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Rock Test Indices are being Successfully Correlated with Tunnel Boring Machine Performance

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SUMMARY Prediction of the performance of tunnel boring machines has in the past been based partly upon intuition and partly upon single simple rock tests. Recent studies have correlated the observed performance of tunnel boring machines with combinations of several rock tests. Predictor equations having good correlation coefficients with actual performance have been developed.

Tunnelling may be considered in terms of 4 major aspects:

- Rock breaking
- Materials handling
- Support
- Surveying & environment

Geomechanics is of major importance in 2 of these aspects (rock breaking and support) and can be of significance in materials handling.

Over the past decade or so there has been an evolution away from past practice with regard to predictions in the fields of rock breaking and support.
This past practice can be summarized as
" quoting a single number, from which one or several predictions follow ".
The single number was, for example

the degree of weathering, or
the Mohs scratch hardness or
the Rock Quality Designation (R.Q.D.) or
the unconfined compressive strength.

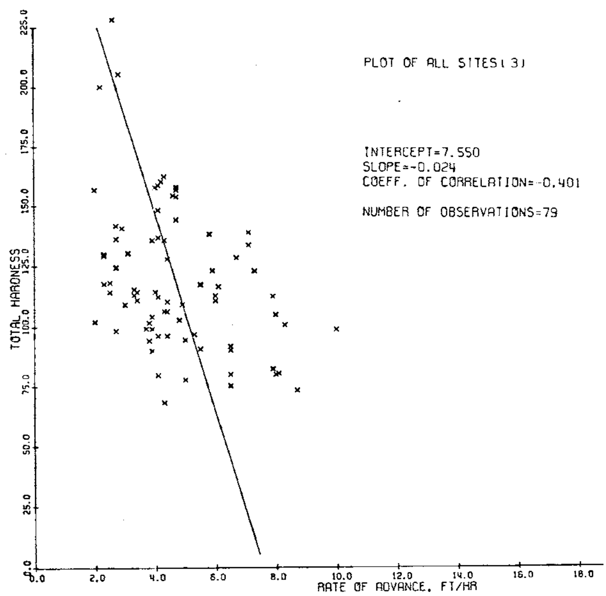
The next stage in the evolution of applied scientific methods lies in
" back - analysis "
the empirical correlation of one or more rock properties with the performance of tunnelling machines or with the support required when tunnelling through a rock mass.
The correlations, if successful and convincing (i.e. apparently logical) can then be used as a basis for future predictions.
They need not necessarily be deterministic i.e. based upon an agreed mechanism of rock failure, but need only be shown to have given good correlations, for whatever obscure reasons.

The next stage in the evolution of "scientific" predictive methods comes with a better understanding of the mechanisms of failure of rock under the action of a disc cutter or drill bit, or in the immediate surrounds of a tunnel, where the rock mass is both relaxed and stress-concentrated. This stage is now upon us.

Let us now return to the previous stage, and discuss the state of the art in machine tunnelling estimation.
In 1975 Peter Tarkoy, in his doctoral thesis work at the University of Illinois, correlated the performance of tunnel boring machines with 2 rock properties.
These were
the Schmidt rebound hammer hardness and
the Taber abrasion hardness
They were combined into what he termed
"total hardness"

$$H_R * \sqrt{H_A}$$

Tarkoy expressed satisfaction with the correlation of t.b.m. advance rate with "total hardness" shown as Figure 1 but, as can be seen, the coefficient of correlation was only 0.4



Plot of Data, Statistical Parameters, and Least Squares Fit Curve

FIGURE 1

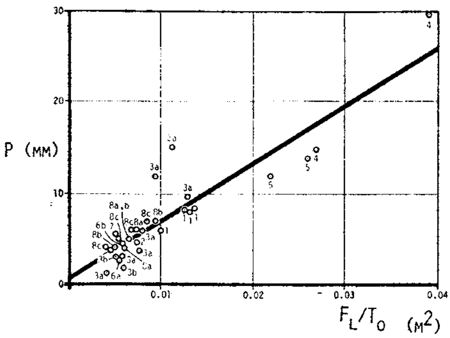
The case study reported by Gill & Lafrance in 1979 compared some of the existing prediction methods with the actual performance of a tunnel boring machine in Montreal, Canada.
Table 1 shows how inaccurate the unconfined compressive strength was for prediction.
It also shows that the methods using 2 or more physical properties were slightly more accurate, as were the punch tests, where a small - scale rock failure is induced, analogous with the rock failures induced by the full size cutters on the tunnel boring machine.

TABLE 1

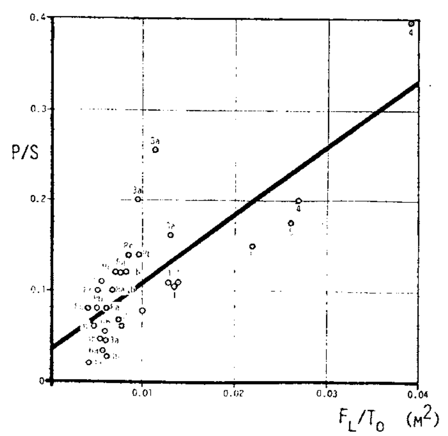
MONTREAL ISLAND MACHINE-BORED TUNNEL CASE STUDY

PREDICTION METHOD	RELEVANT MECHANICAL PROPERTIES	PREDICTED PENETRATION RATES (M/HR.) ZONE I	ZONE II	ZONE III
MORREL ET. AL.	SHORE HARDNESS DENSITY	2.00	-	2.80
MORREL & LARSON	SHORE HARDNESS DENSITY STATIC E	2.04	-	2.89
CALDER	UNCONFINED COMPRESSIVE STRENGTH	0.95	-	1.40
MORRIS	PUNCH TEST (P'/E)	1.46	-	2.26
HANDEWITH	PUNCH TEST (POUNDS/INCH)	1.60	2.00	2.53
	ACTUAL PENETRATION RATES:	2.38	3.25	2.59

Some 1980 work by Ian Farmer (Figure 2) shows that the ratio between the force on a cutter and the tensile strength of the rock being penetrated can be used as an "x" value from which the penetration per revolution of the cutting head can be predicted.



PENETRATION PER REVOLUTION (P) PLOTTED AGAINST THE RATIO BETWEEN CUTTER FORCE (F_L) AND ROCK TENSILE STRENGTH (T_0)



PENETRATION / SPACING RATIO (P/S) PLOTTED AGAINST CUTTER FORCE / ROCK TENSILE STRENGTH RATIO (F_L/T_0)

FIGURE 2

Priscilla Nelson, in her 1983 doctoral thesis work at Cornell University, correlated machine penetration rates with various rock properties, but found only low correlation coefficients with strengths or rebound hammer hardness. (See Table 2 and Figure 3)

TABLE 2

SUMMARY OF DEGREES OF CORRELATION BETWEEN ROCK PROPERTIES AND PENETRATION RATES AND FIELD PENETRATION INDICES

ROCK INDEX PROPERTY	CORRELATION WITH PENETRATION RATE			CORRELATION WITH FIELD PENETRATION INDEX		
	Low[a]	Moderate[b]	High[c]	Low[a]	Moderate[b]	High[c]
Hardness Indices						
Rebound	x				x	
Abrasion		x			x	
Total		x				x
Linear Combination of Rebound and Abrasion		x				x
Uniaxial Compressive Strength	x			x		
Point Load Index	x			x		
Brazilian Tensile Strength	x			x		

[a] coefficient of determination less than 0.50.

[b] coefficient of determination between 0.50 and 0.80.

[c] coefficient of determination greater than 0.80.

Moderate correlations were found between "total hardness" and the machine penetration rate, with r^2 (the coefficient of determination) = 0.49

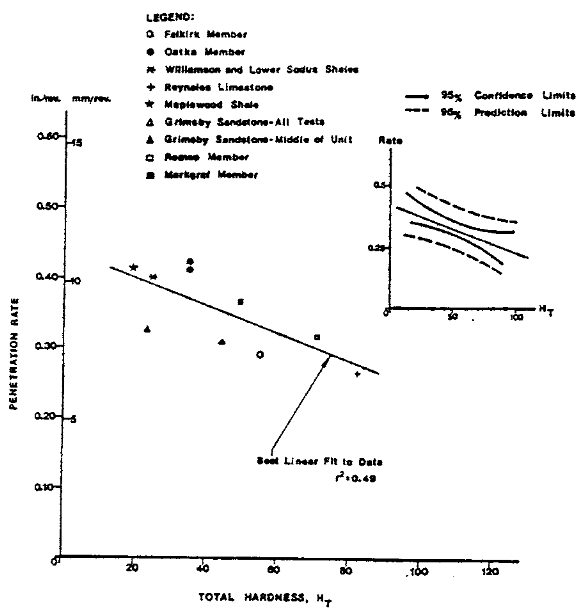


FIGURE 3
Plot of penetration rate versus "total hardness"

By using a "field penetration index", defined as

$$R_f = \frac{\text{average thrust per cutter}}{\text{penetration per revolution of the cutting head}}$$

she significantly improved the correlation between "total hardness" and the "field penetration index" as shown in Figure 4, with r^2 = 0.85

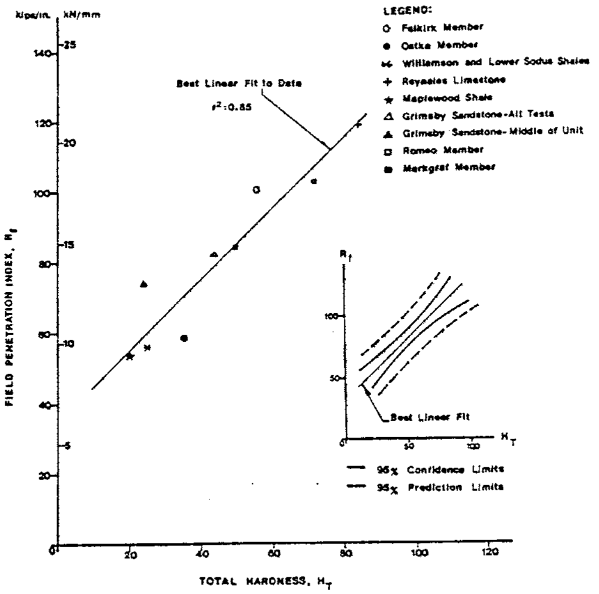


FIGURE 4
Plot of field penetration index versus "total hardness"

In my own doctoral thesis work I correlated the performance of a Robbins machine boring 2 tunnels near Melbourne with the results of a wide range of mechanical property tests and drillability tests performed upon samples of the rocks penetrated. Table 3 shows the best correlations achieved, for penetration rates and cutter consumption rates.

TABLE 3
Highest coefficients of determination found in each phase of the multiple linear regression analyses

	PENETRATION RATE		CUTTER CONSUMPTION RATE	
	T.Y.T. R^2	ALL ROCK DATA R^2	T.Y.T. R^2	ALL ROCK DATA R^2
Any 3 Rock Mechanical Properties	0.40	0.51	0.76	0.76
Any 3 Rock Mechanical Properties and PROPEL	0.54		0.83	
Any 3 Drillabilities	0.32	0.23	0.82	0.81
Any 3 Drillabilities and PROPEL	0.40		0.84	
Any 3 Rock Properties	0.55	0.68	0.87	0.86
Any 3 Rock Properties and PROPEL	0.91		0.99	

The linear regressions using any 3 mechanical properties were improved when the machine propel thrust was added as a 4th independent variable.
For the best correlations with penetration rate r^2 increased from 0.40 to 0.54, while for the best correlations with cutter consumption rate r^2 increased from 0.76 to 0.83

The linear regressions using any 3 laboratory drillability tests were improved when the machine propel thrust was added as a 4th independent variable.
For the best correlations with penetration rate r^2 increased from 0.32 to 0.40, while for the best correlations with cutter consumption rate r^2 increased from 0.82 to 0.84

The linear regressions using 3 independent variables were improved when these variables included 1 or 2 mechanical properties, and 2 or 1 drillability tests.
For the best correlations with penetration rate r^2 increased from 0.40 to 0.55, while for the best correlations with cutter consumption rate r^2 increased from 0.82 to 0.87

The linear regressions using any 3 mechanical and drillability test values were significantly improved by adding the machine propel thrust as a 4th independent variable.
For the best correlations with penetration rate r^2 increased from 0.55 to 0.91, while for the best correlations with cutter consumption rate r^2 increased from 0.87 to 0.99

Penetration rate is best predicted by a combination of :

Schmidt rebound hammer hardness
Machine propel thrust force
N.C.B. Cone Indenter Index and
Angle of shearing resistance, phi

The actual equation is :

Penetration rate (m/hr) = 0.535 * Schmidt Hardness
- 8.49
- 0.00344*Thrust (tonnes)
- 0.000823 * NCBCI (N/mm)
+ 0.0137 * Phi (degrees)

In the 3 equations having the highest coefficients of determination, the most significant independent variables, in decreasing order of importance, were found to be :

Schmidt rebound hammer hardness
Propel thrust force
Goodrich wear number
Rock Impact Hardness Number
Unconfined compressive strength.

Cutter consumption rate is best predicted by a combination of :

Schmidt rebound hammer hardness
Machine propel thrust force
Rock Impact Hardness Number and
Angle of shearing resistance, phi

The actual equation is :

Cutter Consumption Rate (cutters/kilometre)
= 1.73 * Schmidt Hardness
- 18.3
+ 0.0259*Thrust (tonnes)
- 0.0319 * RIHNo.
+ 0.0344 * Phi (degrees)

The means of the best 5 equations showed the most significant variables, in decreasing order of importance, to be :

Schmidt rebound hammer hardness
Propel thrust force
Rock Impact Hardness Number
Density
Shear Wave velocity

These correlations are "backward-looking", as they imply only intuitive knowledge of how the rock actually fails under the action of the cutting tools mounted upon a tunnel boring machine.
Research work being conducted in the U.S.A. [U.S.B.M. Twin Cities Research Center and the Colorado School of Mines], in Sweden [Luleå

Technical University], in England [Transport and Road Research Laboratory and the University of Newcastle Upon Tyne], in Switzerland [Institut CERAC, at Ecublens, near Lausanne], in West Germany [Ruhruniversitat, Bochum], and in Australia [University of N.S.W. and Melbourne University] is progressing towards :

agreed mechanisms of rock failure;

the definition of the most significant properties;

methods of designing tunnel boring machines from a knowledge of these properties for the rock being tunnelled through;

techniques for monitoring the forces on the cutters, and the efficacy of the cutting process, in "real time".

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