.

Table 2. Working-cycle duration on Tunnel "Grič"
Tablica 2. Trajanje radnoga ciklusa na tunelu Grič

Operation no.	Description	Duration
		Category II
1	Drill start preparations	15 min
2	Drilling blast holes and drilling anchors in calotte	2 h 30 min
3	Charging blast holes	2 h
4	Detonation / Ventilation	45 min
Duration		5 h 30 min

Operation number 1 consists of placing tunnel drill at the top heading, electrification, stabilization and positioning of drill hands. The duration of operation number 2 includes effective time of drilling and adjustments of drill hands in the course of drilling. Operation number 3 includes time of preparation, charging of blast holes with explosive charges and establishing network structure of the blast field.

Table 3.Working cycle duration on Tunnel "Mala Kapela"
Tablica 3. Trajanje radnoga ciklusa na tunelu Mala Kapela

Work Op. No.	Description	duration
		II category
1	Drill start preparations	15 min
2	Drilling blast holes	3 h 45 min
3	Blast holes charging	2 h 30 min
4	Detonation / ventilation	35 min
Duration		7 h 05 min

Operation number 4 includes the duration of detonation of the blast field, ventilation and inspection of the top of the tunnel site where the detonation had occurred.

4.1.1 Drilling. Drilling scheme for the "Grič" Tunnel contains 131 blast holes, and for the "Mala Kapela" Tunnel 126 blast holes. The number of the holes that were drilled and charged may vary slightly depending on the quality of the rock on top heading, that is, on the presence of cracks filled with clay and crushed material filling. Such holes require additional work before charging (air-blowing and cleaning), that is, if rock is falling out in smaller pieces, such holes are not charged at all or smaller charging quantities are used.

The total length of drilled blast holes in the "Grič" Tunnel is 458.8 m and in the "Mala Kapela" Tunnel (where whole length of excavation is 5 meters) 630 meters for a single working cycle. In the first case, drill time per meter is 1.8 sec shorter. This difference can be ascribed to withdrawal of the drill from shorter drill hole. For 1000 meters of drilling, the time difference amounts to 30 minutes. If one looks at the number of working cycles that are needed for same advance in both tunnels, the "Mala Kapela" Tunnel is compensating the difference in drill time with fewer numbers of maneuvers of the tunnel drill, which is included in the time needed for preparation of the drilling. In case of the "Grič" Tunnel, there is simultaneous work on rock bolt boreholes and blast holes, which saves time. In case of the "Mala Kapela" Tunnel, rock bolting is a separate operation which is taking place in the tunnel tube even up to 100m behind the top of the site, which is made possible by more favorable rock mass.

Overlapping, that is, simultaneous performance of operations, results in significant saving of time. In case of simultaneous performance of several operations one should pay special attention to safety of people and the equipment in order to avoid any accidents due to the speed of work progress.

4.1.2 Blasting. Blasting in the "Grič" Tunnel is done by use of patroned explosives and electric initiation. There are 7 workers working at the construction site. Charging is done simultaneously with blast holes drilling, leaving 2 rows of empty holes between the charged holes and the drilled holes, for safety reasons. Charging is done both from the ground level of the tunnel and from the platform of the tunnel drill. Upon completion of the drill procedure, second platform is introduced, so that two platforms and ground level charging are used. The duration of charging and network building of one 3.5m long blast hole is less than one minute, that is, 55 sec. Total explosive consumption is 325 kg, while duration of charging of one kilogram of explosives is 22 sec. Blasting in the "Mala Kapela" Tunnel is done by use of patroned or pumped explosive. There are 4-5 workers who are performing the charging of blast holes using one self-propelled platform. Non-electric initiation system is used. Charging is done simultaneously from the ground level and from the platform. In case of use of patron explosives, charging and network building time of one 5m long blast hole is 1 min and 11 sec. For 1 kg of explosives (total consumption is 480 kg) 19 sec is needed. It can be noticed that average charging time for longer blast holes is significantly shorter. Taking into consideration the cited data on the number of workers, equipment as well as achieved progress, savings are even greater. Through monitoring of pumped explosive charging, it was established that the duration of working cycle is between 3 and 4 hours.

Table 4. Main parametters of blast field
Tablica 4. Glavni parametri minskoga polja

	Tunnel Mala Kapela	Tunnel Grič
Number of blast holes	126	131
Cut	V	V
Holes lenght (m)	4,8-5,0	3,5
Diameter of blast holes (mm)	51	45
Tunnel face surface (m^2)	72	78,11
Initiation	non electric	electric
Number of ignition level	22	18
Retardation between level (ms)	100-1000	80
Max explosive charge per level (kg)	33,075	64,416
Tunnel cat.-blast field	II	II
Tunnel cat.-measurement profil	II	II
Total blasting time (ms)	6000	1440
Summary explosive mass (kg)	479,72	325,0

Time consumption is considerable, because of the impossibility to charge a great number of blast holes simultaneously with one pump. Using two pumps or one pump with two hands would reduce charging time in half. Use of adequate pumps and non-electric system of initiation, that ensures simple and safe network building of the blast holes, results in manifold savings – saving time, fewer number of workers and less equipment.

4.2 *Measurements of Seismic Effects*

4.2.1 Ground Oscillation Caused by Blasting. Energy liberated by initiation of the explosive charge in a blast hole manifests itself in two forms, as a shock pulse (dynamic part) and as energy of the expansion of explosion products (pseudo static part). The percentage of the specific form in the liberated energy depends on explosive type, initiation mode, explosive charge (patroned or pumped explosives) and quality of the blast hole plug. The shock pulse energy, expands like an elastic wave radially in all directions starting from the blast hole and it can cause unwanted effects on the rock mass and tunnel support system. Oscillation velocity is proportional to rock deformation, and it is reliable indicator for determination of possible damages caused by blasting, which is used as marginal value in standards in order to define marginal values of allowed oscillation velocities for different types of constructions. The value of maximum allowed velocity for surface industrial objects, according to majority of the world standards, is 50 mm/s for ground oscillation frequencies greater than 50 Hz. There are no standards for underground facilities and tunnels. The quantities of explosive charge that does not cause damage of the rock and support system is defined according to the oscillation intensity as the function of the quantity of explosive charge per level of ignition, distance between the blast field and the support system, attenuation of seismic waves as the consequence of geological characteristics of a rock and maximum allowed value of ground oscillation.

4.2.2 Measurements. The comparison of seismic effects in category II of the rock mass was done on the basis of seismic measurements in both tunnels. Main parameters of blast field for both tunnels are given in Table 4.

Three component seismographs were used to measure ground oscillation velocities. These component velocities are the following: vertical, transversal and radial component. The instruments used for their measurements were: the White Mini-Seis II (MO-2 and MO-4), BlastMate II (MO-1) and BlastMate series III (MO-3). Measurements were carried out in the tunnel tube parallel to the tube containing the blast field at the profile that was the closest to the blast field. At that position, the distance between the explosive charge and second tunnel tube is the shortest. The position of the profile with blast field is shown on Figure 4.

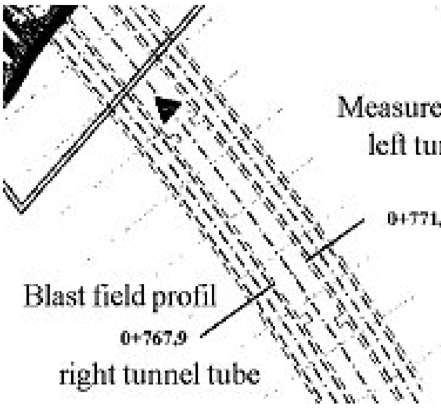

Figure 4. Position of profile with blast field

Slika 4. Pozicija profila s minskim poljem

Ground oscillation velocities are highest at the closest distance, which makes that profile a critical one because of possible damage on primary tunnel support system. Figure 5. shows the places of observation, that is, the positions of the geophones in the profile of the tunnel tube.

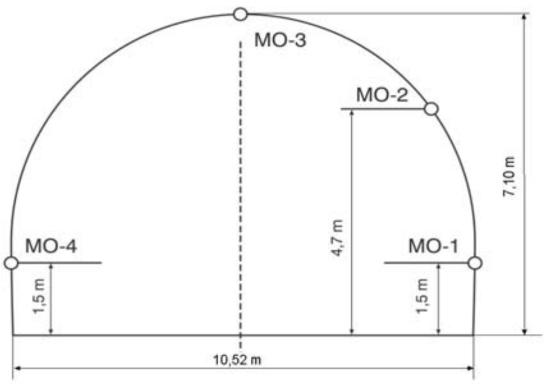

Figure 5. Measurement points
Slika 5. Točke mjerenja

Triaksial geophones are distributed along the periphery of the parallel tube. The geophones are distributed in such way that two instruments were positioned in left and right tunnel wall, 1.5 m above the tunnel ground (MO-1, MO-4), the next instrument was position 4.7m above the tunnel ground in the tunnel right wall (MO-2) and the last instrument was position on the top of the tunnel tube (MO-3). Positions of points of measurements on the profile were chosen with the purpose of establishing distribution of ground oscillation velocity in order to determine the points of highest velocities. Points (places) of observation are shown in Figure 5. Geophones are fixed in concrete sprayed rock with rock bolt and screws. Geophones fixed in that way ensure good and tight contact with the rock, that is, they ensure good transmission of oscillation from the rock to the geophone. The critical position in both cases with highest velocity of ground oscillation is point of measurement MO-2. Position MO-2 has maximum degree of freedom regarding the connection between the tunnel wall and the tunnel ground level and the top of the tunnel profile, and at the same time that tunnel wall is the closest to the blast field. Predominant frequencies of ground oscillation velocities are greater than 100 Hz. In the "Grič" Tunnel maximum oscillation velocity was caused by contour holes with total explosive charge of 64.41 kg, and in the "Mala Kapela" Tunnel those values amount to 33.07 kg for cut holes. The cited values of explosive charge quantities that caused maximum ground oscillation velocities did not cause any damage of the support system. Table 5. shows the values of ground oscillation velocities, while Figure 6. shows characteristic seismogram in the "Mala Kapela" Tunnel.

Table 5. Ground oscillation velocity (MO-2)
Tablica 5. Maksimalne brzine oscilacija (MO-2)

Velocity	Tunnel Mala Kapela	Tunnel Grič
Vertical (v_v) (cm/s)	18,69	9,34
Transversal (v_t), (cm/s)	15,43	10.97
Radial (vr), (cm/s)	19,10	10,56
Peak vector sum, (cm/s)	23,07	14,90

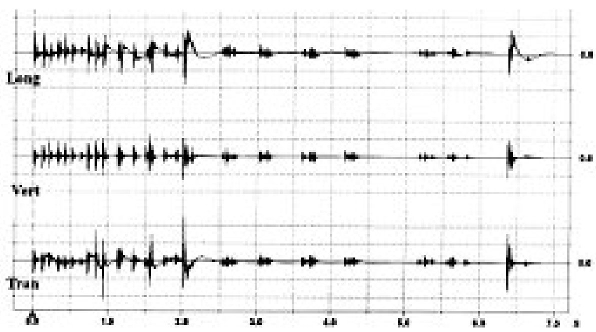

Figure 6. Characteristic oscillations velocity diagrams
Slika 6. Karakterističan dijagram brzina oscilacija

5. Results and comparison of measurements

5.1 *Comparison of Working Cycle Effectiveness*

When comparing the effect of individual working cycle as well as the achieved effects within 24-hour interval in the same category of the rock mass, it can be concluded that there is lesser degree of progress in the "Grič" Tunnel in the category II of the rock mass when compared to the "Mala Kapela" Tunnel. However, the entire 24-hour interval is more effective in the "Grič" Tunnel, backed by completion of support system after every single phase of advancement, that is, blasting. This difference is achieved by overlapping of individual operations, which primarily refers to simultaneous drilling and charging of blast holes, as well assimultaneous drilling of blast and rock bolt holes. The most critical point in the "Grič" Tunnel's working cycle is network building of the blast holes, because of the use of electric initiators, which requires expert coordination of the tunnel crew because of connection of electric conductors. Network building by non-electric system is quicker and simpler, and the possibility to leave out certain charges is smaller. The support system in the "Mala Kapela" Tunnel is not constructed after every single phase of advancement, but rather after several phases of advancement. The state of the top of the site after each blasting process is very good and it provides a basis for realization of the following course of the working cycle. However, the organization itself of the operations on the "Mala Kapela" Tunnel does not include the closing of the support system immediately after blasting has been done, which is understandable, taking into account the expected favorable geological profile and the situation in the field, with the objective of achieving quality construction as well as better dynamics of the works.

5.2 *Effects of Blasting on Primary Support System of the Parallel Tunnel Tube when Using Different Blasting Methods*

In order to avoid detrimental effects of close blasting on primary support system of the tunnel, it is necessary to carry out control measurements of seismic effects. On the basis of these measurements it is necessary to adjust blasting (number of blast holes, retardation, depth of blast holes, maximum explosive charge, sealing, type of used explosive, initiation) taking into consideration optimal working cycle of the excavation and the costs. Measurements of that kind can be used for determination of critical ground oscillation velocities for excavation of tunnels or underground chambers using blasting of the rocks of limestone and dolomite composition.

6. Conclusion

When drilling and blasting are used, according to principles of NATM, for tunnel construction, it is very important to monitor the effects of drilling and blasting, as well as the influences of blasting on surrounding objects, in this case particularly on the support system of the parallel tunnel tube, in order to achieve better and more optimal effects of blasting. The direct result of this is saving of time, more qualitative construction, and therefore, better cost-effective implementation. Active monitoring of blasting parameters and their optimization is an inevitable part of successful construction of a tunnel, which is in best interest of both the Investor and the Contractor. By analyzing drilling and blasting methods in both tunnels, conclusion is that choice of equipment and drilling machine as well as the explosives primarily depends on geo-technical characteristics of the rock mass and drifting profile. This conclusion indisputably ensues from achieved effect of the single working cycle as well as the achieved effect in 24-hour interval, which is based in the "Mala Kapela" Tunnel on predominant category II of the rock mass, so the entire effect of the excavation is based in the organizational sense on the predominant category, which creates problems in the achievement of the optimal effect in other categories of the rock mass. On the contrary, in the "Grič" Tunnel, the choice of explosives and equipment and drilling machine is not exclusively based on predominant category of the rock mass, but rather the entire geological and geotechnical influence of the rock mass on the effect of the excavation is taken into account. Therefore, the entire effect of the excavation is based on firm organizational component, wherein the expert coordination of the work shift team notably represents the most important component in the entire socio-technical system, and the result of such approach is better effectiveness of a working cycle.

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