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• Rock & rock mass cuttability assessment
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EXCAVATION METHOD SELECTION CRITERIA

ROCK MASS

PROJECT

ENVIRONMENT

- Rock Mass Conditions
- Rock Compressive Strength

Drill & Blast
- Shield Machines
- Mechanical Excavation with Breakers / Splitters

Hardrock TBM

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MECHANICAL TUNNEL EXCAVATION

- Part face excavation
- Hard (stable) rock
- Mechanical Tunnel Excavation
- Soft (loose) rock
- Full face excavation
ROADHEADER TUNNEL EXCAVATION

CAI - CERCHAR Abrasivity Index [mm]

UCS - Uniaxial (Unconfined) Compressive Strength [MPa]

- Limestone (867): UCS=85MPa, CAI=1.1
- Sandstone (1197): UCS=80MPa, CAI=2.2
- Basalt (64): UCS=119MPa, CAI=2.5
- Diabase (17): UCS=152MPa, CAI=2.2
- Arenite (3): UCS=85MPa, CAI=2.9
- Gneiss (145): UCS=101MPa, CAI=3.0
- Quartzite (51): UCS=153MPa, CAI=3.9
- Schist (136): UCS=65MPa, CAI=1.8
- Dolomite (127): UCS=113MPa, CAI=1.8
- Siltstone (120): UCS=73MPa, CAI=1.2
- Diorite (89): UCS=114MPa, CAI=3.9
- Coal (56): UCS=24MPa, CAI<0.5
- Shale (133): UCS=52MPa, CAI=0.9
- Gneiss (145): UCS=101MPa, CAI=3.0
- Limestone (867): UCS=85MPa, CAI=1.1
- Quartzite (51): UCS=153MPa, CAI=3.9
- Arenite (3): UCS=85MPa, CAI=2.9
OVERALL CUTTING PERFORMANCE TOO LOW
CUTTING TOOL CONSUMPTION TOO HIGH
EXCAVATION METHOD SELECTION CRITERIA

CRITERIA FOR ROADHEADER SELECTION

• Complex and variable geology
• Free access to tunnel face
• Ability for partial face excavation
• Smooth excavation process
• Not sensitive against squeezing rock mass
• High cutting performance in weak and medium strong rock mass
EXCAVATION METHOD SELECTION CRITERIA

CRITERIA FOR ROADHEADER SELECTION

• Flexible system in terms of profile shape and size
• Accurate excavation resulting in less over-break and less concrete installation work
• Low primary investment
• Fast mobilization
GEOTECHNICAL CHARACTERIZATION

DIFFERENTIATION BETWEEN ROCK AND ROCK MASS

• Rock:
  Natural aggregate of components including minerals, rarely glasses, fragments of minerals and rocks, binding agent and X-ray amorphous substances.

• Rock mass:
  Combination of rock and discontinuities, separating rock into different rock bodies and forming characteristic areas of homogeneity.
REPRESENTATIVE ROCK SAMPLING

KEY SUCCESS FACTOR FOR ROCK CUTTABILITY ASSESSMENT

Select typical rock samples in correct quality and sufficient quantity
PRECISE LABORATORY ROCK TESTING

LEADING TO REPRESENTATIVE ROCK TEST RESULTS

Rock test results representing intact rock properties
INTERPRETATION OF ROCK TEST RESULTS

PRINCIPALLY SIMPLE, BUT VERY EFFECTICE EVALUATIONS

Quick characterization of rock fracturing behavior

Rock toughness & Fracture energy
## SUMMARY OF ROCK TEST RESULTS

PROVIDING CLEAR OVERVIEW OF ROCK CHARACTERISTICS

<table>
<thead>
<tr>
<th>RATING FIGURES</th>
<th>very low</th>
<th>low</th>
<th>average</th>
<th>high</th>
<th>very high</th>
<th>ABRASIVENESS RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_c$ = 154</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>extremely abrasive</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_c:\sigma_t$ = 15</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>highly abrasive</td>
</tr>
<tr>
<td>Toughness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{tot}:V_{el}$ = 0,97</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>very abrasive</td>
</tr>
<tr>
<td>Plasticity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_d:\sigma_c$ = 114</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>considerably abrasive</td>
</tr>
<tr>
<td>Relative elasticity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>moderately abrasive</td>
</tr>
<tr>
<td>$W_l:\sigma_c$ = 0,48</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>little abrasive</td>
</tr>
<tr>
<td>Specific fracture energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>not abrasive</td>
</tr>
</tbody>
</table>

* $F^* = 0.046 \times CAI^{2.68}$

CAI 3.49 1.69
Net Cutting Rate for MR/MT/MH620 (300 kW installed cutter head power)
equipped with Cutter Head 105-G 57+ and 22 mm TC Diameter Picks
according to Uniaxial Compressive Strength for Intact to Moderately Fractured Rock Mass
for Cross Sections > 35 m²

The volume of cut rock per effective net cutting time (counted in net cutting hours ... nch) defines the net cutting rate. The effective net cutting time is defined by the time the cutter head is in contact with the rock and actually cutting. Thus, supplementary actions of the cutter head like profiling and loading or any idling time during cutting operation does not contribute to the effective net cutting time.

For calculating machine productivity or excavation performance, please consider that the ratio of machine operating hours to net cutting hours is usually about 2:1 (ranging from 1.5:1 to 2.5:1). This difference in the times is caused by a number of delays and standstills (non-productive times) during cutting operation, when the machine is operated at the face.

Uniaxial Compressive Strength measured on H:D=1:1 specimen with 50 mm diameter @ 10

\[ \text{NCR}_{\text{theor}} = 24 \text{ solid m}^3/\text{nch} \]
\[ \text{UCS}=100 \text{ MPa} \]
\[ \text{UCS:BTS}=8-15 => \text{normal rock} \]

very tough rock  normal rock  very brittle rock
Net Cutting Rate for MT620/720 (300 kW installed cutter head power) equipped with Cutter Head 105-G 72 and 25 mm TC Diameter Picks according to Uniaxial Compressive Strength of Intact Rock with Normal Fracturing Behavior for Different Cross Sections.

The volume of cut rock per effective net cutting time (counted in net cutting hours ... nch) defines the net cutting rate. The effective net cutting time is defined by the time the cutter head is in contact with the rock and actually cutting. Thus, supplementary actions of the cutter head like profiling or loading or any idling time during cutting operation do not contribute to the effective net cutting time.

For calculating machine productivity or excavation performance, please consider that the ratio of machine operating hours to net cutting hours is usually about 2:1 (ranging from 1.5:1 to 2.5:1). This difference in the times is caused by a number of delays and standstills (non-productive times) during cutting operation, when the machine is operated at the face.

Uniaxial Compressive Strength measured on RD=1:1 specimen with 50 mm diameter @ 10 kNs

Technical limit defined by machine
Economical limit defined by operation

For cross sections > 35 m²
For cross sections < 35 m²
Specific Pick Consumption (SPC) for Low Speed Cutting with Transverse Cutterhead and 22 mm TC Diameter Picks of High Quality

Uniaxial Compressive Strength measured on H:D=1:1 specimen with 50 mm diameter @ 10 kN/s

Effective minimum specific pick consumption: 0.005 picks/solid m³

SPC=0.1 picks/solid m³ @ UCS=100 MPa & CAI=1.0

CAI .... CERCHAR Abrasivity Index measured on rock surface of natural roughness (e.g. surface of broken Brazilian Tensile Strength test specimen) using original CERCHAR testing apparatus and test picks with HRC=54-56
ROCK TESTING

OPERATING LIMITS DEFINED BY SPC
EVALUATION OF ROCK MASS CUTTABILTY

USING GEOTECHNICAL REPORTS OR DOING JOB SITE INVESTIGATIONS

Mapping and recording of all relevant rock types and rock mass features/discontinuities like bedding planes, fractures, etc.
EFFECT OF ROCK MASS ON CUTTING

PRINCIPLES OF ROCK MASS INFLUENCE ON ROADHEADER CUTTING

Excavation predominantly by activation of parting planes:
„RIPPING ZONE“

Activation of existing parting planes and generation of new fracture planes:
„INTERMEDIATE ZONE“

Excavation predominantly by generation of new fracture planes:
„CUTTING ZONE“
ROCK MASS CUTTABILITY RATING

SYSTEMATIC APPROACH FOR ROCK MASS EVALUATION

<table>
<thead>
<tr>
<th>Rating of uniaxial compressive strength</th>
<th>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>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rating of joint conditions</th>
<th>Rating of orientation of joint set</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>
Influence on cuttability by roadheaders

<table>
<thead>
<tr>
<th>Score Range</th>
<th>Influence Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 - 60</td>
<td>no to little influence</td>
</tr>
<tr>
<td>25 - 40</td>
<td>moderate influence</td>
</tr>
<tr>
<td>15 - 25</td>
<td>considerable influence</td>
</tr>
<tr>
<td>10 - 15</td>
<td>high influence</td>
</tr>
<tr>
<td>&lt; 10</td>
<td>dominating influence</td>
</tr>
</tbody>
</table>
ROCK MASS CUTTABILITY RATING

EVALUATION OF RMCR VALUE AND ITS INFLUENCE ON NET CUTTING RATE

<table>
<thead>
<tr>
<th>Rating of uniaxial compressive strength</th>
<th>Rating of block size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block size [m³]</td>
<td>Rating</td>
</tr>
<tr>
<td>UCS [MPa]</td>
<td></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>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface</th>
<th>Aperture</th>
<th>Wall/Fill</th>
<th>Rating</th>
<th>Influence on cuttability</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>rough</td>
<td>closed</td>
<td>hard, dry</td>
<td>30</td>
<td>very favorable</td>
<td>-12</td>
</tr>
<tr>
<td>slightly rough</td>
<td>&lt; 1 mm</td>
<td>hard, dry</td>
<td>20</td>
<td>favorable</td>
<td>-10</td>
</tr>
<tr>
<td>slightly rough</td>
<td>&lt; 1 mm</td>
<td>soft, dry</td>
<td>10</td>
<td>fair (and if block size &lt;0.03m³)</td>
<td>-5</td>
</tr>
<tr>
<td>smooth</td>
<td>1 - 5 mm</td>
<td>soft, damp</td>
<td>5</td>
<td>unfavorable</td>
<td>-3</td>
</tr>
<tr>
<td>very smooth</td>
<td>&gt; 5 mm</td>
<td>soft, damp to wet</td>
<td>0</td>
<td>very unfavorable</td>
<td>0</td>
</tr>
</tbody>
</table>

Evaluation of Rock Mass Influence on NCR
(Low cutting speed - 1.4 m/s)

NCR_{eff}/NCR_{theor} = 45.553RMCR^{-0.9821}
R^2 = 0.9332

Graph showing NCR_{eff}/NCR_{theor} vs RMCR for different locations.

Locations: Erzberg, Stillwater, Pozzano, Premadio, Athens, Bileca, Fresnillo, Montreal.
EXCAVATION STRENGTH

EVALUATED AND DEFINED BY RMCR

Rock Mass Cuttability Rating (RMCR)
Reduction of Rock Mass Strength ($UCS_{RM}$) related to Rock Strength ($UCS_R$) for SANDVIK Roadheaders using Low Cutting Speed (~1.4 m/s)

- $UCS_{RM}$ ~ 120 MPa
- $UCS_R$ ~ 200 MPa

RMCR = 30

$UCS_{RM}$ vs $UCS_R$ graph with different RMCR values.

UCSR [MPa]
UCSRM [MPa]
RMCR = 10
RMCR = 15
RMCR = 20
RMCR = 25
RMCR = 30
RMCR = 35
RMCR = 40
RMCR = 45
RMCR = 50

UCS_{RM} \approx 120 \text{ MPa}
UCS_{R} \approx 200 \text{ MPa}
ROCK TESTING
OPERATING LIMITS DEFINED BY RMCR
FACTS & DEVELOPMENTS IN DRILL & BLAST
DRILL & BLAST CYCLE

CURRENT TRENDS

• Hole size and round length slightly increasing
• Rock supporting tasks with jumbo are becoming more important (e.g. short & long bolt holes, self-drilling anchors, injection hole drilling & grouting, casing, installation of steel arches, rod handling)
• Multifunctional use of drilling jumbo increasing (e.g. installation works, charging, ground monitoring, profile measurement, scaling, water leakage testing)
• Faster round cycle times
• Quality and cost awareness increasing
• Stricter safety and environmental requirements
DRILLING PERFORMANCE

NET PENETRATION RATES (M/MIN)

• Rock drillability
• Percussion power level (and feed force)
• Bit diameter, type and rotation speed
• Flushing
• Rock drill (and impact frequency)

GROSS PENETRATION RATES (DRM/H)

• Boom moving and collaring time
• Fast feed and possible anti-jamming time
• Set-up time (cables, hoses and jacks)
• Navigation time (Data & TCAD jumbos)
• Marking of tunnel face
• Cleaning tunnel floor for bottom hole charging
• Idle of booms (bit changes, repairs, etc.)
## TUNNEL ADVANCE RATES

### SINGLE OR MULTIPLE FACE OPERATION

For one equipment set in 3-shift continuous operation

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Average advance rate (m/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single heading</td>
</tr>
<tr>
<td>Easy</td>
<td></td>
</tr>
<tr>
<td>- Competent rock</td>
<td>200 - 300</td>
</tr>
<tr>
<td>- Minimum rock support (some</td>
<td></td>
</tr>
<tr>
<td>bolts)</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
</tr>
<tr>
<td>- Varying rock conditions</td>
<td>150 – 250</td>
</tr>
<tr>
<td>- Regular support (bolts, some</td>
<td></td>
</tr>
<tr>
<td>shotcrete)</td>
<td></td>
</tr>
<tr>
<td>Difficult</td>
<td></td>
</tr>
<tr>
<td>- Soft &amp; fractured rock</td>
<td>&lt; 150</td>
</tr>
<tr>
<td>- Heavy rock support (bolts,</td>
<td></td>
</tr>
<tr>
<td>shotcrete, mesh / steel arches)</td>
<td></td>
</tr>
</tbody>
</table>
## ROCK BOLTING

## BOLT TYPES

Selection criteria referring to lifespan and cost

<table>
<thead>
<tr>
<th>BOLT TYPE</th>
<th>LIFESPAN</th>
<th>RELATIVE COST</th>
<th>GENERAL COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement grouted rebar</td>
<td>Permanent</td>
<td>1</td>
<td>Low cost, good availability, no immediate support</td>
</tr>
<tr>
<td>Resin grouted rebar</td>
<td>Permanent (if fully grouted)</td>
<td>2</td>
<td>Reasonable cost, availability of resin may be problem, immediate support</td>
</tr>
<tr>
<td>Expansion shell (grouted)</td>
<td>Temporary / permanent (if fully grouted)</td>
<td>1.5</td>
<td>Fairly low cost, fast installation, immediate support</td>
</tr>
<tr>
<td>Cement grouted wedge-type</td>
<td>Temporary / permanent (if fully grouted)</td>
<td>1.25</td>
<td>Fairly low cost, fast installation, immediate support</td>
</tr>
<tr>
<td>Swellex</td>
<td>Temporary (longer than split-set)</td>
<td>3</td>
<td>Expensive, fast installation, immediate support</td>
</tr>
<tr>
<td>Split-set (or copy)</td>
<td>Temporary</td>
<td>1</td>
<td>Low cost, fast installation, immediate support</td>
</tr>
<tr>
<td>CT-bolt</td>
<td>Permanent</td>
<td>4...5</td>
<td>Expensive, immediate support, good bolt properties</td>
</tr>
</tbody>
</table>
AUTOMATION FEATURES

FULL-AUTOMATIC FACE DRILLING

• Possibility to drill the whole face automatically
• System handles boom movements and hole drilling automatically
• Hole sequences can be imported from drill plan and/or created onboard
• Well-functioning hole sequences & roll-overs can be retrieved from previous rounds (Sandvik patented feature)
• Operator supervises the drilling process
• Booms have self-collision avoidance
Access Protector

If the Sandvik Access Protector system recognizes a person in the detection field, boom and drilling movements will automatically be stopped. In other words, the Sandvik access protector prevents anyone from entering the working area of the booms while they are in operation in automatic mode. If boom operation is automatically stopped, the system must be reset by pressing the acknowledgement button, after ensuring that no-one is in the hazard zone.

It’s possible to use the Access Protector as Detector – version while automatic drilling cycle is not used.
LATEST & ONGOING ROAD-HEADER DEVELOPMENTS
EXCAVATION CONTROL

PROFILE CONTROL

• Profile and tunnel planning with office tool and transfer of plans to machine
• Solution fully integrated into machine control system
• Profile control
• Cutter head is kept within profile limits
• Visualization of cutting process for machine operator
AUTOMATED EXCAVATION

CUTTING AUTOMATION

• Planning of cutting path referring to tunnel profile
• Fully automated cutting of one round length / sump distance
• Automated profiling in fast speed
TELE-REMOTE OPERATION

AUTONOMOUS MACHINE WITH VISUALLY SUPPORTED TELE-OPERATION
Thank you for your attention!!!