Assessment of the Efficiency of the Applied TBM Excavation Regime

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Summary

Deployment of a tunnel boring machine (TBM) for excavation of tunnel structures in particular rock mass environment requires to provide an efficient TBM advance rate by application of the proper excavation regime. The applied regime has to respond to the changes in the excavated rock mass and to the wear of cutting discs installed on the TBM cutterhead. The paper describes a method for the control of excavation efficiency using the excavation process variables monitored during the TBM operation, with subsequent calculation of specific cutting energy, contact pressure of cutting discs and theoretical torque of the TBM cutterhead.

Keywords: specific energy, rock cutting, rock strength, cutting forces

Introduction

Highway tunnels belong to geotechnical structures applying wide knowledge from mining and civil engineering. Building of tunnels generally runs in two phases – destruction and construction. The main activity in destructional phase is rock cutting, while constructional phase is related to the activities of tunnel lining. Geotechnics is a connecting research area between the mining and the civil engineering, covering a range of aspects from geology, engineering geology and hydrogeology, through rock and soil mechanics, foundation engineering and underground constructions.

At present, there are four operating highway tunnels with total length 8015 m, and other 8 highway tunnels are in construction. For the first two highway tunnels Branisko and Visnove, the longest ones so far, the exploratory galleries were excavated using the TBMs with detailed engineering-geological investigation. The tunnelling machines were equipped with the monitoring systems, developed and constructed on-demand at the Instituted of Geotechnics SAS using the deep knowledge and findings from previous long-term research of rock cutting mechanism, based on the optimization of rock cutting process with a view to achieve the minimum specific cutting energy. The monitoring systems were based on a PC platform and served for scanning, recording and archiving of the values of the monitored variables (parameters of TBM operation and performance). The designed database filled with such detailed (thrust force, revolutions, disc penetration depth, energy consumption, time) and dense (one dataset for every 2 seconds of excavation) data has been since then used for basic research of the interaction between the TBM's cutterhead and the rock mass, with a view to identify the dominant factors affecting the TBM excavation efficiency.

Methodology for assessment of the TBM excavation efficiency

Excavation process' efficiency is quantified by application of specific cutting energy. The specific cutting energy, or SE (specific energy), defines the amount of stress and strain in the very moment of rock disintegration, and thus it expresses the energy needed and consumed for the disintegration of a unit volume of rock debris from the solid rock body. It is possible to calculate the values of SE directly from the monitored excavation data in real-time during the excavation process. The main factors affecting the values of SE are: (1) structural and performance parameters of TBM, (2) geometry of cutterhead's roller discs, (3) applied excavation regime and (4) rock mass properties.

The formulas for SE calculation, where there are numbers of modifications [1-7], cover usually only the parameters of excavation regime and structural parameters of TBM cutterhead:

$$SE = \frac{2\pi .n.M_k}{S.v} \quad , \qquad SE = \frac{2M_k}{h.r_H^2} \quad , \quad (MJm^{-3}) \qquad (1)$$

where:
n (s^{-1}) stands for the cutterhead revolutions; M_k (kNm) – torque of the TBM's cutterhead; h (mm) disc penetration depth, v (mms^{-1}) – net advance rate ($v=h.n$), S (m^2) – surface area of tunnel face defined by the radius r_H (m) of TBM's cutterhead ($S = \pi r_H^2$). The value of torque and disc penetration depth is implicitly affected by the rock mass strength and by the rock mass jointing degree. The rock mass strength is numerically expressed by the stress value in the moment when the rock is disintegrated. In the in-situ conditions, the measured rock strength is decreased by the secondary influence of the rock mass jointing degree, where the increasing number of discontinuities reduced the overall strength of rock mass.

As mechanical rock cutting is based on the contact force effect induced by the cutting tool, the rock disintegration is represented by a dynamic process characterized by cyclic load and relief of the cutting tool active on the rock surface. The process dynamics is then reflected in the measured values of the cutterhead's torque and the disc penetration depth. During the loading phase, the torque gets high and the penetration depth (related to the instantaneous advance rate) decreases. After the moment of rock disintegration, the torque decreases and the measured penetration depth achieves higher values.

The research team at the Institute of Geotechnics SAS has developed a methodology for assessment of the excavation process in specific tunnel, using a fast visualization of measured values, and derived the formulas for calculation of a theoretical specific energy SE_{SA} and theoretical torque M_{kt}.

$$SE_{SA} = \frac{4}{5}\sqrt{\frac{1}{d}} \cdot \frac{F}{r_H\sqrt{h}} \quad , \quad (MJm^{-3}) \qquad (2)$$

$$M_{kt} = F_{Ct}\sum r_{DD_i} \quad , \quad (kNm) \qquad (3)$$

where:
d (mm) – roller disc diameter; F (kN) – thrust force of TBM's cutterhead; $\sum r_{DDi}$ (m) – sum of radii of concentric tracks of roller discs; F_{Ct} – theoretical value of the tangential force defined in [8] by the relationship:

$$F_{Ct} = \frac{4}{5}\sqrt{\frac{p}{d}}.F_N \quad , \quad (kN) \qquad (4)$$

where:
$F_N = F/N$ – normal disc force, N – number of roller discs installed on the TBM's cutterhead. The previous relations were derived in the paper [9].

The above mentioned theoretical values of the specific energy and torque define the case of rock cutting by a single individual disc rolling on a planar surface with normal force acting on a disk. In such configuration of disc action on rock surface, the disc might disintegrate the rock by crushing or chipping of small elements without use of cooperation of neighbouring discs, i.e. with no mechanism of volume disintegration related to formation of large rock chips. Such mechanism of rock disintegration is denoted as chipping. For the case when the inequality $SE < SE_{SA}$ is valid, the rock cutting process is efficient and there are large chips of rock produced. In case of $SE < SE_{SA}$, the applied regime of rock cutting is inefficient and unfavourable, and should be changed.

For assessment of the rock cutting regime efficiency, comparison of monitored torque values M_k and theoretically calculated torque M_{kt} values might be used:

$$M_{kt} = F_{Ct}\sum r_{DD_i} \quad , \quad (kNm) \qquad (5)$$

The energy-efficient regime of TBM excavation, when large volume rock chips are produced, is defined by the inequalities $M_k < M_{kt}$ and $SE < SE_{SA}$. For a better visualization of the relations between SE and SE_{SA}, these are depicted related to the contact pressure of the disc p_N defined as:

$$p_N = \frac{F_N}{S_k} \quad , \quad (MPa) \qquad (6)$$

where:
F_N – normal force acting on a disc, S_k – flat area of contact surface (i.e. function of penetration depth).

Selected example and discussion

Selected example shows a section 60 cm long, excavated in granodiorites of exploratory gallery Višňové, stationing 2202.20 – 2202.82 m from the eastern portal. The dataset covered 390 measurements of torque M_k, thrust force F and TBM advance rate v, measured in time intervals of 1.98

s. The TBM VoestAlpine ATB 35HA excavated the section in almost 13 minutes. Considering the time 4.8 s for one revolution of the cutterhead, this represents approximately 160 revolutions of the cutterhead.

The rock mass comprised of granodiorites with individual sections of jointed rock. Intact granodiorite exhibited the rock strength determined by Schmidt rebound hammer over 120 MPa, while in tectonically jointed sections it ranged only from 56 to 70 MPa. The detailed engineering-geological investigation determined the following values of rock strength determined by Schmidt rebound hammer as presented in the Table 1.

Behaviour of monitored values of thrust force F, torque Mk and advance rate of TBM v (Fig. 1.ms that after achieving of the quasi-constant advance rate of excavation, the ratio of F to M_k is changed, which is with high probability caused by the change of strength properties of the rock on the tunnel face. The Fig. 1. visible dynamics of rock cutting process. The presented regime variables in the Fig. 1.cific energy in the Fig. 2 do not visibly show up the efficiency of excavation in the

Tab. 1. Values of rock strength determined by Schmidt rebound hammer in selected section, as determined by the engineering-geological investigation

Tab. 1. Wartości twardości skały określone przy użyciu sklerometra Schmidta w wyznaczonym miejscu, określonym na podstawie badań inżynieryjno-geologicznych

Stationing	**Rock strength**	**Note**
2200 m	56.1 MPa	Tectonic failure
2202 m	>120 MPa	intact granodiorite
2204 m	68.9 MPa	block in crushed zone

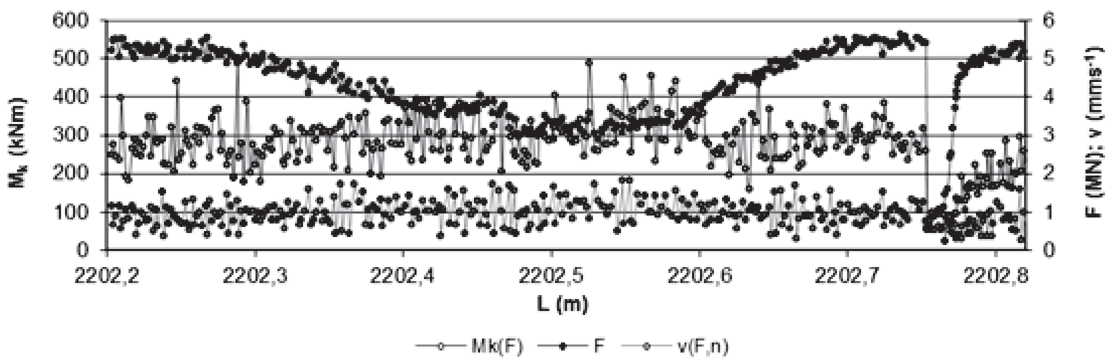

Fig. 1. Behaviour of monitored values of thrust force F, torque M_k and advance rate of TBM v depending on the stationing

Rys. 1. Zachowanie uzyskanych wartości siły odporu F, obrotu M_k oraz prędkość wykopu TBM v zależności od lokalizacji stacji

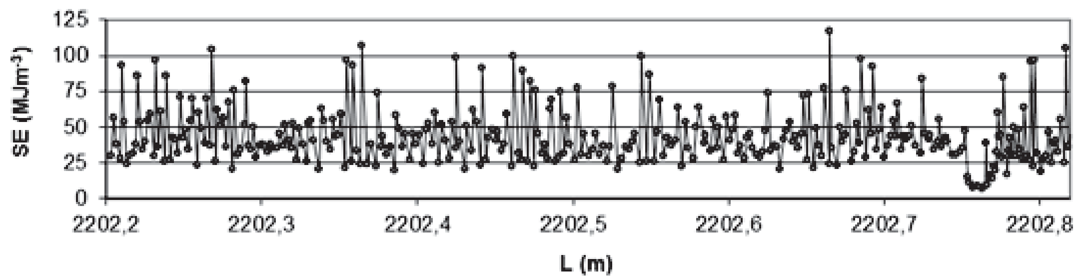

Fig. 2. Behaviour of specific energy SE in the observed tunnel section (stationing L)

Rys. 2. Zachowanie określonej mocy SE w obserwowanym tunelu (stacja L)

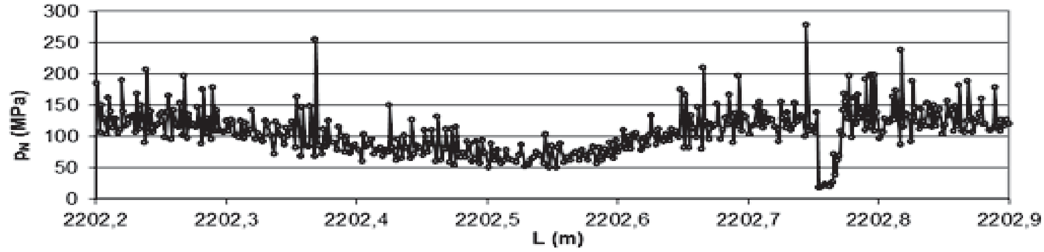

Fig. 3. Behaviour of the calculated values of the disc contact pressure p_N depending on the stationing

Rys. 3. Zachowanie wyliczonych wartości nacisku tarczy tnących p_N, w zależności od lokalizacji

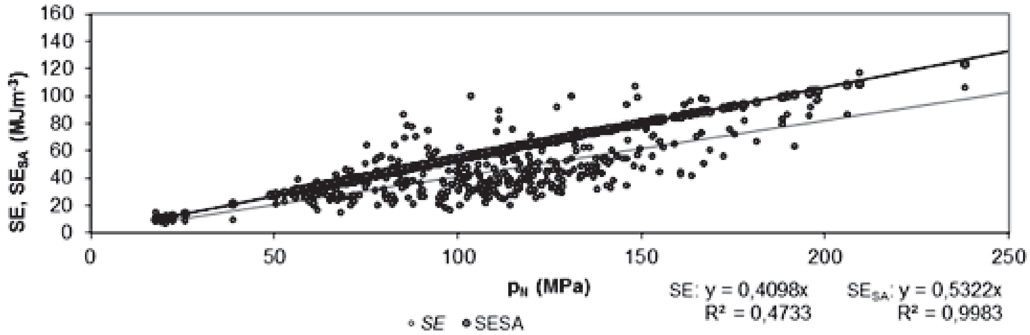

Fig. 4. Relation of the specific energy *SE* and the theoretical values of specific energy SE_{SA} depending on the disc contact pressure p_N

Rys. 4. Związek określonej mocy *SE* z teoretycznymi wartościami określonej mocy SE_{SA} w zależności od nacisku tarczy tnących p_N

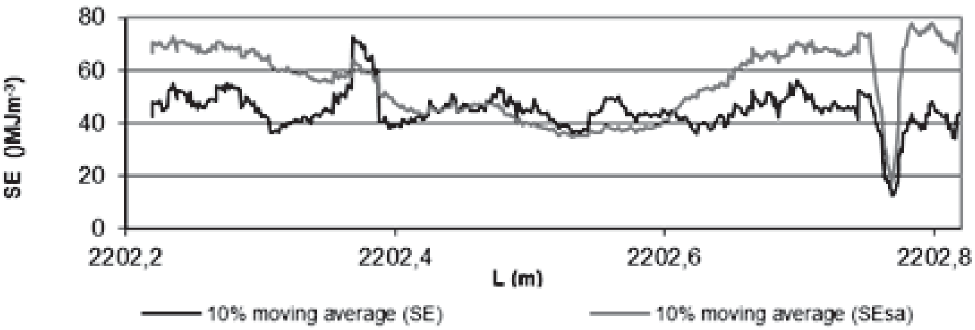

Fig. 5a. Moving average of specific energy *SE*, SE_{SA}

Rys. 5a. Średnia krocząca wartości energii rozporządzalnej *SE*, SE_{SA}

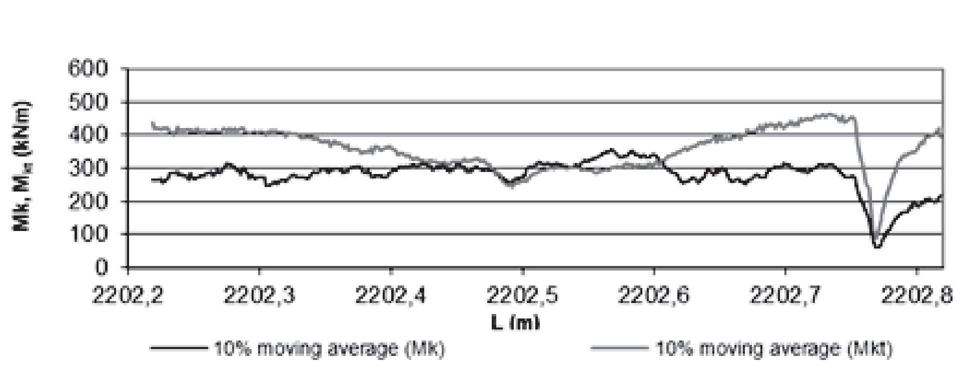

Fig. 5b. Moving average of torque M_k, M_{kt}

Rys. 5b. Średnia krocząca wartości obrotu M_k, M_{kt}

selected section; however the lower values of *SE* are more favourable for energy efficiency.

Previous research at the IGT SAS proved [10,11] that there is a strong linear correlation between the rock strength determined by Schmidt rebound hammer test and the contact pressure of the roller disc p_N. The Fig. 3 illustrates the changes of the disc contact pressure p_N in the observed tunnel section and indicates jointed sections of granodiorite in the stationing from 2202.5 to 2203 m from the eastern portal, with rock mass strength decreasing down to 70 MPa. We assume that the monitoring of TBM excavation regime parameters delivers more detailed characterization of the excavated rock mass with more specified Table 1.

The Fig. 4 shows relation of the specific energy *SE* and the theoretical values of specific energy SE_{SA}, both depending on the disc contact pressure pN. The ratio of SE/SE_{SA} implies that an efficient excavation regime was applied and the TBM employed the volume rock cutting mechanism.

A shorter part (only ca. 10 cm long) of the excavated tunnel section was characterized by decreased ration of volume rock cutting mechanism (chipping) to unfavourable crushing. This is documented in the following figures where the moving average values with the period of 10 are presented for better illustration: moving average of the specific energy *SE* and SE_{SA} (Fig. 5a) and moving average of torque M_k, M_{kt} (Fig. 5b).

Conclusion

The paper describes an alternative method for continuous assessment of the tunnelling process using the specific energy. Effective volume disintegration on the tunnel face is characterized by two ratios, i.e. $SE < SE_{SA}$ and $M_k < M_{kt}$. Both ratios were acquired during the excavation (in-situ conditions) along with monitoring of the process variables of the tunnel excavation regime.

Tunnelling process data analysis showed that the process of rock cutting by disc cutter runs in cyclic modes, i.e. with constantly alternating phases of loading and relieving of the thrust force *F*, torque $M_k(F)$ and advance rate $v(F,n)$. Individual disc cutters are supposed to exhibit even larger variances of the cutting forces. These forces increase along with the running deformation until the moment when the fissures and cracks occur. Subsequently, the cutting forces decrease significantly and the rock is crushed, split or chipped. Another cycle of rock disintegration occurs only after deployment of disc cutter acting on the rock surface. During the processing of the monitored TBM data these have to be tested by statistical methods, respectively Shewhart control charts.

Monitoring of the TBM excavation process delivers a unique possibility to identify and quantify the changes of rock mass properties during the excavation. Acquired knowledge from the detailed analysis of the excavation of highway tunnels Branisko and Visnove logically lead to the design and formation of a prediction system for dangerous failure zones in the excavated rock mass and for a control optimization system for TBM excavation process.

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Określenie wydajności zastosowanego Schematu Wykopu Maszyną Drążącą

Rozmieszczenie Maszyny Drążącej (ang. TBM) do wykopu tuneli, w szczególności w przypadku masy skalnej, wymaga uzyskania wydajnego wykorzystania TBM poprzez zastosowanie odpowiedniego schematu wykopu. Użyty schemat powinien reagować na zmiany w masie skalnej i na zużycie tarczy tnących umieszczonych na głowicy skrawającej TBM. Artykuł opisuje sposoby kontrolowania wydajności wykopu poprzez sprawdzenie zmiennych wykopu obserwowanych podczas pracy TBM z późniejszymi wyliczeniami rozporządzalnej energii tnącej, nacisku tarcz tnących i teoretycznej wartości obrotu głowicy skrawającej TBM.

Słowa kluczowe: energia rozporządzalna, cięcie skał, twardość skały, siły tnące