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Research Paper

Assessment of blasted excavation inaccuracy at tunnel face and influences on tunnelling effectiveness

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ABSTRACT

Blasting has been the most effective solution for tunnel excavation in hard rock. The accuracy of the blasting works is demonstrated by the similarity between the design and the actual excavation boundary. Hence, the overbreak and underbreak of the tunnel boundary are used to evaluate the tunnel excavation. Widely applied for rock tunnelling, New Austrian Tunnelling Method (NATM) has been used for almost all highway tunnels in Vietnam. The assessment of the previous projects is essential since it provides learnt experiences and enriches the knowledge to handle the tunnelling technology. With this aim, the paper studied the case of a 500m NATM tunnel located on the N^{0}1 national highway in Central Vietnam. The practical excavation zone was examined, and the overbreak and underbreak of the tunnel boundary during the excavation by explosive was investigated. The dependences of the overbreak and underbreak on the geological and technical conditions were indicated. The tunnelling effectiveness was then assessed through the additional materials and works for the face correction activities.

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1 Introduction

Blasting has been the most effective among different technics to excavate a rock tunnel due to its robust rock-cutting capacity, conventional equipment, reduced time, and money consumption. The New Austrian Tunnelling Method (NATM) using Drilling and Blasting (D&B) has been widely applied for many transport and hydraulic tunnels. Besides the advantage of the technics, some disadvantages limit the application scoop of the related tunnelling methods: ground vibrations, noise and dust, hazardous accidents, etc. The overbreak and underbreak of the tunnel boundary is an undesirable but inevitable phenomenon caused by the inappropriate rock breakage by the explosive. It is defined as the discrepancy between the design excavation profile and the actual one.

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The overbreak and underbreak are affected by many factors: geological and geometrical conditions of the tunnel and rock mass; explosive characteristics and blasting design; construction machinery; workmanship and experiences; etc. Different overbreak types have been classified: Technical overbreak (caused by the excavation technology), Geological overbreak (caused by the geological conditions) and Specific overbreak (caused by the bench cut, the pit construction, etc.) [1]; or Quasi-static overbreak (caused by stress redistribution and deformation in the rock mass) and Dynamic overbreak [2] (caused by the impact of explosive on rock) [3]. Several expressions of the overbreak and underbreak can be used:

- Maximal gap between the actual and the design contour of the tunnel boundary:

$$\Delta = R_{actual} - R_{design} \tag{1}$$

where R_{actual} is the radius of the actual tunnel boundary in meters, and R_{design} is the radius of the designed tunnel boundary in meters. When $\Delta>0$, it is the overbreak. When $\Delta<0$, it is the underbreak.

- Differences between the actual and the design surface of the excavation face:

$$\mu_S = \frac{S_{actual}}{S_{design}} \tag{2}$$

Or:

$$\mu_S = \frac{\left(S_{actual} - S_{design}\right)}{S_{design}} \times 100\% \tag{3}$$

where S_{actual} is the surface of the actual excavation face in square meters, and S_{design} is the surface of the designed excavation face in square meters. When $\mu_S>1$, it is the overbreak. When $\mu_S<1$, it is the underbreak.

- Differences between the actual and the design excavated volume:

$$\mu_V = \frac{V_{actual}}{V_{design}} \tag{4}$$

Or:

$$\mu_V = \frac{\left(V_{actual} - V_{design}\right)}{V_{design}} \times 100\% \tag{5}$$

where V_{actual} is the actual excavation volume in cubic meters, and V_{design} is the designed excavation volume in cubic meters. When $\mu_V>1$, it is the overbreak. When $\mu_V<1$, it is the underbreak.

The data of the overbreak and underbreak during the tunnel excavation could be used to assess the blasted excavation quality and accuracy. After the excavation, the overbreak and underbreak is measured to evaluate the work and provide the necessary face correction solutions. Among different methods for tunnel profile measurement, manual surveying using the total stations to build up the actual excavation contour has been widely applied. The comparison between the design and the measured values is a good basis for the assessment and the payments of the additional construction activities caused by the overbreak and underbreak. More time and money must be paid since additional construction activities much be provided to correct the excavation face.

Aiming at gaining experiences from a past road tunnel project, a road tunnel constructed by NATM was studied in the paper. The overbreak and underbreak variations on the tunnel boundaries were measured. The dependences of the overbreak and underbreak on the geological and technical conditions were investigated. The additional materials and works for the excavation face correction were determined, and the effectiveness of the blasted tunnel excavation was concluded.

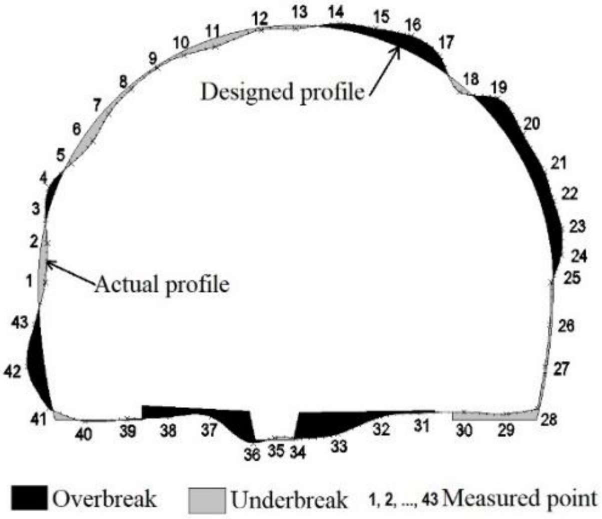

Fig. 1 – Measurement of the excavation face profile.

Table 1 – Geological characteristics of the surrounding rock mass.

Rock type	Detail
CI	Fractured but stable granite. Faults and irregular cracks. C=80÷2800kN/m^2;φ=160÷370; E=1600÷15400MPa; RMR=41÷60
CII	Severely fractured and unstable granite. Low strength with developed joints. C=80÷190kN/m^2;φ=160÷330; E=1600÷11000MPa; RMR=31÷40
DI	Boulders and highly weathered granite. Highly or completely fractured, partially loose sand. Low strength, containing considerable amount of fractured or shear zone, often causing shear crack of rock mass. Ratio of overburden height and tunnel diameter not smaller than 2. C=80÷143kN/m^2;φ=160÷290; E=1600÷7130MPa; RMR<30
DII	Boulders and highly weathered granite. Highly or completely fractured, partially loose sand. Low strength, containing considerable amount of fractured or shear zone, often causing shear crack of rock mass. Ratio of overburden height and tunnel diameter smaller than 2. C=80÷143kN/m^2;φ=160÷290; E=1600÷7130MPa; RMR=0

Table 2 – Characteristics of the tunnel support systems.

Parameter	CI	CII	DI	DII
Length of tunnel support system (m)	166.89	354.71	183	157.40
Length of drilling sequence (m)	3.50	2.00	1.00	1.00
Number of drilling sequence	48	177	183	157
Number of drilling hole per sequence	Crown: 158 Bench: 59	Crown: 157 Bench: 36	Crown: 122 Bench: 36	Crown: 133 Bench: 39
Shotcrete thickness (mm)	100	150	200	250
Lining concrete thickness (mm)	300	300	350	350

2 Case study

In this paper, the case of a road tunnel in the central region of Vietnam was studied. Located on the N^{0}1 national highway, the tunnel is 500m long and consists of two parallel tubes, each tube provides two uni-directional vehicle lanes and one pedestrian walkway. It was constructed by NATM with the excavation by explosives. The surrounding rock masses were divided into four types (CI, CII, DI, DII) following the ground classification in the Japanese standard for mountain tunnelling [4] (see Table 1). Corresponding to four rock types, four tunnel support systems (CI, CII, DI, DII) were applied (see Table 2).

The manual measurement using the total stations was executed at every excavation face. The recorded data were used to draw the tunnel's actual profile. The overbreak and underbreak were detected by comparing the actual and the designed profile (see Fig. 1).

3 Results and discussions

The overbreak and underbreak were determined based on the measured data of the actual contour of the excavation faces along the tunnel. The maximal overbreak values in four rock types were shown in Table 3.

Table 3 – Maximal overbreak values of tunnel boundaries in four rock types.

Rock types	Crown		Bench		Total	
	μ_S	Δ (m)	μ_S	Δ (m)	μ_S	Δ (m)
CI	1.16	1.22	1.37	1.22	1.19	1.22
CII	1.18	1.31	1.26	0.96	1.20	1.31
DI	1.25	1.37	1.32	1.11	1.24	1.37
DII	1.18	1.30	1.53	1.60	1.30	1.60

The variation of the overbreak μ_S (%) with the RMR value of the surrounding rock masses was investigated, and a logarithmic correlation between them was found (see Fig. 2). The obtained reversal correlation was confirmed by other authors [1, 5]. When all the surrounding rock masses were in the highest category, the maximal overbreak could be reduced by 11.99%.

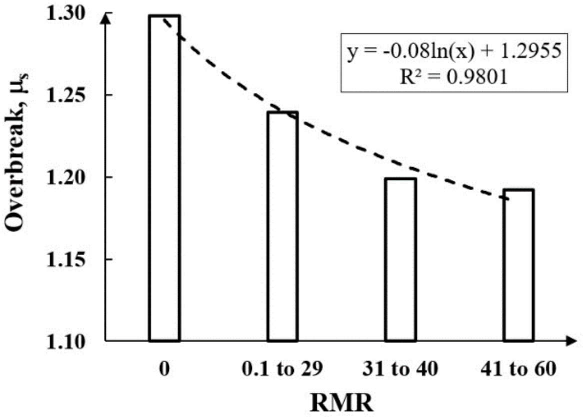

Fig. 2 – Variation of the maximal overbreak μ_S with RMR.

The overbreak surfaces (in square meters) on three components of the excavation face (crown, sidewall, and invert) were studied. It was found that the crown's overbreak surfaces were always the largest, while the sidewall's values were always the smallest in all rock types. The variation of the overbreak surfaces on 50 tunnel boundaries in the rock type CII was shown in Fig. 3 as the representative of all rock types.

The obtained tendency of the overbreak surfaces on a tunnel boundary was explained by the technical characteristics of the hole drilling and blasting work. The operations for the holes in the crown (in the upward direction) and the invert (in the downward direction) were more complicated and lower appropriate in more limited working spaces than the operations for the holes in the sidewall (in the horizontal direction). The total overbreak and underbreak volume (in cubic meters) for the whole tunnel was calculated using the average values of the overbreak and underbreak surface in four rock types(see Table 4). The tunnel portal structures were not included in the table.

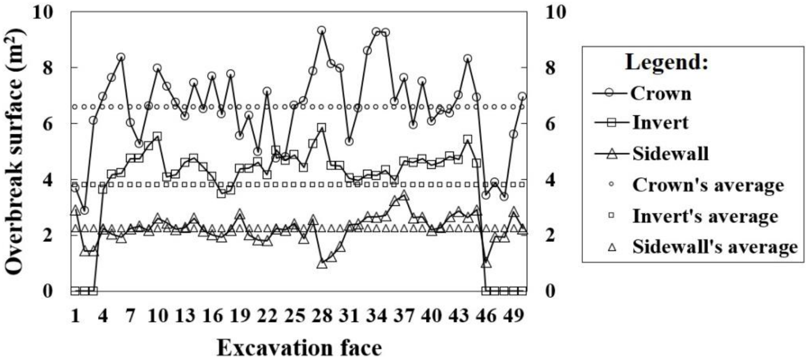

Fig. 3 – Overbreak surface of tunnel boundaries in the rock type CII.

Table 4 – Overbreak and underbreak quantity of the whole tunnel.

Rock type	Tunnel segment length (*m*)	Average overbreak surface (m^2)	Average overbreak volume (m^3)	Average underbreak surface (m^2)	Average underbreak volume (m^3)
CI	166.89	6.69	1115.89	9.50E-04	0.16
CII	354.71	12.63	4480.90	0.00E+00	0.00
DI	183.00	13.35	2442.66	1.13E-03	0.21
DII	157.40	13.79	2170.24	1.34E-03	0.21

The lining concrete was used for filling the voids created by the overbreak in the tunnel segments in the rock type CI, while the shotcrete was used for filling the voids created by the overbreak in the tunnel segments in the rock type CII, DI and DII. The payments for the filling materials, the excavation at the overbreak, the re-drilling work at the underbreak, and the related rock mucking were considered additional payments due to the non-accuracy in tunnelling using explosives. The additional items in tunnelling caused by the overbreak and underbreak were shown in Table 5.

Table 5 – Additional items in tunnelling caused by the overbreak and underbreak.

Item	Additional mount (m^3)	Increment compared to design (%)
hotcrete	9093.81	143.96
Lining concrete	1115.89	31.00
Rock excavation	10209.70	14.11
Rock re-drilling	0.58	0.05
Rock mucking	10210.28	14.11

Using the construction estimating norms promulgated by the Vietnam Ministry of Construction, the price estimate of each item was calculated, including the machinery, consumables, and labour price[6]. Besides, the additional time needed to finish the items must be counted. The working time for the additional rock excavation was determined following the norms of horizontal tunnel excavation by explosive (code AB.5815 for the crown, code AB.5821 for the sidewall and invert) [6](see Table 6). The working time for other additional items was determined in the same manner.

The reduction in tunnelling effectiveness was reflected by the payments and time spent increment due to the non-accuracy of tunnelling by explosive. The additional 1340.31 hours, equivalent to 55.84 working days, was the prolonged period for the additional rock excavation caused by the overbreak and underbreak. The total delay time for all the additional items shown in Table 5, which were much longer, showed the significant impact on the technical and economical effectiveness of the tunnel's construction of the overbreak and underbreak in D&B tunnelling.

Table 6 – Delay time for additional rock excavation caused by the overbreak and underbreak.

Item	**Amount (m^3)**	**Shift of machine (*shift*)**	**Working time (*h*)**
Crown	5062.30	97.93	783.40
Sidewall and invert	5147.40	69.61	556.91
Total	10209.70	167.54	1340.31

4 Conclusions

The tunnelling effectiveness of a road tunnel located on the $N^0$1 national highway in Vietnam was studied considering the blasted excavation accuracy. The overbreak and underbreak on the tunnel boundaries caused by the explosive during the tunnelling by NATM were investigated. The effect of the geological conditions of the surrounding rock masses on the overbreak and underbreak was confirmed by a correlation equation of RMR and μ_S. Besides, the effect of the technical construction conditions on the overbreak and underbreak was proven by the descending order of the overbreak surface from the crown to the invert and the sidewall. The payments and the time consumption for the tunnel construction were enlarged by the additional excavation face correction. The tunnelling effectiveness was reversed to the increment of the additional machinery, consumables, and labour caused by the face non-accuracy.

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