Theoretical Investigations on the Influence of Artificially Altered Rock Mass Properties on Mechanical Excavation

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Abstract This study presents a theoretical analysis of the influence of the rock mass rating on the cutting performance of roadheaders. Existing performance prediction models are assessed for their suitability for forecasting the influence of pre-damaging the rock mass with alternative methods like lasers or microwaves, prior to the mechanical excavation process. Finally, the RMCR model was chosen because it is the only reported model incorporating a range of rock mass properties into its calculations. The results show that even very tough rocks could be mechanically excavated if the occurrence, orientation and condition of joints are favourable for the cutting process. The calculated improvements in the cutting rate (m^3/h) are up to 350% for the most favourable cases. In case of microwave irradiation of hard rocks with an UCS of 200 MPa, a reasonable improvement in the performance by 120% can be achieved with as little as an extra $0.7 \text{ kWh}/\text{m}^3$ ($= 1\%$ more energy) compared to cutting only.

Keywords Mechanical excavation · Performance prediction · Alternative rock cutting · Microwave irradiation · Laser cutting · High-pressure water jet

1 Introduction

Mechanical hard rock excavation technologies are widely used in underground mining and tunnelling for the development of major infrastructure projects as well as for

guaranteeing the access to mineral deposits and for extracting the valuable minerals from these deposits. Mechanical excavation tools like full-face tunnel boring machines and roadheaders use either discs or conical picks for applying the required forces into the rock mass. The efficiency of the processes is mainly governed by the mechanical properties of the rock type, especially strength and abrasivity. Roadheaders are limited by a uniaxial compressive strength of 150 MPa, TBMs by roughly 300 MPa. In particular, the development of underground mines furthermore requires a high flexibility of the used equipment which is mainly characterised by the turning radius of the machine. The rather simple relationship is the harder the rock, the bigger the machine, the lower the flexibility.

In order to improve the performance of their machines, most machine manufacturers on the market have introduced new machine concepts recently. Many of which change the cutting principle and apply the so-called undercutting technology (e.g. Aker Wirth “Mobile Tunnel Miner”, Atlas Copco “Mobile Miner”, Joy Mining “Oscillating Disc Cutter”, Caterpillar “Rock Straight system” and Sandvik “MX650” (Sifferlinger et al. 2017)).

In addition to changing the machine concept, the goal of extended research activities all over the world during the last decade is focussed on overcoming the highlighted restrictions. The major focus is set on artificially altering the rock mass properties in order to ease the machines’ life by reducing the UCS and rock mass rating. This can be done by introducing cracks and/or slots in the rock mass which help the subsequent cutting process with a conical tool. The technologies under consideration are high-power lasers (Batarseh et al. 2003; Parker et al. 2003; Graves and Bailo 2005), microwaves (Toifl et al. 2017; Hartlieb and Grafe 2017), high-pressure water jets (Ciccu and Grosso 2010; Miller 2016) and activated tools (Keller and Drebenstedt

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2017). Current R&D activities focus on testing principles and methods by mainly qualitatively analysing the results of tests performed on small-scaled laboratory units. In some cases, qualitative analysis of the influence of the alternative treatment method has been performed and clearly demonstrated the potential of the technology under the given circumstances of the mining environment (Hartlieb and Grafe 2017).

This paper aims at investigating and assessing the theoretical improvements which are possible by the proposed methods. Therefore, existing performance prediction models, especially for the excavation with roadheaders, will be analysed in detail. The findings will be used to demonstrate the potential of the described preconditioning methods and provide suggestions for the best application of these technologies in an industrial set-up.

2 Performance Prediction of Roadheaders

A range of performance prediction models for axial and transversal-type roadheaders has been presented over the past 20 years. These models are mostly determined empirically in specific mine sites and are valid for a limited range of rock and rock mass properties, whereas some of the models incorporate some idea about the rock mass (e.g. by taking the RQD into account) and others focus on the rock strength and some also on abrasivity and hardness of the rock.

Bilgin et al. (1996, 1997, 2002) developed a model for axial-type roadheaders. Based on the rock mass cuttability index (RMCI), they calculate the net cutting rate (NCR) according to the following formulas:

$$\text{RMCI} = \text{UCS} * \left(\frac{\text{RQD}}{100} \right)^{2/3} \quad (1)$$

and

$$\text{NCR} = 0.28 * P * (0.974)^{\text{RMCI}}. \quad (2)$$

A similar model for radial-type roadheaders is proposed by (Copur et al. 1998). Here, the NCR is based on the roadheader penetration index (RPI) with

$$\text{RPI} = P * \frac{W}{\text{UCS}} \quad (3)$$

and

$$\text{NCR} = 27.11 * e^{(0.0023 * \text{RPI})} \quad (4)$$

where P is the power of the cutter head in kW and W is the weight of the machine in t.

A range of models calculate the specific energy [SE (kWh/m³)] as a basis for further calculating the instantaneous cutting rate (NCR (m³/h), Rostami et al. 1994).

$$\text{ICR} = k * \frac{P}{\text{SE}} \quad (5)$$

with k being the energy transfer ratio (usually 0.8, Balci et al. 2004; Bilgin et al. 2005, but also values between 0.45 and 0.55 are reported by Bilgin et al. 2014), P being the cutting head power (kW or hp).

A rather complex equation for calculating SE is presented by Comakli et al. (2014a, b). This model was invented for chromite, galena, haematite and smithsonite ores, based on empirical studies. The authors claim that a roadheader could achieve a three times higher production rate than conventional drilling and blasting in these rock types. The model works best for rocks with the following properties: UCS 7.9–66.3 MPa, BTS 1.1–7.5 MPa, point load test 0.5–3.0 MPa, Schmidt hammer value 15.5–37.9, p-wave velocity 2.5–5.7 km/s, dry density 2.4–6.3 g/cm³ and porosity 2.0–31.4%. SE is calculated according to

$$\begin{aligned} \text{SE} = & 56.1 - 0.16 * \sigma_c + 4.24 * \sigma_t - 1.08 * R_n \\ & - 0.99 * V_p - 6.43 * \rho - 0.34 * n \end{aligned} \quad (6)$$

where σ_c is the uniaxial compressive strength (MPa), σ_t is the Brazilian tensile strength (MPa), R_n is the Schmidt hammer value, V_p is the p-wave velocity (km/s), ρ is the density (g/cm³), and n is the porosity (%).

Another equation for SE was developed for 44 not specified rock types (Tiryaki 2008). The model is best suited for the following rock properties: quartz content 0–99%, dry density 2.2–2.7 g/cm³, effective porosity 0–22.9%, Brazilian tensile strength 1–10.3 MPa, modulus of elasticity 5.6–65.7 GPa, UCS 7–192.9 MPa and cone indenter hardness (CI) 1.3–12. The specific energy is calculated based on

$$\text{SE} = 2.15 * \text{UCS}^{0.24} * \text{CI}^{0.68} \quad (7)$$

Tumac et al. (2007) estimate cuttability based only on the shore hardness (SH) and the UCS. Two different formulae are given for calculating the SE:

$$\text{SE} = 0.2316 * \text{SH1} - 2.0066 \quad (8)$$

and

$$\text{SE} = 0.1705 * \text{SH2} - 3.9468 \quad (9)$$

where SH1 is the average of 50 points and SH2 is the result of 15 tests at one location.

Yilmaz et al. (2015) use the hybrid dynamic hardness (HDH) to estimate the SE. The HDH is a relation between different measured rebound hardnesses based on the following equation:

$$\text{HDH} = \text{ESH}_s^2 * \text{ESH}_t \quad (10)$$

where ESH_s is the surface hardness averaging 20 rebound tests and ESH_t is the peak hardness of one single spot. SE is based on these measurements with

$$SE = 0.2662 * HDH + 0.1975. \quad (11)$$

A very simple way of calculating the ICR of transversal-type roadheaders (empirically for a 250 kW cutter-head) is also provided by Gehring (1989) with

$$ICR = \frac{719}{\sigma_c^{0.78}}. \quad (12)$$

Furthermore, Thuro and Plinninger (1999) suggested the following equation for predicting the performance of a 132 kW transversal-type roadheader:

$$ICR = 75.7 - 14.3 \ln \sigma_c. \quad (13)$$

Amongst all the reported models and approaches, the RMCR model is probably the most comprehensive way of assessing the performance of roadheaders in mining and tunnelling (Restner and Gehring 2002). It combines a range of rock and rock mass parameters, calculating the so-called rock mass cuttability rating (RMCR). The effective net cutting rate (NCR_{eff}) is then calculated based on these input parameters. The input parameters used to calculate the RMCR are UCS, block size (BS), joint conditions (JC) and the orientation of joint sets (Orj), which are all rated within a certain range specific for each parameter.

$$RMCR = R_{UCS} + R_{BS} + R_{JC} + R_{Orj} \quad (14)$$

where R stands for the rating of the respective parameters.

Additionally, the rock toughness (a relation of UCS:BTS) is used for calculating the efficient net cutting rate NCR_{eff}

$$NCR_{eff} = k_1 * k_2 * k_3 * \dots * k_i * NCR \quad (15)$$

where k_1 is a factor for the rock toughness, k_2 is a factor for the influence of discontinuities (k_2 is calculated depending on the cutting speed of the machine; for low cutting speed it is $45.6 * RMCR^{-0.9821}$ and for high cutting speed it is $9.43 * RMCR^{-0.5614}$), k_3 is a factor for the stress conditions (usually $k_3 = 1$), k_i are other project-specific factors and NCR is the theoretical NCR for intact rock with P being the power of the cutter head (kW):

$$NCR = 7 * P / UCS. \quad (16)$$

The RMCR model is the only of the described models which takes into account the influence of the rock mass, especially the nature, orientation and frequency of joints and joint sets. All other models are mostly focusing on very distinct parameters like hardness or abrasivity. Furthermore, they are only applicable in a rather narrow range of rock and rock mass properties specific for the respective study, whereas the introduction of RMCR allows for analysing a rather wide range of different properties. The goal of this paper is to demonstrate how artificially

introduced cracks and joints can influence the performance of roadheaders. The lack of analysing abrasivity, etc. in the RMCR model is considered as not being of high influence for this study. This is because hardness and abrasivity cannot be altered by any of the methods mentioned above and the respective change can therefore also not be investigated.

A brief comparison of the results of the different performance prediction models is provided in Fig. 1. It shows the net cutting rate as a function of UCS. Not all discussed models include the UCS in their calculations, and therefore this is only a small collection. The figure shows nicely how different the same rock mass properties will be assessed by different models. Especially the low values of the Tyriaki and Comakli equations at low UCS are striking. Equations presented by Copur et al. (1998) seem to predict the highest values over the entire range. The only model which allows for an incorporation of the rock mass (by means of the block size) is the RMCR model. It is demonstrated in the graph how changing the block size from < 0.03 to 0.6 m^3 will lower the cutting rate significantly. This trend is not so much reflected in the models presented by Bilgin et al. It is, however, eye-catching that these models predict a cutting rate of almost 0 at high UCS and high RQD. Only in a UCS-range between approximately 50 and 150 MPa—the Bilgin and RMCR models show similar predictions of the net cutting rate.

Fig. 1 Comparison of some performance prediction models for roadheaders (net cutting rate [m^3/h] as a function of UCS [MPa]). The following parameters were used for the calculations where appropriate in the equations: $P = 300 \text{ kW}$, machine weight = 100 t, Schmidt hammer value = 20, p -wave velocity = 4000 m/s, $\rho = 2.7 \text{ g/cm}^3$, porosity = 15%, cone indenter hardness = 6, very unfavourable conditions for RMCR model

Fig. 2 Scatterplot showing possible variations of net cutting rate, depending on the rock mass cuttability rating for rocks of different UCS according to the RMCR model

3 Rock Mass Properties and Cutting Rate

The RMCR model demonstrates how high the variation of the net cutting rate can be, depending on the properties of the rock mass (Fig. 2), whereas for low UCS production rates of 1500 m³/h are predicted (which are not displayed in the graph) even at high UCS the predicted rates can be very high (up to 100 m³/h), provided the rock mass properties would be very favourable for cutting. This high performance at high rock strength is considered as not very realistic. However, the calculation shows that under extremely favourable rock mass conditions (open and smooth cracks, good orientation of the cracks, close spacing of discontinuities) theoretically also rock masses with very high UCS could be cut economically. As also seen by the point density in the figure, the majority of cases will show an extremely low performance at high rock strength (provided the rock mass is intact).

Similarly, this can be expressed by showing the relative net cutting rate as function of RMCR. It clearly demonstrates that the lower the ranking is the better the performance will be, compared to the intact rock based on considering UCS as the only influencing parameter (Fig. 3). Very tough rocks (with low UCS:BTS ratio) show less improvement in this respect than very brittle rocks.

Saying that one has to be well aware that the occurrence of extremely favourable conditions is not very likely to happen in reality, nor can it be controlled by any alternative or hybrid rock cutting method. Figure 4 is developed to show the possible variations in net cutting rate as a function of the UCS for what is considered as realistic input properties of rock mass conditions. Furthermore, the cutting rate is set into relation to the theoretical net cutting rate. Thus, the theoretically possible improvements can be displayed.

Fig. 3 Influence of different RMCR and varying rock toughness (lines depending on rock toughness given in the legend) on the net cutting rate (after Restner and Gehring 2002)

Whilst calculating the model for one of the presented influencing parameters, the other parameters have been set to the most unfavourable conditions. As seen in Fig. 2, theoretical improvements can be very high and unrealistic if the rock mass conditions are defined to be extremely favourable. This is considered as being very unlikely in reality. The chosen way therefore helps identifying the minimum improvement based on a variation of each single parameter. If the assessment of other parameters in nature is better, then the possible improvements will be even higher.

Rock Toughness According to the RMCR model, the rock toughness is calculated as the relation of UCS:BTS. Low values represent very tough rocks, whereas high values represent very brittle rocks. The graph shows the influence of various toughness—conditions on the relative net cutting rate. It can be seen that brittle rocks will have a theoretical improvement in the cutting rate of up to 140% at high UCS, and that tough rocks will remain below the theoretical value at around 80%. A similar but not as well-pronounced trend can be seen at low rock strength.

Joint Orientation The RMCR correction factor for the joint orientation varies from 0 (= unfavourable) to −12 for very favourable conditions. Also here, the model shows that very favourable joint orientation can lead to an improvement in the cutting rate by approximately 140% in very hard rocks.

Joint Conditions The ranking for joint conditions ranges from 0 (very smooth surface, > 5 mm opening, soft/wet filling) to 30 (rough surface, closed cracks, hard/dry filling). The model therefore shows that favourable, smooth joints would be able to improve the cutting performance by up to 350% in high-strength rock conditions.

Block Size The RMCR model includes possible block sizes ranging from < 0.01 to > 0.6 m³. It is shown that large

Fig. 4 Variations of different rating properties of the RMCR model and their influence on the relative cutting rate (NCR_{eff}/NCR_{theory}). The varied parameters are given in the legends of each respective graph. **a** Variation of the block size, **b** variation of joint conditions,

c variation of joint orientation and **d** variation of rock toughness. All other parameters have been set to the least favourable conditions according to the RMCR model

blocks ($> 0.1 m^3$) will have no positive influence on the cutting performance irrespective of the rock strength. This is expressed by values being at approximately 100%. Smaller block sizes will lead to a, partly significant, improvement of up to 120% of the theoretical net cutting rate at high UCS.

As already mentioned above, the goal of different alternative fragmentation or preconditioning technologies is to introduce new cracks and fractures in the previously undisturbed rock mass. This can be either achieved by introducing longitudinal slots, preferably with lasers or high-pressure water jets, single spots in a certain arrangement (lasers, Fig. 5) and a network of radial damage patterns caused by high-power microwave irradiation (Fig. 6). Several studies confirmed experimentally that the described patterns are beneficiary for the rock cutting process, either with discs

or conical picks (e.g. Hagan 1992; Ciccu and Grosso 2010; Dehkhoda 2014; Hartlieb and Grafe 2017).

The question to solve therefore will be of how influential the respective pre-damage methods are and especially what their best possible application might be. The parameter which can be most easily controlled will be the fracture frequency, equalling the block size within the rock. Introducing slots and cracks is equivalent to reducing the size of a block towards a more efficient cutting rate. Whilst for slotting the opening width, depth and orientation of cracks can be controlled to a certain degree, this cannot be done easily in case of microwave application. Generally, microwave irradiation results in a more complex network of cracks beneath the surface. This would make a very detailed study of each single parameter necessary, which is not in the focus of this study.

Fig. 5 Possible pre-damage scenarios for slotting a rock mass with lasers or water jets. **a** Single spots in a linear alignment, **b** single spots in a random alignment, **c** parallel slots and **d** inclined slots. The solid line in **(a)** and **(b)** represents the cutting groove. **a** and **b** Topview, **c** and **d** sideview

Fig. 6 Schematic representation of damage caused by high-power microwave irradiation. Damage is originating in central spots and stretches out to a certain radius. Simplified after (Toifl et al. 2017)

Thus, the variation of other parameters than the block size will not be considered subsequently.

3.1 Slotting

In terms of block size, the parameters which can be controlled and varied are the slot spacing and the slot depth. It has already been shown 25 years ago how these two parameters will positively influence the performance of disc cutters (Hagan 1992). According to the RMCR model, a close spacing is related to a small block size (= good cutting performance). The depth of the slot, however, is very complicated to assess, whereas from a technical point of view, slots in a depth range of $\frac{1}{2}$ of the spacing would be sufficient (hard rock cutting with conical picks is mostly performed with spacing/depth $\approx 2/1$), and this might not make sense from a practical point of view. Ultimately, it will be easier to introduce rather deep slots, so that the repetition rate is

comparably low. However, very deep slots mean increasing the theoretical block size in the model. Figure 7 shows nicely how the factor depth influences this theoretical investigation. For the same slot distance (which in that case is considered as the most influential factor), the increase in depth would lead to a significant reduction in theoretically achievable values. For example, for a slot distance of up to 500 mm, a depth of 20 mm leads to a theoretical improvement in NCR of 145%, whereas increasing the depth up to 170 mm decreases the theoretical improvement to “only” 120%, which still would be a significant improvement compared to the undisturbed rock. However, for the 20-mm case one would have to introduce another slot after every single pass of the pick which is considered as technically complicated. This procedure will not be necessary in other cases where the slots are deeper and repetition will only be necessary after 5–10 passes.

Furthermore, in practice it should be considered that slots, irrespective of they are introduced by lasers or water jets, will always be open. The width will depend on the parameters (like water pressure, nozzle diameter or wavelength) used for the treatment. It is assumed that these open “cracks” will be even more beneficiary for the process. Still, the presented results are meant to be worst-case scenarios (closed cracks with rough surface) highlighting that even under bad conditions the proposed technologies can have a huge positive impact on the cutting performance of roadheaders.

3.2 Microwave Cracking

When irradiating rocks with microwaves, one has only little influence on the nature of cracking. As shown in the literature, cracks will mainly develop along grain boundaries

Fig. 7 Theoretical net cutting rate as a function of slot distance [mm] and depth of slot [mm]. Input parameters are UCS = 200 MPa, conditions, orientation and toughness very unfavourable

(Toifl et al. 2016) and, depending on the applied microwave power and frequency, a certain orientation along the surface might be achieved (Hartlieb and Grafe 2017). Also, the crack opening cannot be influenced. It is assumed that it is generally comparably narrow, cracks will potentially not be connected to one another and surfaces will be rough.

For excavation, microwave irradiation of the rock surface using an open-ended waveguide which is directed towards the rock mass is believed to be the most viable solution. When the absorption properties of the rock are good (e.g. in basalt) this can even lead to spallation at the surface (Hartlieb 2013). Although this is spectacular, it does not lead to a deeper going or widely spread network of cracks. For slower heating rocks, the damage pattern will qualitatively look like represented in Fig. 6. The central point of irradiation will be significantly damaged. Branches of cracks will reach out from this point. The crack density will therefore be governed by the distance of the irradiated spots to one another. Similar to slotting, also here the depth influence of the cracks can only hardly be assessed meaningfully. The deeper cracks go the lower, the necessary repetition rate will be. The volume of single blocks is calculated according to $V = r^2 * \pi * h/5$. This is because the observations reported in the literature describe a branching into five segments as a result of microwave irradiation. The maximum depth of cracking reported in the literature is approximately 200 mm.

Figure 8 shows the interrelation of net cutting rate, depth of damage and radius. $2 * r$ would be the spot-to-spot distance for the irradiation patterns. Assuming very small radii below 200 mm results in a theoretical improvement in the net cutting rate of 147% compared to completely intact rock, irrespective of the assumed depth of crack. This is the maximum achievable improvement when calculating with the given parameters. This is because due to the narrow crack spacing in the centre of the circles represented in Fig. 6; the calculated block size will always be below 0.01 m^3 in this area. Only when the block size exceeds that volume, the calculated performance will theoretically decrease.

Realistically, a minimum depth of 20 mm will be required in order for the cutting process to be performed. This would still mean an unrealistic high repeat rate (new microwave irradiation after every single pass of the cutting pick). However, this is the minimum depth, if cracks are deeper, a certain amount of ripping might occur (Hartlieb et al. paper under review), but this is to this point not considered in the presented study. The goal will be to decide on the optimum relation of spacing of spots, depth of damage and cutting parameters. As shown in the graphs, the radius around one irradiation spot might be up to approximately 1 m to still achieve a reasonable improvement in the cutting rate by 120%. This means that irradiation spots can be spaced as far as 2 m from each other. Introducing some overlap to be on the safe side, it is suggested that 1.5 m would be an

Fig. 8 Possible improvements in net cutting rate based on the radius [mm] of a single microwave irradiation spot. Lines represent damage depth in mm

acceptable distance. Previous experimental results show that the cutting forces can be reduced by roughly 10% when irradiating granite with microwaves (Hartlieb and Grafe 2017). This study was performed with a spot spacing of 100 mm and did only report the forces but not the net cutting rate which would have to include the breakout volume, wear of tools, availability of the machine and some more. Although it can be assumed that the order of magnitude of savings of these experiments is in the same range, the calculations presented in this study show that potentially these results could also be achieved with a much wider spacing of irradiation spots. A wider spacing will ultimately result in significant reduction in treatment time and energy spent on microwave irradiation. Whilst the specific energy consumption ranges from 198 to 992 kWh/m³, for the set-up reported in the literature the value could theoretically be decreased to 0.7 kWh/m³ (calculating with: spacing 1.5 m, 45 s irradiation time, 30 kW microwave power and 200 mm depth of damage). This set-up would add additional 10% of installed power to the roadheader (300 kW cutting drum + 30 kW microwave), but improve the cutting efficiency by 20% and consume only 1% more energy than cutting only.

4 Conclusions

A discussion on existing performance prediction models for roadheaders in mining and tunnelling is presented. The focus is set on the capability of these models to forecast the productivity of mechanical cutting concepts in very hard rocks, especially when these rocks are pre-damaged and the integrity of the rock mass is reduced. The RMCR model proves itself as most promising model because it is

the only one which considers the structure of the rock mass and includes the size of blocks as well as the condition and opening width of cracks and faults.

The results of this study show that the theoretical performance of roadheaders is strongly depending on the rock mass properties. Introducing artificial cracks will significantly improve this performance, even if other rock mass parameters are extraordinary tough.

Two different artificial types of reduction in the structure of the rock mass are presented. It is shown how “slotting” which can happen with high-power lasers or high-pressure water jets introduces parallel artificial cracks with comparably wide opening. “Microwave cracking” as the second method of pre-damage introduces a network of cracks stretching out from a central point of irradiation. This leads to a very finely distributed crack network in the centre of these irradiation points. The theoretical improvement in the net cutting rate of a roadheader can be as high as 147% when irradiating rocks with microwaves. For hard rocks with an UCS of 200 MPa, a reasonable improvement in the performance by 120% can be achieved with as little as an extra 0.7 kWh/m³ compared to cutting only.

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