ABSTRACT: Hard rock excavation by roadheaders presents an interesting alternative to mechanical excavation methods or conventional drill and blast excavation. The very low vibration emissions and precise profile of a roadheader excavation may effectively contribute especially to projects with sensible infrastructure in the vicinity. However, the higher susceptibility of this excavation method regarding the rock and rock mass properties does in fact imply a significant risk potential to the application of this method. In order to limit risks connected to insufficient excavation performance and high tool wear rates, the most important rock mass features, such as intact rock strength, rock toughness and rock fracturing must be assessed carefully in the course of preliminary site investigation. Once under operation, additional investigations, like performance documentation, tool wear analysis and rock mechanical field and laboratory investigations may be able to give a better understanding of the development of performance and tool wear as well as consequent operating costs.

1 INTRODUCTION

Even if the very low vibration emissions and precise excavation profile of a roadheader may significantly contribute especially to projects with sensible infrastructure in the vicinity, this method is still regarded as rather “exotic” alternative to commonly used methods such as drill & blast or TBM excavation. Reasons for this are usually the significant susceptibility regarding encountered rock and rock mass properties as well as general uncertainties about their application.

An assessment on roadheader application will include estimates on excavation performance and cutting tool wear, both parameters being significantly dependent from rock strength, rock abrasivity and rock mass structure. The presented paper outlines an integrated approach to minimize operational risk by giving easy-to-apply prediction tools and guidelines for preliminary site investigation methods.
KEY PARAMETERS FOR ROADHEADER ASSESSMENT

For an assessment of roadheader efficiency, the following key parameters are used as standard parameters:

The Net Cutting Rate \([\text{solid m}^3/\text{nch}]\) (NCR), is calculated from the excavated solid rock volume divided by the Net Cutting Time \([\text{nch} \cdots \text{net cutting hour}]\). The Net Cutting Time includes solely the time, when the cutter head is in contact with the rock mass and disregards any time necessary for moving of the cutterhead, loading and mucking, repositioning the roadheader, time for maintenance or so on. Given this, the Net Cutting Rate represents a parameter which is mainly influenced by the machinery layout and the geotechnical parameters of the rock mass.

The Cutting Rate \([\text{solid m}^3/\text{ch}]\) (CR) is calculated from the excavated solid rock volume divided by the Cutting Time \([\text{ch} \cdots \text{cutting hour}]\) and besides the cutting includes all secondary operations of the roadheader. Besides the influences coming from the machinery layout and geology this parameter also includes any site specific logistical and operational influences.

The Specific Pick Consumption \([\text{picks/solid m}^3]\) (SPC), also known as „pick wear rate“ or „quantitative pick wear“ is calculated from the consumption of point attack picks divided by the excavated solid rock volume in that period of time. This parameter describes the duration of use from inserting the new tool into the cutter head until it has to be removed regarding the amount of rock volume excavated.

AN INTEGRATED APPROACH FOR PERFORMANCE ASSESSMENT

The basic aim of the proposed performance assessment procedure is, to refer to internationally used, intrinsic rock and rock mass parameters and common testing standards in order to allow a rock mechanical understanding of the parameters that „steer“ the application of a roadheader. Additionally, the application of “standard” rock properties and the fact, that these might already be available from other investigations, do much contribute to the cost effectiveness of this approach.

However, it has to be kept in mind that most preliminary site investigation programs and testing procedures still are focused on the assessment of rock mass stability and some of the tests need to be adapted or be corrected in order to serve as input parameters for the purpose of rock excavatability assessment.

It has to be noted, that neither the proposed concept, nor the applied quantifications of influencing factors itself represent a completely “new” approach: Gehring (1995) introduced a similar concept for the estimation of TBM penetration, which has found broad application, and the specific rock and rock mass properties referred to in this concept have extensively been investigated by various authors as for instance Gehring (2000), Restner & Gehring (2002) or Thuro & Plinninger (2003).

3.1  Deriving NCR from Intact Rock Strength (UCS)

In a massive to moderately fractured rock mass, the theoretical net cutting rate (NCR) of a roadheader depends on the intact rock strength (UCS; [MPa]) and the nominal cutting power (P; [kW]) installed on the roadheader. This “basic” Net Cutting Rate can be approximated as presented in Equation 1.

\[
\text{NCR} = \frac{7 \cdot \text{P}}{\text{UCS}}
\]

Application remark: Besides the use of this general equation, the authors strongly recommend to refer to the empirical, machinery-specific so-called “cutting charts” which are provided by the manufacturers for specific NCR assessment.
3.2 Adjusting NCR by use of k-factors (→ NCR_{eff})

Besides the intact rock strength, a number of other rock and rock mass properties have been found to play an important role for roadheader performance, especially rock toughness and mechanically active discontinuities. In order to adjust the basic Net Cutting Rate to the specific circumstances of a project, an integrated approach is proposed by the authors, as described in the following Equation 2.

The presented equation allows a free adjustment of the number and parameters covered by the so-called “k-value” correction factors. However, examples and suggestions for k_{1}, k_{2} and k_{3} factors are provided in the following Sections 3.2.1 to 3.2.3.

\[
NCR_{eff} = k_1 \cdot k_2 \cdot k_3 \cdot \ldots \cdot k_i \cdot \frac{7}{UCS} \cdot P
\]

With: NCR_{eff} = effective Net Cutting Rate [solid m³/net cutting hour]; k_{1}, k_{2}, k_{3} ... k_{i} = site specific correction factors; UCS = Unconfined Compressive Strength [MPa].

3.2.1 Rock Toughness Rating (k_{1})

The specific “rock toughness” will determine the ability of a rock to withstand fracture propagation. With an increasing (“tough” behaviour) or decreasing (“brittle” behaviour) rock toughness, the specific energy demand required for rock fragmentation will decrease or increase by approximately ± 20-25% according to empirical data.

A number of rock mechanical concepts are available for the assessment of rock toughness, including energy-related approaches, based on analysis of the stress-strain path of UCS tests in the pre- and/or post-failure section (for instance “fracture energy”, “destruction work” concept). Nevertheless, toughness assessment based of the ratio of Unconfined Compressive Strength (UCS) and Brazilian Tensile Strength (BTS), also referred to as “Toughness Coefficient” (TC) is a quite common, economical and proven method and this procedure is also recommended by the authors.

However, it has to be considered, that for an appropriate assessment of the Toughness Coefficient UCS tests and BTS tests must be conducted on the same rock types and – in isotropic rock types – must be tested in the same orientation regarding anisotropic structure (i.e. foliation, bedding planes).

Based on empirical data, classification terms and values for k_{1} factor are given in the following Table 1.

<table>
<thead>
<tr>
<th>Toughness Coefficient TC</th>
<th>Classification</th>
<th>Correction factor ( k_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 6</td>
<td>very tough</td>
<td>-25% / 0.75</td>
</tr>
<tr>
<td>6 - 8</td>
<td>tough</td>
<td>-15% / 0.85</td>
</tr>
<tr>
<td>8 - 15</td>
<td>normal</td>
<td>±0% / 1.0</td>
</tr>
<tr>
<td>15 - 20</td>
<td>brittle</td>
<td>+10% / 1.1</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>very brittle</td>
<td>+20% / 1.2</td>
</tr>
</tbody>
</table>

Remark: Besides the use of this suggested procedure, the use of other methods, such as rock plasticity, relative rock elasticity, specific fracture energy or destruction work might also be useful.

3.2.2 Discontinuity Rating using the RMCR (k_{2})

The “basic” Net Cutting Rate as derived from Equation 1 (Section 3.1) represents the “worst case” excavation process, where the intact rock has to be chipped to small debris thus demanding a relative high amount of energy. However, rock mass features, like mechanically active bedding planes with spacings lower than 30 cm will significantly assist the cutting performance of a roadheader. This effect might be taken into account by application of a k_{2}-factor for rating the
effect of pre-existing discontinuities. According to the current state of knowledge, four main influencing rock mass parameters have been identified:

1. Strength of the intact rock
2. Block size formed by discontinuities
3. Conditions of discontinuities
4. Orientation of discontinuities (main structures) in relation to the attack direction of the cutting process

Detailed investigations resulted in the creation of a new rock mass rating system for rock mass cuttability assessment, called “Rock Mass Cuttability Rating” (RMCR) first published by Restner & Gehring, 2002. The parameters for calculating the RMCR are presented in Equation 3 and Tables 2 - 5.

$$
RMCR = R_{UCS} + R_{BS} + R_{JC} + R_{Ori}
$$

With: RMCR = Rock Mass Cuttability Rating; $R_{UCS}$ = Rating factor for Unconfined Compressive Strength; $R_{BS}$ = Rating factor for block sizes; $R_{JC}$ = Rating factor for joint conditions; $R_{Ori}$ = Rating factor for orientation of joint set.

### Tables 2 – 5: RMCR Rating factors for UCS, Block Size, Joint Conditions and Orientation of Joint Sets.

<table>
<thead>
<tr>
<th>$R_{UCS}$ – Rating of Unconfined Compressive Strength</th>
<th>$R_{BS}$ – Rating of Block Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCS [MPa]</td>
<td>Rating</td>
</tr>
<tr>
<td>1 - 5</td>
<td>15</td>
</tr>
<tr>
<td>5 - 25</td>
<td>12</td>
</tr>
<tr>
<td>25 - 50</td>
<td>7</td>
</tr>
<tr>
<td>50 - 100</td>
<td>4</td>
</tr>
<tr>
<td>100 - 200</td>
<td>2</td>
</tr>
<tr>
<td>&gt; 200</td>
<td>1</td>
</tr>
<tr>
<td>&lt; 0.01</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$R_{JC}$ – Rating of Joint Conditions</th>
<th>$R_{Ori}$ – Orientation of Joint Sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>Aperture</td>
</tr>
<tr>
<td>rough</td>
<td>closed</td>
</tr>
<tr>
<td>slightly rough</td>
<td>&lt; 1 mm</td>
</tr>
<tr>
<td>slightly rough</td>
<td>&lt; 1 mm</td>
</tr>
<tr>
<td>smooth</td>
<td>1 – 5 mm</td>
</tr>
<tr>
<td>very smooth</td>
<td>&gt; 5 mm</td>
</tr>
</tbody>
</table>

The RMCR value can be used to estimate the $k_2$-factor for the specific influence of the rock mass structure as shown in Equation 4 (see Figure 1 for data background).

$$
k_2 = 45.6 \cdot RMCR^{-0.9821}
$$

With: $k_2$ = correction factor for discontinuity effect; RMCR = Rock Mass Cuttability Rating.

**Application remark:** The following Figure 1 gives rise to the supposition, that the RMCR value is additionally influenced by the specific cutting speed. The higher torque of the cutter gear, which is a consequence of the cutting speed reduction, could explain the effect of the cutting speed on the RMCR value. Consequently, the application of low cutting speed increases the positive effect of rock mass features on the roadheader cutting process. This effect also has to be considered in the rock mass cuttability assessment.
3.2.3 Stress Condition Rating ($k_3$)

Several theoretical analysis as well as empirical experiences give rise to the supposition, that the primary and secondary stress condition during underground excavation might play an additional role for rock excavation and tool wear (Gehring, 1995, Alber, 2008). Regarding these findings, high secondary stress conditions at the face might lead to decreasing excavation rates and increasing tool wear rates.

However, from the author’s point of view there is no sufficient empirical data available in order to derive an appropriate rating. As long as the specific application is well inside the usual range of application it is therefore suggested to use a $k_3$-factor of 1.0.

3.3 Deriving Cutting Rate (CR) from NCR$_{eff}$

In order to derive Cutting Rates from the adjusted Net Cutting Rates (NCR$_{eff}$) several site specific logistical and operational aspects have to be considered. The factor used for decreasing NCR$_{eff}$ is depending on the amount and duration of standstills / secondary works that have to be carried out during operation of the roadheader and as well depending on the skill of the operator.

From the authors experiences a overall factor of about 0.5 might be used for a rough estimation of CR from NCR$_{eff}$.

4 REMARKS ON UCS TESTING

Based on internationally applied rock testing standards UCS testing is usually carried out on cylindrical rock specimen with a length-to-diameter ratio of l:d $\geq$ 2.0 and loading rates between 0.5 and 1.0 MPa/s. However, for the assessment of rock cuttability, adapted tests are commonly carried out, which are performed on cylindrical rock specimen with an l:d ratio of $\approx$ 1.0 and a loading rate of 10 kN/s, which is 5 to 10 times higher than the above mentioned standard rates if referred to a 50 mm diameter specimen. Those tests are usually also referred to in the empirical cutting charts as provided by manufacturers for NCR assessment.

As a reason of these differences, the practical impact of loading rate and l:d-ratio on measured UCS value have in the past been topic of a number of scientific researches as well as numerous disputes on job sites. Based on the actual knowledge and taking into account the investigations presented by Thuro et al, 2003 and Schaffer, 2008 the authors recommend the following:

- The influence of different l:d-ratios for homogenous rock types is in a range of approximately 10 - 20 %, if comparing specimen with l:d = 1.0 to specimen with l:d = 2.0. An additional effect is, that longer samples increase the probability of inherent rock “defects” in the ample, which might reduce measured UCS. It is therefore
advisable to consider the effect of differing load-ratios and to compensate UCS values for instance by application of the Oberth & Duvall formula as presented in the DGGT, 2004 testing recommendation.

- The influence of differing loading rates has recently been investigated by Schaffer, 2008, who found an increase in UCS of only about 5% to 15% as an result of a 9900-times higher loading rate (0.1 kN/s vs. 990 kN/s) in selected homogenous sandstone and granite (see Figure 2). These results are quite in accordance with similar results, as presented for instance by Komura & Inada (2006) or Lajtai et al. (1991) and give rise to the supposition, that in the usual scale of loading rates this effect might practically be neglected.

![Figure 2](Image)

Figure 2. Examples for the loading rate effect on the UCS of granite (left figure) and sandstone (right figure) from: Schaffer, 2008.

REFERENCES


