PREDICTING
TBM PENETRATION RATES
IN
SELECTED ROCK TYPES

By

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ABSTRACT

The capability to predict how a TBM machine will perform (advance rates, cutter costs, and TBM utilization) under the particular conditions of a tunnel contract is of utmost importance to a contractor before he makes his bid. Rock properties are the single most important factors affecting tunneling rates and cutter costs.

Results have shown that several measures of rock hardness utilizing rebound and abrasion, correlate well with TBM penetration rates. Continuing studies are being concentrated on improving this correlation and the evaluation of petrographic parameters, which affect rock hardness, penetration rates, and cutter costs.

A most significant aspect of the study is the sampling of rock directly adjacent (cores are taken from the tunnel wall) to the machine bore. All tests are performed parallel to the tunnel axis thus reducing the number of variables to be considered and allowing comparison of instantaneous rates with local rock properties.

Résumé – La faculté de prédire le comportement (viteses d'avandement, frais d'exploitation, taux de disponibilité…) d'une foreuse à grand diamètre (TBM-Tunnel Boring Machine), dans les conditions précises d'un contrat de tunnel, est d'une grande importance pour un entrepreneur lors de la préparation des offres. Les propriétée du rocher sont les seuls facteurs vraiment importants qui influent sur les vitesses d'avancement et les frais déxploitation.

Les résultats de nombreuses meesures de la dureté du rocher, en uilisant les méthods de rebond et d'abrasion ont montré une bonne corrélation avec les vitesses de pénétration. Des études sont présentement faites afin d'améliorer cette corrélation et afin d'évaluer les effets des paramètres pétrographiques qui affectent la dureté du rocher, les vitesses de pénétration et les frais d'exploitation.

L'aspect le plus significatif de l'étude est l'echantillonnage du rocher au voisinage immédiat de la machine à forer les tunnels (des carottes ont été extraites des parois du tunnel). Tours les essais ont été effectués parallèlement à l'axe du tunnel. Ainsi le nombre de vaiables à considérer est réduit et la comparaison des vitesses momentanées avec les propriétés locales du rocher est possible.

1. Introduction

Pre-bid knowledge of subsurface conditions is of prime importance in tunneling. This is especially true when considering the feasibility of using a TBM. Although much research has been done in this field it has not been amenable to direct interpretation and field use. This study was intended to fill that gap by developing an empirical relationship between several measures of rock hardness and penetration rates. Such a relationship can be used to predict penetration rates on the basis of simple-laboratory tests Independent of, and prior to machine manufacturers' predictions during the pre-bid period.

2. Methods

Measures of rock hardness which are used in this study have been discussed and their relevance justified by Deere (1970), Dietl et al (1973), and Tarkoy (1973). Test equipment, methods, and descriptions are outlined in Table 1.

Cores taken from machine bored tunnels were tested relative to tunnel alignment and the results were compared statistically with actual respective machine penetration rates. Simple and step-wise multiple regression analyses were run with hardness values as independent variables and rates as the dependent variables. This was done individually for each rock type, and subsequently for all data combined.

3. Results

Simple and step-wise multiple regression analyses Indicate good relationships between several measures of hardness and penetration rates. Results are summarized in Table II. For each rock type, the highest correlating variable is noted by an asterisk and a positive correlation slope (expected correlation slope Is negative) is noted by parentheses.

Factors by which the quality of a relationship can be judged are:

1. a consistently high coefficient of correlation (perfect is 1.00) for a particular test for all rock types, and

2. coefficients of correlation which are either consistently positive or consistently negative.

Discussion of results outlined in Table II will be presented first by test method and subsequently by rock type. In the former discussion, irregularities of the test correlation are evaluated; in the latter irregularities are treated by rock type. Upon examination of Table II, it becomes apparent that only H_R has coefficients of correlation which are consistently negative and of all the measurements H_T appears to have the best relationship more often than any other.

3.1 Measures of Hardness

Shore Scleroscope Hardness (H_S). The fine tip of the Shore Scleroscope is mostly an indication of mineral hardness. As the results suggest, with increasing H_S, rates decrease except for the quartzites. Hard quartzite is brittle and therefore fractures almost always develop in the intact material. Fracturing of hard material promotes ease of excavation Orthoquartzite used in the analyses all contained some shaly partings as did the tunnel section. This effect on the test results may possibly be evaluated subjectively but the effect on rates is more difficult to quantify.

Schmidt Hammer (H_R). For all rock types coefficients of correlation are consistently negative (as expected) but generally poorer than other measures of hardness. In the case of the quartzites, H_R merely has a poorer relationship whereas, H_5 develops an inverse relationship. It appears that this may be explained by the fact that the Schmidt Hammer uses more energy, therefore it affects a larger portion of the test sample, and fractures are thus exercised and consequently affects rebound energy.

Abrasion Hardness (H_A). Relatively good correlation (0.41 to 0.96) was found between H_A and penetration rates. Nevertheless correlation is positive for quartzite. Again, the positive slope in the curve may indicate hard but brittle rock, which is fractured on a scale larger than measurable by the abrasion test. Consequently, it appears that abrasion resistant rock is bored at a faster rate because of intense fracturing.

Rock Abrasiveness (A_R). Rock Abrasiveness was originally intended for correlation with cutter costs but was included in the regression analysis with penetration rates. Surprisingly enough, correlation with penetration rates is good and the only positive slope occurs with limestone. Apparently, increasing A_R (decreasing weight loss of the abrader wheel) is representative of more compact, dense limestone which characteristically breaks into large size muck (chips), thus, promoting higher advance rates.

Total Hardness (H_T). Consistently high degrees of correlation are evident for H_T except in the case of quartzite, which has a positive slope. Throughout the previous discussion it has become apparent that the quartzites exhibit significant correlative irregularity. Apparently, the positive slopes of the H_A-RATE relationship for quartzite have affected the H_T-RATE correlation as well.

3.2 Rock Types

Limestone, shale, siltstone, and sandstone appear to have good correlation between all measures of hardness and penetration rates except that A_R has a positive slope for limestone (as discussed for the Shore Scleroscope).

Schist has moderate correlation for all but H_R and H_S. Of these two parameters, the Shore Scleroscope (H_S) appears to be least useful because of the small test surface (diamond tip) and the inherent irregularity and inhomogeneity of schist. Impact energy, test surface, and consequently correlation is higher for the Schmidt Hammer. Nevertheless, poorer correlation was evident for all hardness parameters in the case of schist. Field observations showed Manhattan (mica) Schist to be extremely variable, not only as a result of foliation but also because of the highly variable degree of foliation relative to crystal size. Relative percentages of hard (quartz, feldspar, garnet, staurolite, pyrite) and soft (mica, chlorite, sericite) minerals, determined from thin sections, also indicate relatively high anisotropism.

Orthoquartzites were sampled from a single location (Rochester, New York) and all but one sample (and tunnel section) contained shaly partings about 1/2 inch (1-1/2 cm) thick. Even though these partings are too small to sample they nevertheless affect penetration rates.

Quartzites were collected from pegmatites in the Manhattan Schist (2 samples), New York City and from Hecla Mining Company's Star Mine in Wallace, Idaho (5 samples). By themselves, the samples from New York would yield a negatively sloping least squares fit curve with a high coefficient of correlation, but in combination with data from the Star Mine the slope becomes positive with a lower coefficient for H_S, H_A, and H_R. Mineralogy and micro-fabric of quartzite dictates that it be hard and therefore brittle. Consequently, it is likely to be fractured, especially at depths of 7300 ft. In the faulted and mineralized area of the Coeur d'Alene Mining district, and as a result of high stress concentrations imposed by mining. In reality, during machine boring, large blocks fell out of the face, thus hampering progress. Test samples were actually pried loose from the tunnel walls along joints.

3.3 Plotting H_T vs. Penetration Rates

Although "Total" hardness (H_T) did not always show the best correlation in each case, it did appear to have the highest correlation throughout the entire range of hardness. Figure 1 shows the range of hardnesses for rock used in this study. Total Hardness, H_T has been used to predict advance rates and respective data are plotted in Figures 2 and 3. Figure 2 is a plot of all data used in the foregoing statistical analyses. Although an asymptotic curve may seem more appropriate, a straight line must be used for general analyses before the exact range of rock hardness is known for a specific site. Actually, the most appropriate equation for predicting reliable penetration rates would be one derived from experience most similar (in terms of machine variables and rock type) to the job to be bid.

The mean H_T and rate for each rock type was calculated and plotted In Figure 3. The plot indicates a somewhat better relationship for low values of hardness. Orthoquartzite and quartzite seem to account for the greatest deviation as a result of the unique properties discussed in the previous section. Shaly partings (in orthoquartzite) promote faster rates apparently without lower test results. Similarly, the extreme fracturing of the quartzite in the Star Mine was known to cause large blocks to fall from the face and require regrinding by the machine. No doubt penetration rates were affected as evidenced by rates as low as 0.4 ft/hour in material which was no harder than rock mined at 4 ft/hour. Figure 3 should be used with caution, however, because the slope is to a larger extent a function of the softer materials and may not be valid for machines designed for H_T>~120.

4. Conclusions

Simple laboratory tests for NX core (2.125 inches, 5.4 cm in diameter) have been developed to predict TBM penetration rates. Regression analyses indicate certain tests to be most useful for particular rock types. Although at present Total Hardness (H_T) is being used for pre-bid studies, with added experience, and a wider range of data and rock types, other variables or combinations of variables may be used for more reliable predictions. Therefore, all four of the basic measurements (H_S, H_R, H_A, and A_R) are recommended for use in rock mechanics testing of exploratory core obtained for tunnel exploration.

5. Acknowledgements

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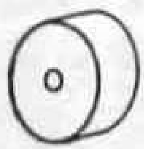
Spring Loaded Plunger

Diamond Tipped Weight

Rock Disk



Abraser Wheel

TABLE 1 Outline of Hardness Test Methods

	Hardness Test	Description	Range of Values	Remarks
H_R	Schmidt (L-type) Hammer Rebound (must be used on core mounted in a test anvil).	10 readings are taken; average of 5 highest values are used.	0-70	Best for mass property measurements because contact point is large [about 1/2-in. (1.3-cm) diameter].
H_S	Shore Scleroscope (C-2 type) Rebound Hardness (must be used on core mounted in a test anvil).	20 readings are taken; average of 10 highest values are used.	0-140	Contact point is fine, therefore measurements are more accurate for individual grains and crystals, but statistical sampling must be taken and averaged for mass properties; can be used to estimate H_R if necessary.
H_A	Rock Abrasion Hardness	2 NX-size discs [1/4-in. (.6 cm) thick] abraded for 400 revolutions on each side; determine weight loss; use average values of 2 discs. H_A=1/average wt. loss (gms).	<1<	This test is sensitive to factors that influence small-scale strength, shearing, crushing, and abrasion.
A_R	Rock Abrasiveness	Measure wt loss of 4 wheels (1 for each side of rock disks) and average. A_R = 1/average wt. loss (gms.)	<1<	Weight loss of the abrader wheel is caused by rock abrasiveness, not necessarily by hardness. The same is true in the case of a cutter.
H_T	"Total" Hardness	Use appropriate average values to compute. $H_T = H_R \sqrt{H_A}$	0-250	This combination of hardness has been successfully correlated with advance rates.

Table II Coefficients of Correlation between Rock Hardness (independent variable) and Penetration Rates (dependent variable) for Several Rock Types

Rock Type	Number of Observations	H_S	H_R	H_A	A_R	$H_T=H_R\sqrt{H_A}$	Maximum Multiple Correlation
Limestone (dolomitic)	4	-0.81	-0.73	-0.96*	(0.93)	-0.83	0.96
Shale & Siltstone	13	-0.77	-0.64	-0.79	-0.70	-0.86*	0.96
Sandstone	33	-0.67	-0.76	-0.71	-0.68	-0.80*	0.82
Orthoquartzite	4	(0.65)	-0.16	-0.64	-0.91*	-0.45	0.91
Quartzite	7	(0.75)*	-0.63	(0.41)	-0.54	(0.12)	0.998
Schist	34	-0.15	-0.32	-0.49	-0.56*	-0.52	0.67
Combined Data	95	-0.85	-0.847	-0.76	-0.42	-0.85*	0.89

* Highest single correlation.

() Least squares fit equation has a positive slope.

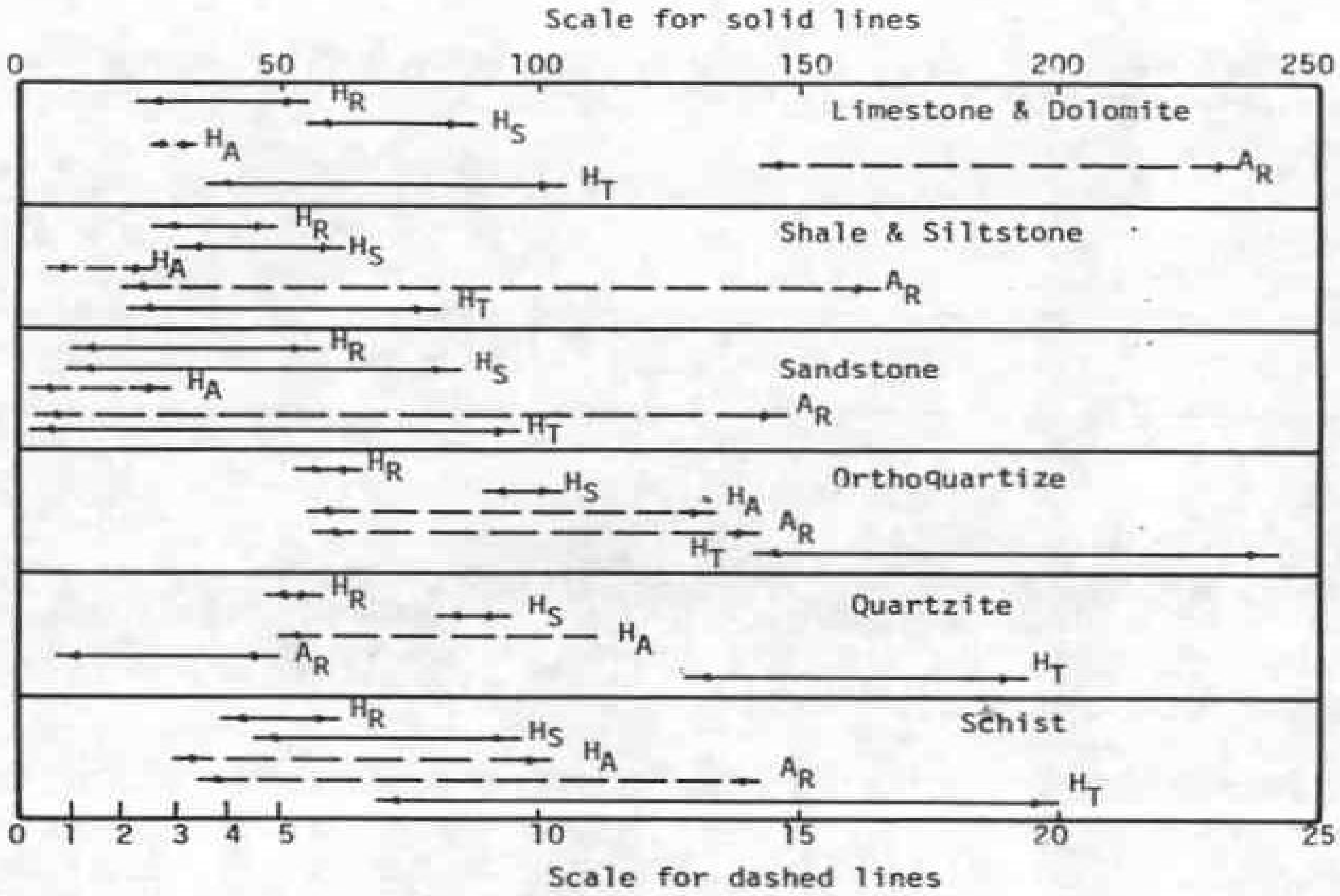


Figure 1. Range of rock hardness parameters for samples utilized in this study.

Données, résultats statistiques et équation d’un lissage par moindres carrés pour 95 échantillons représentant 6 types de roches.

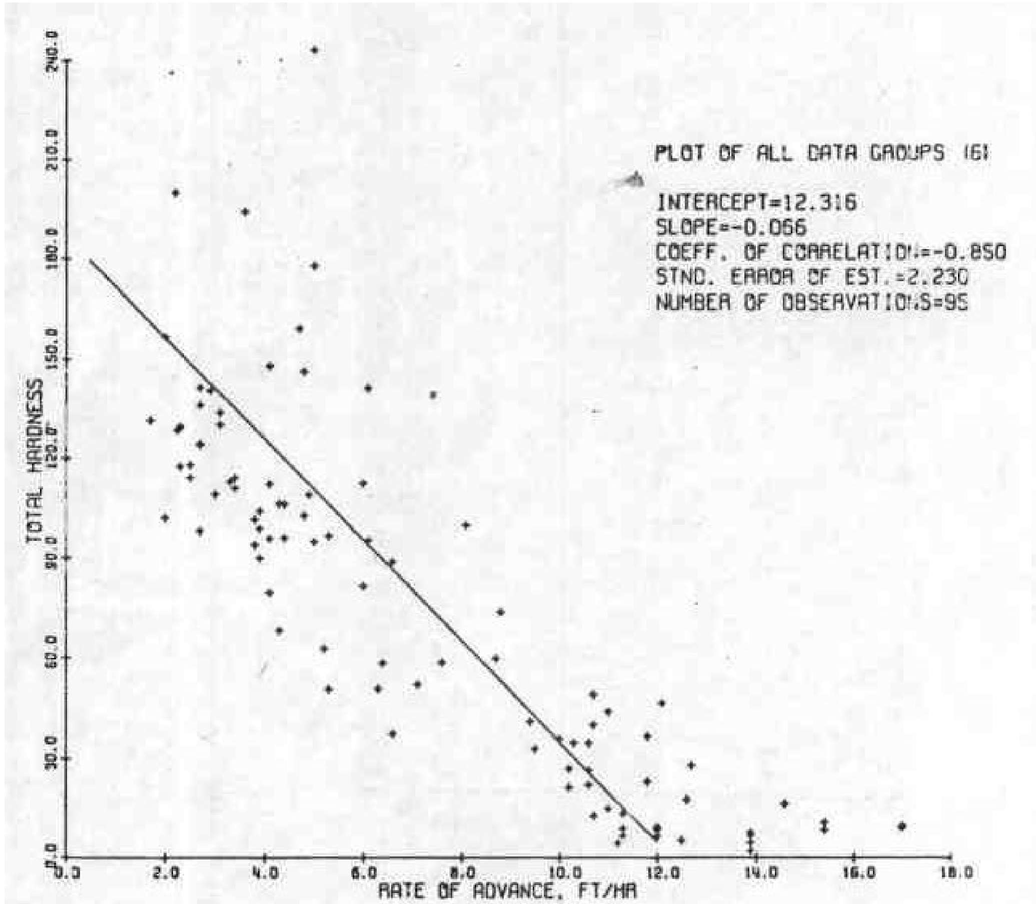


Figure 2. Plot of data, statistical results and least squares fit equation for 95 samples representing 6 rock types.

Données, résultats statistiques et équation d'un lissage par moindres carrés pour 95 échantillons reprisentant 6 types de roches.

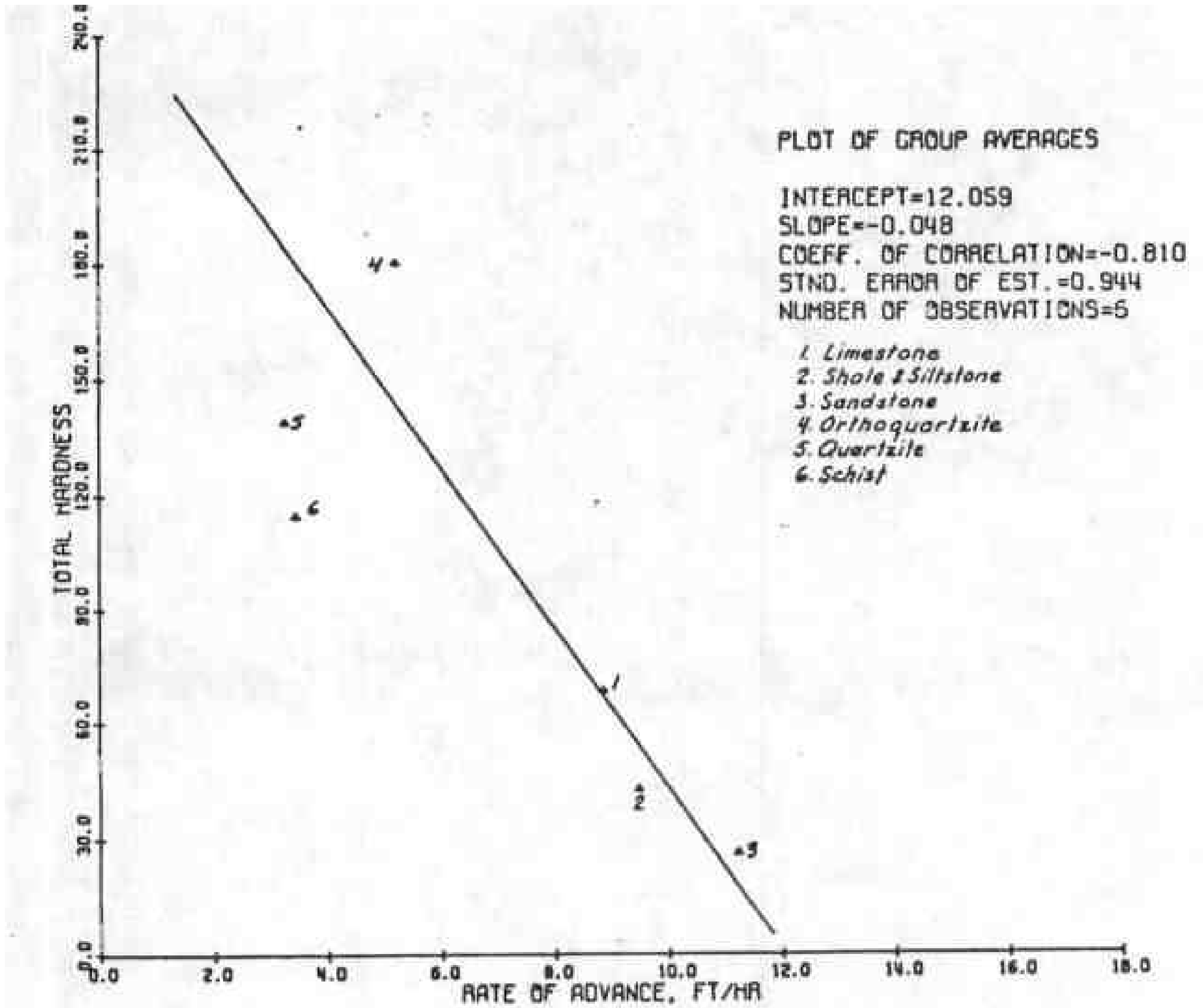


Figure 3. Plot of data, statistical results, and least squares fit equation for the average values for each of 6 rock types.

Données, résultats statistiques et équation d'un lissage par moindres carrés pour les valeurs moyennes de chacun des 6 types de roches.