ROADHEADER PERFORMANCE PREDICTION

Assessment Of Rock Cuttability, And Prediction Of Roadheader Performance

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The problem of the prediction of performance of roadheaders : production rate (cubic metres/hour), and pick consumption rate (picks/cubic metre produced), has been studied in an empirical fashion by several authors during the past 3 decades.

The simplest and most commonly used measure of rock strength which may give an indication of machine productivity is the uniaxial compressive strength: either directly measured, or inferred from the indirect tensile strength as measured in the point-load test.
Although the I.S.R.M. recommends that uniaxial compressive strength test specimens have length:diameter ratios of (2.5±0.5):1, K.-H. Gehring of Voest-Alpine (Tamrock) argues that a length:diameter ratio of 1:1 produces a partially confined mode of failure which is more relevant to the failure produced under a cutting tool.
In a 1:1 specimen shear failure planes are inhibited, and axial cleavage failure is the dominant pattern.
A test of this argument will be reported below.

By itself, a single number such as the U.C.S., whatever shape specimen is used, is not sufficiently discriminating to be able to give more than a qualitative indication of a rock's relative cuttability.

A predictor method should use several factors, to be able to give useful quantitative predictions.

SIGNIFICANT FACTORS FOR ROADHEADER PERFORMANCE PREDICTION

The factors used by the current predictor methods may be listed in 6 different groups :

1. *Strength* Factors : fairly standard measurements of a rock's compressive or tensile strength, or of its resistance to quasi-static penetration;
2. *Toughness* Factors : indications of the amount of work or energy expended in breaking a rock, as distinct from the failure stress;
3. *Cuttability*, under laboratory conditions : the resistance to a rock's penetration by a moving tool or cutter;
4. *Abrasiveness* Factors : measurement of the damage to a steel or tungsten carbide tool or cutter, at the end of a standard laboratory cuttability or penetration test;
5. *Rock Mass Fracture Frequency* : a measure of the continuity and intactness of the rock mass, and therefore of how much breakage has been already done, before the roadheader starts work;
6. *Machine* Factors : the mass and power which the machine is able to bring to bear to cut the rock.

The individual tests or parameters within each group of factors are :

1. Strength Factors :
- Uniaxial Compressive Strength
- Tensile Strength
- Cone Indenter Hardness

2. Toughness Factors :
- Plasticity Index
- Specific Energy, as measured in the Uniaxial compression test
- Tensile / Compressive Strength ratio
- Fracture Toughness, ($MNm^{-3/2}$), K_{Ic}, as measured by the Cracked Chevron Notch Brazilian Disk (CCNBD) method, or K_{SR}, as measured by the Chevron Notched Short Rod (SR) method.

3. Cuttability, under laboratory conditions :
- Goodrich Drillability
- Core Cutting Test Specific Energy

4. Abrasiveness Factors :
- CERCHAR Abrasivity
- Core Cutting Wear Rate
- Goodrich Microbit Wear Rate

5. Rock Mass Fracture Frequency :
- Average Joint Spacing
- Rock Quality Designation (R.Q.D.)

6. Machine Factors :
- Machine Weight
- Machine Cutterhead Power

Table 1 summarizes some of most widely accepted roadheader performance prediction methods, and the input factors.

FACTORS USED IN ASSESSMENT OF EXCAVATABILITY BY ROADHEADERS							
	Bamford 1975	McFeat-Smith & Fowell 1979	Roxborough & Phillips 1981	Farmer 1986	Gehring 1989	Fowell 1991	Bilgin 1997
STRENGTH FACTORS							
U.C.S.				✔	✔		✔
Tensile Strength					✔		
Cone Indenter Index		✔		✔			
TOUGHNESS FACTORS							
Coefficient of Plasticity		✔					
Specific Energy			✔	✔			
C_o/T_o Ratio					✔		
Fracture Toughness						✔	
LAB. CUTTABILITY							
Goodrich Drillability	✔						
Linear Core Cutting Test			✔				
ABRASIVENESS FACTORS							
CERCHAR Abrasivity					✔		
Cutting Wear Rate			✔				
Goodrich Wear Number	✔						
FRACTURE FREQUENCY							
Joint Spacing				✔	✔		
R.Q.D.							✔
MACHINE FACTORS							
Machine Weight	✔	✔	✔	✔	✔	✔	✔
Cutterhead Power			✔		✔		✔

TABLE 1

It may be seen that each of the methods listed in Table 1 attempts to combine some of the factors. Correlations of observed roadheader performance with each author's combination of laboratory measurements, with or without rock mass characteristics, have led to some success in "ball-park" predictions of future field performance.

The predictions have generally been based on empirical correlations, rather than on deterministic or design calculations.
Rock properties are notoriously size-dependent, so there will inevitably be problems in scaling up properties measured in the laboratory to the field scale.
Also, the machine efficiencies and utilization rates are not fixed properties and therefore the actual cutting rates per hour or per shift will only be a small and variable fraction of any calculated instantaneous cutting rates.

Laboratory cuttability tests are a useful short-cut, in using a small-scale simulation of the action of a real cutting tool as mounted on a roadheader.
Strength and toughness factors do not have to be measured, and the mutual damage done by tool to rock and rock to tool can be measured.
Scaling up to the full size field situation is still a problem, as neither the size nor the geometry of the laboratory cutting rig corresponds exactly to the field situation.

Therefore, prediction of field performance can probably not be much better than qualitative or semi-quantitative.
Nevertheless, this can be useful to a contractor, in estimating approximate performances for a new project, especially if he has some experience from past jobs as to the precision and/or variability of the relationships between predicted and actual performances.

It is of interest to note that 4 of the 7 methods listed in Table 1 use some strength estimate :

- McFeat-Smith & Fowell use the Cone Indenter Index
- Farmer uses Uniaxial Compressive Strength and the Cone Indenter Index
- Gehring uses Uniaxial Compressive Strength and Tensile Strength
- Bilgin uses Uniaxial Compressive Strength

5 of the 7 methods listed in Table 1 use some toughness estimate :

- McFeat-Smith & Fowell use " Coefficient of Plasticity " - a measure of work-hardening exhibited under repeated hammer blows in the scleroscope test
- Roxborough & Phillips use the Specific Energy measured during linear cutting
- Farmer uses the Specific Energy measured during a Uniaxial Compression test
- Gehring uses the Compressive/Tensile Strength Ratio
- Fowell uses the Fracture Toughness

3 of the 7 methods listed in Table 1 use some abrasiveness estimate :

- Bamford uses the Goodrich Wear Number (damage done to a rotating tungsten carbide chisel bit)
- Roxborough & Phillips use the Core Cutting Wear Rate (damage done to a linearly translating tungsten carbide pick)
- Gehring uses the CERCHAR Abrasivity Rate (damage done to a linearly translating steel needle)

2 of the 7 methods listed in Table 1 use small-scale laboratory cuttability :

- Bamford uses the Goodrich Drillability (depth of penetration by a rotating tungsten carbide chisel bit)
- Roxborough & Phillips use the Core Cutting Test (volume of excavation by a linearly translating tungsten carbide pick, and measurement of the necessary work)

3 of the 7 methods listed in Table 1 use rock mass fracture frequency :

- Farmer uses the joint frequency across the face of the excavation
- Gehring uses the average joint spacing across the face of the excavation
- Bilgin uses the R.Q.D.

5 of the 7 methods listed in Table 1 use machine weight and cutterhead power, in a qualitative sense :

- Bamford has empirically correlated the ranges of the ratio Goodrich Drillability /Wear Number which can be cut by typical models of roadheaders, of different sizes
- McFeat-Smith & Fowell and Fowell produce predictions for "typical medium-weight" and "typical heavy-weight roadheaders"
- Roxborough & Phillips and Farmer have empirically correlated production estimates from laboratory tests with a small range of specified roadheader models

2 of the 7 methods listed in Table 1 use machine weight and cutterhead power, in a quantitative sense:

- Gehring calculates roadheader production from the laboratory test values, using a series of numerical ratings which vary to a roadheader's weight and installed power
- Bilgin uses actual machine weight and cutterhead power in his equations for calculating roadheader production from the rock strength and R.Q.D.

COMPARISONS BETWEEN PREDICTION TECHNIQUES

The Transfield Obayashi Joint Venture is currently constructing the Burnley and Domain Tunnels, as part of the Melbourne City Link Project.
In 1997 the performance of several roadheaders supplied by Mitsui-Miike and Voest-Alpine for these tunnels was studied as a final-year research project by Melbourne University civil engineering student Mark Zurowski.
Rock samples were taken from several faces for testing in the Rock Mechanics laboratory at the University of Melbourne.
Full suites of tests were performed, so that each of the roadheader prediction methods could be performed, and the predictions compared with the observed geological conditions and roadheader performances in the vicinity of the sampled sites.

Table 2 shows correlations between Predicted Cutting Rates and observed Production Cutting Rates.

PREDICTION METHOD	Coefficient of Determination r^2	CORRELATION FORMULA y = PRODUCTION CUTTING RATE (m^3/hr) x = PREDICTED CUTTING RATE (m^3/hr)
BILGIN (2.5:1)	0.78	$y = 10.75*(x^{0.349})$
FOWELL & McFEAT-SMITH	0.51	$y = 20.56 + 0.488x$
BILGIN (1:1)	0.5	$y = 5.65 + 10.225*\ln(x)$
VOEST-ALPINE (2.5:1)	0.39	$y = 26.06 + 0.219x$
FOWELL	0.38	$y = 29.17 + 0.101x$
VOEST-ALPINE (1:1)	0.31	$y = 28.02 + 0.154x$
FARMER	0.19	$y = 22.72*(x^{0.124})$

TABLE 2

The brackets (2.5:1) or (1:1) shown in the captions for the Bilgin and Voest-Alpine predictions refer to the length:diameter ratios of the Uniaxial Compression test specimens.
Gehring's argument that 1:1 specimens give a more accurate estimate of cutting strength, mentioned near the beginning of this paper, was tested by applying the 2 alternative Uniaxial Compressive Strength values in the formulas - the strength for length:diameter = 2.5, and the strength for length:diameter = 1.0
It may be seen that the 2.5:1 values appear to give more accurate predictions than the 1:1 values.

The best correspondence between predicted and actual production rates was given by Bilgin's method, with the uniaxial compressive strength test specimens prepared with a length:diameter ratio of 2.5:1
The next best predictions were given by the Fowell & McFeat-Smith method.
Figures 1 and 2 show these correlations.

It is interesting to note that input to Bilgin's method includes a Strength factor, a Rock Mass Fracture Frequency factor, and Machine power and weight; input to the Fowell & McFeat-Smith method includes a Strength factor and a Toughness factor.

It might be concluded that a predictor method which accepts all of these inputs :
Strength, Toughness, Fracture Frequency, and Machine factors might be even more accurate.
The Voest-Alpine (Gehring's) method in fact has all of these inputs.
Its apparent low accuracy in this comparison is probably misleading, and is due to the fact that the method as published by Gehring is valid for transverse head roadheaders, whereas most of the roadheaders used on the Citylink Project had the longitudinal type head configuration.
For the purpose of this study, "chalk and cheese" were compared; i.e. some predictions for transverse head machines were compared with actual production achieved by longitudinal head machines.
Bilgin gives different formulae for each head configuration, so allowing more valid matching of predictions with actual production.
In view of the fact that the Voest-Alpine method is the only method to give a prediction of cutter consumption, it is worth using for this purpose
It may also be of interest to further refine the method, using the present or similar inputs to predict production by transverse head machines.

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CUTTING STRENGTH

Current informed opinion about cutting strength is that it is probably
- proportional to Uniaxial Compressive Strength
- proportional to the square root of a "toughness factor"

This "toughness factor" may be taken as:

1. Inverse of the tan of the Angle of Shearing Resistance (ϕ)

   So Cutting Strength $\propto C_o/\sqrt{(\tan \phi)}$

2. Inverse of the Brittleness Coefficient:

   $$\frac{\text{Uniaxial Compressive Strength - Tensile Strength}}{\text{Uniaxial Compressive Strength + Tensile Strength}} \quad (= \sin\phi)$$

   So Cutting Strength $\propto C_o/\sqrt{(\sin \phi)}$

3. Inverse of the Compressive/Tensile Strength ratio

   So Cutting Strength $\propto C_o/\sqrt{(C_o/T_o)}$

   $\propto \sqrt{(C_o.T_o)}$

4. Rock Toughness Index

   $$= 1000 * \frac{\text{Specific Energy (Strain Energy At Failure)}}{\text{Uniaxial Compressive Strength (MPa)}}$$

   $$= \frac{\text{Specific Energy (kJ/m}^3\text{)}}{\text{Uniaxial Compressive Strength (MJ/m}^3\text{)}}$$

   So Cutting Strength $\propto C_o*\sqrt{(R.T.I.)}$

   $\propto C_o*\sqrt{(1000S.E./ C_o)}$

   $\propto \sqrt{(C_o*1000S.E.)}$

5. Fracture Toughness

   Cutting Strength $\propto C_o*\sqrt{K_{Ic}}$

Further work to apply these definitions and estimates of Cutting Strength, as a function of Uniaxial Compressive Strength and Toughness, should be worthwhile doing.