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INVESTIGATION OF PROCESS DYNAMICS OF TBM EXCAVATION

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Abstract: *Full-profile tunnelling with TBM enables to monitor the excavation process data, serving for further investigation of rock cutting mechanism. The monitored data provides calculation of the specific cutting energy, the contact stress of the disc cutter acting on rock surface in the instant of rock disintegration, which defines the rock compressive strength, or other useful variables. The paper discusses the relation of such calculated rock strength and specific energy in the dynamic process of rock excavation in natural conditions of rock formation. Process dynamics was described by first order linear differential equation with constant coefficients.*

Keywords: Mechanized tunnelling, Rock mass, Dynamics of rock cutting.

1. Introduction

Excavation of highway tunnels in Slovakia delivered the deployment of TBM technology. The tunnelling machines were installed with monitoring systems that were recording the data on tunnelling process variables, which were later confronted with the engineering-geological prospecting information. Large databases of acquired data were used for the investigation of the rock cutting mechanism of TBM excavation in the in-situ conditions. TBM tunnelling involves an interesting feature - the dynamics of the interaction of disc cutters with the rock on the excavated tunnel face. The synergy of disc operation is determined by the TBM's cutterhead structure, by the wear condition of the individual disc cutter contact surface, and by the applied regime of TBM operation. All of these parameters affect the excavation effectiveness in the present geological formation.

2. Theoretical Background

TBM excavation is delivered by the simultaneous action of disc cutters installed on the TBM cutterhead. During their operation, the intervals of alternated loading and relieving of the rock under the pressing disc cutter induce the increase of rock stress, which, after crossing the rock strength limit, causes chipping of rock from the compact rock mass. The mechanism of rock chipping is characterized by the crushing of rock under the disc cutter. The size of rock chips is limited by the distance or span of the neighbouring disc cutters' tracks and by the disc penetration depth. Such mechanism uses the tensile and shear stresses, making the rock chipping a less energy-consuming mechanism, as the rock shear and tensile strength is lower than the rock compressive strength.

When speaking about the energy-consumption of the rock cutting/excavation process, the issue is described as the specific energy SE, expressed by the formula

$$SE = \frac{2\pi.n.M_k(F)}{S.v(F)} \qquad [MJ.m^{-3}] \tag{1}$$

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where n [s^{-1}] – revolutions of the TBM cutterhead, M_k [kNm] – torque of TBM cutterhead, and v [$mm.s^{-1}$] – advance rate of TBM cutterhead. Revolutions, torque and advance rate represent the regime variables affected by the applied thrust force F [kN] acting on the tunel face. S [m^2] is the face area and it is a constant parameter for the respective TBM.

Specific cutting energy has become a universal parameter for the assessment of total energy demand in a rock cutting process during previous years, (Bilgin et al., 2006). SE is commonly used for the quantification of the cutting process, as it determines the size of strength and deformation in the moment of rock breaking. It is a parameter that can be determined in real time from the data recording of the cutting process by TBM. There is a correlation SE to the mechanical properties of the rock mass. In case of rock cutting regime with minimum SE, there is a relationship between the specific cutting energy and the rock strength characteristics.

Specific energy of rock cutting by a normal pressure SE_T is determined by the rock compressive strength, as described in the following equation

$$SE_T = \frac{E}{V} = \frac{1}{2}\frac{F_N}{S_N}\frac{h}{h} = \frac{1}{2}\sigma , \quad [MJ.m^{-3}] \qquad (2)$$

where E [MJ] is the energy necessary for rock cutting under pressure, V [m^3] is the volume of cut rock, the ratio F_N/S_N represents the contact pressure of the disc cutter pressing on rock in the instant of rock chipping, i.e. contact stress in the direction of normal force F_N and h is the penetration depth of disc cutter in the rock.

Theoretically, the graphic interpretation of the relation $SE_T = f(\sigma)$ is given by the line (Fig. 1). The real conditions however involve the partial action of shear and tensile stresses.

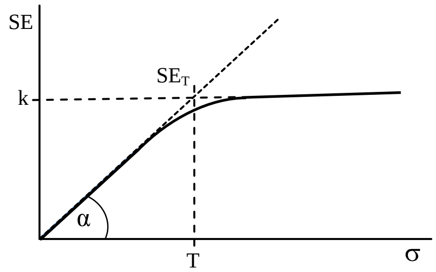

Fig. 1: Relation of specific energy and stress of rock cutting.

3. Data Processing Method

First order linear differential equation with constant coefficients and non-zero right-hand side was used for the modelling of the dependence curve of specific energy on calculated rock strength σ or the specific energy SE_T in the following form

$$SE = k\left(1 - e^{-\frac{\sigma}{T}}\right), \quad [MJ.m^{-3}] \qquad (3)$$

where the parameter k expresses the maximum value of specific energy for the selected dataset and parameter T determines the value of rock compressive strength with the SE_T value equal to maximum SE (as in Fig. 1).

The rock cutting effectiveness assessment implies from the assumption that the less energy-consuming cutting is defined by a lower k-value and higher T-value. If k=T, the tg**α** of the line $SE_T = f(\sigma)$ equals 1, i.e. 45°.

4. Results and Analysis

The initial database for analysis comprised monitored data from excavation of the exploratory tunnel Branisko. Rock mass of the tunnel was classified by engineering-geological survey into the quasi-homogeneous geological sections according to the dominant rock type occurring in the respective section, (Bohyník, 1998). The paper describes analysis of the geological sections from GC5 to GC27, with the sequence of paleogene rocks, transiting to crystalline rocks through significantly mylonitized zones further to the compact amphibolite formation. Five rock types (RT) were identified in the sections 5-27: mylonites (Kmy), biotitic gneisses (Rbp), amphibolic gneisses (Rab), granitoids (G) and prevailing amphibolites (A). Table 1 shows mean values of individual parameters for geological sections 5-27: GC – geological section; L – chainage; ΔL – section length; k – calculated parameter expressing maximum SE; T – rock mass strength value with SET equal to maximum SE; σ - calculated modelled rock compressive strength, SRH – compressive strength derived from Schmidt rebound hammer test by engineering-geological survey; PLT – compressive strength rebound hardness and PLT – rock strength derived from point load test by engineering-geological survey; α - angle of SE_T line. The table also contains mean values of monitored regime parameters in respective section: SE – specific energy; F – thrust force of cutterhead; M_k – torque of cutterhead; h – calculated penetration depth.

Tab. 1: Mean monitored and calculated values of excavation parameters from Branisko exploratory tunnel.

GC	***L*** [m]	***ΔL*** [m]	***k*** [-]	***T*** [-]	***σ*** [MPa]	***SRH*** [MPa]	***PLT*** [MPa]	***α*** [°]	***SE*** $[MJm^{-3}]$	***F*** [kN]	M_k [kNm]	***h*** [mm]	***RT***
GC5	*226*	*70*	*30*	*52.5*	*127*	*101*	*107*	*31*	*26*	*1410*	*116*	*3.38*	*G*
GC6	*297*	*49*	*27.5*	*39*	*48*	*41*	*62*	*35*	*18*	*1015*	*112*	*3.38*	*Rbp*
GC7	*345*	*64*	*35*	*39.5*	*66*	*50*	*69*	*42*	*23*	*1200*	*118*	*3.85*	*Rbp*
GC8	*453*	*26*	*36*	*38.5*	*75*	*53*	*75*	*43*	*26*	*1305*	*121*	*3.51*	*Rab*
GC9	*493*	*34*	*40.5*	*58*	*83*	*68*	*90*	*35*	*26*	*1337*	*113*	*3.26*	*Rab*
GC10	*527*	*14*	*31*	*29.5*	*20*	*6*	*35*	*46*	*12*	*592*	*75*	*5.15*	*Kmy*
GC11	*541*	*49*	*50*	*68.5*	*90*	*62*	*96*	*36*	*27*	*1279*	*104*	*3.05*	*A*
GC12	*590*	*62*	*33.5*	*38*	*63*	*62*	*96*	*41*	*22*	*1001*	*85*	*3.02*	*A*
GC13	*652*	*29*	*58,5*	*83*	*52*	*43*	*65*	*35*	*20*	*1060*	*104*	*4.21*	*Kmy*
GC14	*680*	*39*	*48*	*65.5*	*83*	*81*	*114*	*36*	*29*	*1461*	*125*	*3.29*	*A*
GC15	*720*	*51*	*47.5*	*66.5*	*108*	*75*	*116*	*36*	*33*	*1617*	*116*	*2.73*	*A*
GC16	*770*	*80*	*40*	*44*	*83*	*62*	*72*	*42*	*32*	*1473*	*116*	*2.80*	*A*
GC17	*851*	*67*	*41*	*40.5*	*93*	*81*	*114*	*45*	*33*	*1459*	*126*	*2.91*	*A*
GC18	*917*	*30*	*40.5*	*37*	*62*	*40*	*55*	*48*	*33*	*1440*	*123*	*2.95*	*A*
GC19	*947*	*43*	*51.5*	*55.5*	*119*	*87*	*88*	*43*	*42*	*1645*	*120*	*2.19*	*A*
GC20	*1033*	*20*	*47.5*	*38.5*	*78*	*56*	*57*	*51*	*36*	*1376*	*123*	*2.74*	*Kmy*
GC21	*1053*	*18*	*54*	*56.5*	*55*	*77*	*70*	*44*	*32*	*1089*	*110*	*2.55*	*A*
GC22	*1071*	*37*	*56*	*56.5*	*66*	*46*	*77*	*45*	*37*	*961*	*11*	*2.20*	*A*
GC23	*1109*	*48*	*44.5*	*43*	*118*	*70*	*81*	*46*	*38*	*1255*	*112*	*2.00*	*A*
GC24	*1193*	*34*	*57*	*88*	*147*	*98*	*136*	*33*	*44*	*1917*	*128*	*2.24*	*A*
GC25	*1242*	*1*	*57*	*88*	*84*	*54*	*78*	*33*	*32*	*1506*	*115*	*2.59*	*A*
GC26	*1274*	*21*	*48.5*	*54.5*	*147*	*92*	*140*	*42*	*44*	*2072*	*130*	*2.17*	*A*
GC27	*1295*	*4*	*44*	*41*	*141*	*105*	*129*	*47*	*42*	*2083*	*133*	*2.30*	*A*

Torque M_k, which is affected by size of the tangential force F_t, is a determining variable for calculation of specific energy SE according to the Eq. (1). Calculation of the specific energy of rock disintegration under pressure load SE_T involves the applied thrust force F as a determining variable ($F = F_N.N$, where N- number of disc cutters on TBM cutterhead; F_N – normal force of individual disc cutter). There is a non-linear relation between the variables F_t and F_N, which is transformed into the relation of specific energy on rock strength $SE = f(\sigma)$ and defined by the Eq.(3).

All the above-mentioned factors affect the resulting values of searched parameters k and T by various shares. The values of specific energy and measured rock strength change dynamically according to the instant condition of the regime parameters (thrust force, torque and penetration depth).

The value of the applied thrust force has risen with sequential advance to the middle of the excavated tunnel due to preserving the effective disc penetration depth. The sections with higher thrust force show also higher values of SE (Fig. 2). Such results provided graphic identification of unfavourable excavation regime in the geological sections 20 – 23, which resulted in emergent changes of worn disc cutters. This section long 123 m required 25 discs changes.

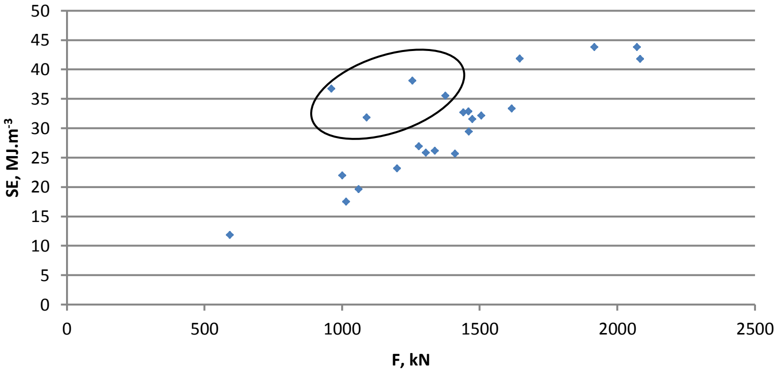

Fig. 2: Relation of specific energy on thrust force.

Averaged values of k and T for different rock formations (G, Rab, Rbp, Kmy, A) are presented in Tab. 2 and the relations of specific energy to rock strength are shown in the Fig. 3.

RT	***K [-]***	***T [-]***	***A [°]***
G	*30*	*52*	*30*
Rbp	*31*	*39*	*39*
Rab	*56*	*61*	*43*
Kmy	*45*	*49*	*42*
A	*46*	*54*	*40*

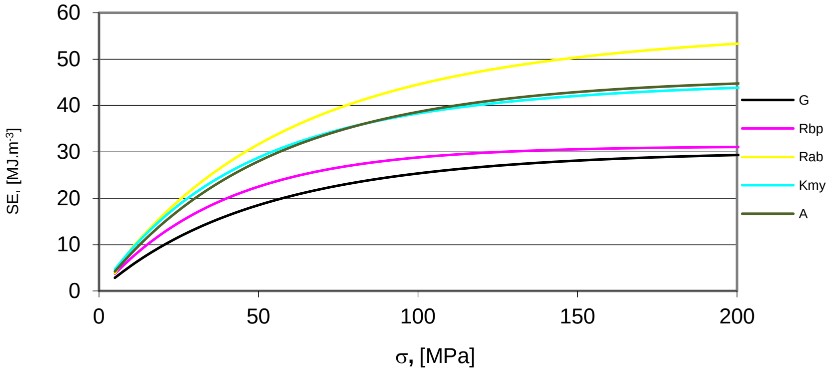

Fig. 3: Graphic interpretation of the Eq.3 for rock formations: G – granitoids, Rbp - biotitic gneisses, Rab - amphibolic gneisses, Kmy - mylonites, A - amphibolites.

The most energy-convenient excavation occurred in granitoids, the most unfavourable situation was during the excavation in amphibolic gneisses.

5. Conclusions

Obtained results confirmed the validity of theoretical assumptions on energy interpretation of rock strength. Even the TBM tunnelling process involves a number of affecting factors, the presented method provided visual identification of differences in energy consumption of the excavation in different rock types in the in-situ conditions.

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