Correlation of Laboratory Cutting Data With Tunnel-Boring Machine Performance

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Results of rock-cutting experiments conducted under constant normal force and constant penetration are discussed. Independent as well as interacting groove-spacing regions are identified and classified through determination of optimum and critical spacings. Specific energy, muck weight, groove depth, cutting coefficient, and size distribution of muck for the independent and interacting grooves of laboratory cutting are examined, and forward thrust, torque, advance rate, and muck size distribution in field operations are presented and discussed. Satisfactory correlation is obtained between laboratory cutting results and field performance data.

Although significant developments in underground excavation have occurred in the past two decades (3), the state of the art is not keeping pace today with developments in other related fields. Improved methods of underground excavation are highly desirable for developing new mineral reserves and opening up underground avenues of transportation for men and materials.

The continuing search for improved tunneling methods usually includes evaluation in the field of each new innovation or development. The major drawbacks of this approach include excessive cost and the duplication of time and effort that results from setting up a system to operate under varying values of controlling parameters. Only limited progress has been made by using this approach.

Less costly and quicker results can be achieved by assessing innovative equipment designs in the laboratory under instrumentation. Series of tests can be repeated until conclusive evidence of the merits of a specific design is established. Testing new tunneling techniques in the laboratory can make possible significant progress toward the development of technology for rapid and efficient underground excavation. The observations and recommendations presented in this paper are aimed at bringing that goal closer.

EXPERIMENTAL PROCEDURES AND EQUIPMENT

Laboratory rock-cutting experiments can be performed in either of two modes: constant penetration or constant normal force. In constant penetration, the cutter is fixed in its position relative to the rock surface as it traverses the surface. Thus, the penetration or groove depth is preset at the beginning of the test to, say, 1 mm (0.04 in), and normal force and cutting force—and possibly the groove width resulting from such penetration—are measured and recorded. In the constant normal force mode, the cutter traverses the face of the rock as it is being forced against the surface by a hydraulic cylinder that produces a nearly constant normal force. In these tests, normal force is preset during the test, and groove depth, groove width, and cutting force are recorded or measured as a function of normal force.

Laboratory rock-cutting data were produced at the Colorado School of Mines (CSM) by using a modified milling machine equipped with a 15-cm (6-in) disk cutter with a constant penetration ranging from 0.75 to 3 mm (0.03 to 0.12 in) that traversed the rock specimen at a speed of 8.2 mm/s (0.33 in/s). Laboratory rock-cutting data were produced at the Twin Cities Mining Research Center (TCMRC) by using a specially designed constant-thrust machine equipped with a 17.5-cm (7-in) cutter traversing under a normal thrust of 31 kN (7000 lbf) and at a speed of 7.5 cm/s (3 in/s).

The CSM experiments were performed on cores 15 cm (6 in) in diameter, obtained from three tunnel sites: the Nast tunnel in Basalt, Colorado; the Lawrence Avenue tunnel in Chicago; and the Climax tunnel in Climax, Colorado. Table 1 shows some of the geologic and strength data for these rocks. The TCMRC experiments were performed primarily on blocks obtained from commercial quarries marketing marble, limestone, granite, and quartzite. The specimens measured approximately 61 by 61 by 20 cm (24 by 24 by 8 in).

In the laboratory rock-cutting experiments, the normal and horizontal forces applied to the cutter shaft were determined by sensing the outputs of two properly aligned strain-gauge systems. Normal force and cutting force were then computed from the strain-gauge output recordings. The cutting force recorded by the strip-chart recorder is the force applied at the cutter shaft (Figure 1). This value is sufficient for comparing data obtained by the same machine. If results obtained by two laboratory cutting machines are to be compared, then the cutter diameter and the loading geometry will affect the results in such a way that direct comparisons are not possible unless proper corrections are made. For the purpose of consistency, in this paper the force applied to the rock surface is used to calculate the values of specific energy and cutting coefficient. The force at the rock surface, or the rock-resistance force, is determined by multiplying the force measured at the shaft by the ratio of the lever arms for the shaft and the cutter tip. The cutting coefficient was obtained by dividing corrected cutting force by normal force. The total work done by the corrected cutting force was divided by the weight of the total muck to obtain the value of specific energy for that groove. Data on groove geometry and muck size distribution were also determined for each test. Figure 2 shows the appearance of grooves in limestone.

Field data collected on the operation of boring machines (1, 7) included total forward thrust, cutterhead torque, and muck size distribution.

RESULTS

The performance of a rolling rock-cutting element in a specific rock generally depends on normal force, groove depth, cutter diameter, included angle of disk, cutting speed, groove spacing, and cutter sharpness (2, 4, 5). All of these parameters are interrelated so that if one parameter is increased the cutting performance may be kept consistent by decreasing another appropriate parameter. In some cases, two or three parameters can be changed systematically without affecting the overall cutting performance. Rad and McGarry (4) and Rad and

Table 1. Properties of rock specimens used in experiments of Colorado School of Mines.

Rock	Geologic Description	Compressive Strength (MPa)	Apparent Density	Shore Hardness
Tennessee marble[a]	Holston limestone	71.7	2.69	49.5
Valders limestone[a]	Cordell dolomite (member Manistique)	108.2	2.55	56.2
Gray granite[a]	St. Cloud gray, Granodiorite gneiss	183.4	2.72	84.4
Barre granite[b]	Barre granite	220	2.64	102
Sioux quartzite[a]	Sioux quartzite	560	2.64	89.1
Nast tunnel[c]	Fine-grained granite	89.7 to 241.3	2.42 to 2.66	—
Lawrence Avenue tunnel[c]	Fine-grained limestone	55.2	2.81	46

Note: 1 MPa = 145 lb/in².

[a] From Rad and Olson (6). [b] From Rad and McGarry (5). [c] From Haller, Pattison, and Shimizer (1).

Figure 1. Instrumentation for linear cutter apparatus.

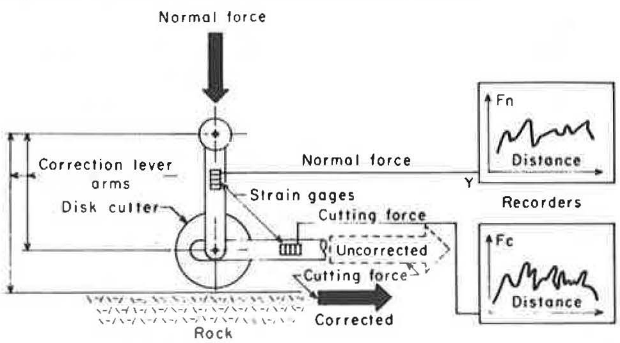
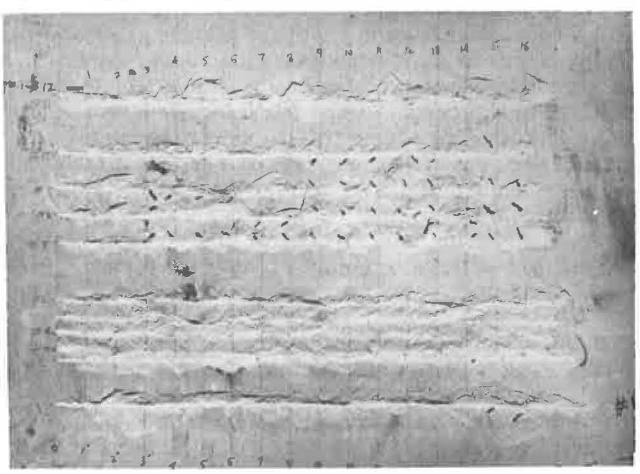


Figure 2. Appearance of grooves in limestone.



Olson (5) have shown that, for the purpose of studying specific aspects of the cutting process, several of these parameters can be systematically reduced from their field value without noticeably affecting results such as values of specific energy, cutting coefficient, and muck size distribution.

One of the more important characteristics of cutter design is the circumstances under which the cutter operates optimally and those under which it does not. Rad and Olson (5) conducted a study of cutting performance as a function of spacing and identified the three basic performance regions. The results indicated that increasing the spacing is analogous to increasing the speed, diameter, and included angle of the cutter and to decreasing normal thrust and groove depth. Such findings indicate that the concepts discussed here are applicable to laboratory and field studies regardless of what parameters are changed to obtain the various performance levels.

Performance Regions

For a fixed cutter diameter and fixed normal force, there exists a critical spacing for parallel grooves. Critical spacing is the closest distance two neighboring grooves can be to each other without interacting (Figure 3). Stated another way, critical spacing is the largest spacing at which there is interaction between neighboring grooves. At spacings slightly greater than critical spacing the grooves become independent, and at spacings slightly smaller than critical spacing there is chipping between adjacent grooves. The chips, formed by breakout between grooves, are considerably larger than those produced by independent grooves. In the interacting regions, the amount of muck is greater than that of independent regions and the value of specific boring energy is less than that of independent specific energy, as shown in Figure 4. By definition, specific energy and muck size at critical spacing are the same as those for all independent grooves with greater spacings.

For each set of cutting conditions, there is an optimum spacing at which the highest amount of muck and the lowest value of specific energy are obtained (Figure 5). Any decrease or increase in groove spacing from the optimum spacing will result in a reduction in cutting efficiency.

As the groove spacing decreases below the critical spacing, the average chip size increases from that produced at independent spacings (6). However, if the spacing is less than optimum, the maximum chip size is controlled by the groove spacing and is thus smaller for smaller spacings (4, 6). Identification of the preoptimum region was facilitated by arbitrarily calling the smallest spacing used in each series minute spacing and reporting the values of such factors as muck specific energy for this spacing.

Although a cutter operating in the preoptimum range is subjected to relatively high lateral forces, it is occasionally desirable to design a machine so that the cutters operate in the preoptimum region. In such a design, if cutting conditions worsen (normal thrust drops, the cutter tip wears, or there is a transition into harder rock), the cutter will gradually move into the postoptimum cutting region, which is very efficient. If, however, the cutter is initially operating in the postoptimum region, it cannot continue to operate satisfactorily because such a worsening of cutting conditions will move the cutter from the postoptimum region very close to or into the independent region. It becomes apparent, therefore, that cutters on boring machines intended for use on uniform rock type should be designed to operate at the optimum point or in the postoptimum region and machines intended for use on variable rock type should be designed to operate in the preoptimum region in softer formations such as marble and shale and in the postoptimum region in harder formations such as granite and quartzite.

Figure 3. Performance regions for gray granite defined by muck weight.

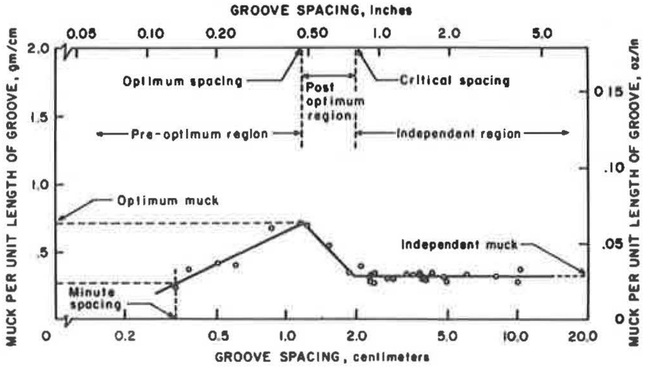


Figure 4. Performance regions for gray granite defined by specific boring energy.

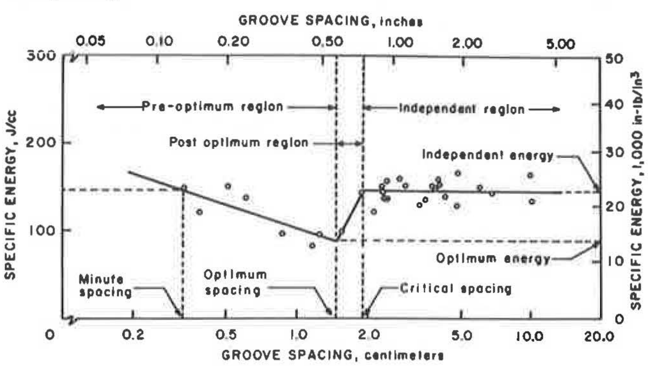
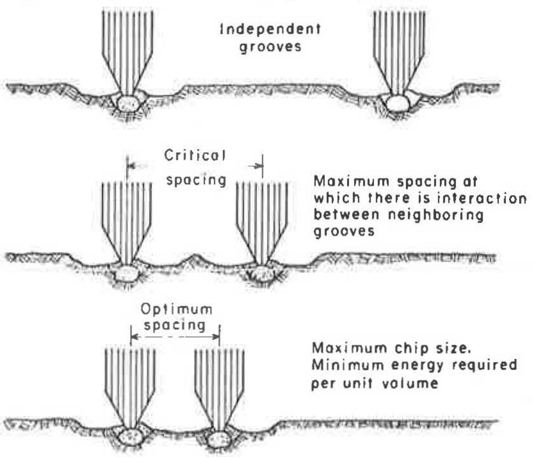


Figure 5. Optimum and critical groove spacings.



Normal Thrust

Experiments (2, 4) have shown that increasing the thrust or decreasing the cutter diameter results in deeper grooves and larger chips (Figure 5). This supports the theory (4, 5, 6) that critical and optimum spacings increase with normal force. As shown in Figure 6, the amount of muck removed for each groove increases smoothly but in a nonlinear pattern throughout the range of values investigated in these experiments. Coarser material was obtained at higher normal forces although independent specific energy did not vary substantially with increasing thrust (2).

Steady State

In actual field conditions, the boring-machine cutters repeatedly traverse the same circular path and keep breaking chips away from the roughened advance face. At the steady state thus reached by the boring-machine cutters, two factors contribute to the muck-removal process: (a) The cutters continue to penetrate farther into the groove on each pass by removing additional muck from the groove, and (b) neighboring grooves almost always interact with each other, which causes large chips to be formed.

Results obtained by Rad and McGarry (4) and Rad and Olson (5, 6) have shown that the interaction between the two neighboring grooves is the major contributing factor. Repeated passes in independent grooves resulted in successively smaller amounts of muck (4). Repeated passes in interacting grooves become more efficient until they reach a steady state corresponding to the cutting conditions (normal force, cutter diameter, and so on).

Figure 7 shows values for specific energy obtained from multiple passes on Barre granite. A series of 15 parallel, equidistant grooves were made on the smooth surface of the specimen, one groove at a time; this constituted one pass. Subsequent passes were made by repeating this process. The value of specific energy decreased on the second and third passes and reached the steady state on the sixth pass. The muck weights for these passes are shown in Figure 8. Although the scatter in the muck data is quite significant, it can be seen that muck weight also reaches the steady state at the sixth pass. The optimum spacing at the steady state is 1.5 times that found for smooth surface grooves (4). At the steady-state optimum spacing, the amount of muck increased 20 percent and the value of specific energy decreased to 50 percent of that found for the optimum cutting conditions for the smooth surface grooves (4).

Another interesting observation was that it takes a smaller number of passes to reach the steady state in postoptimum and preoptimum regions than in cases where the spacing is near critical (5). In other words, the number of passes required to reach the steady state was found to be somewhat proportional to groove spacing.

CORRELATION OF LABORATORY DATA WITH FIELD PERFORMANCE

The values of specific energy and advance rate obtained for field operations were compared with their corresponding laboratory parameters as functions of cutting coefficient and advance rate. A comparison of muck size distribution was also conducted for field and laboratory data.

Specific Energy

The value of specific energy for laboratory experiments is obtained by determining the work done by the rock-resistance force at the cutter tip and then dividing it by the volume of material removed. The cutting-coefficient value is the ratio of rock-resistance force to normal force, as shown in Figure 1. Essentially the same principle is applied in determining specific energy and cutting coefficient for field operations: (a) The value of specific energy is the amount of work done by the cutterhead to remove the unit volume of muck, and (b) the cutting-coefficient value is the cutting-coefficient average for all cutters.

The value of specific energy for a boring machine is obtained by using the following equation (Equations 1 and 2 were formulated in customary units, and thus no SI equivalents are given in the term definitions):

$$E_s = 2NT/0.60\,R \quad (1)$$

where

E_s = specific energy (in·lbf/in^3),
N = speed of rotation of cutterhead (rpm),
T = torque required by the cutterhead (lbf·ft), and
R = advance rate (ft/h).

The cutting coefficient is obtained from the boring-machine parameters by using the following equation (7):

$$C = (4/D) \cdot (T/F) \quad (2)$$

where

Figure 6. Groove depth versus normal thrust for independent grooves.

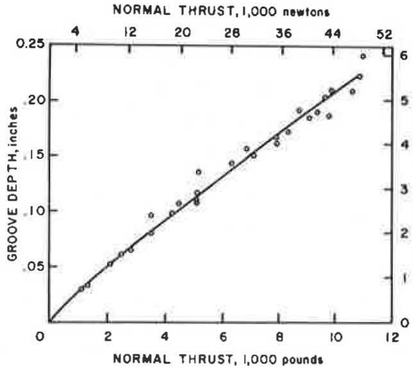


Figure 7. Steady-state specific energy.

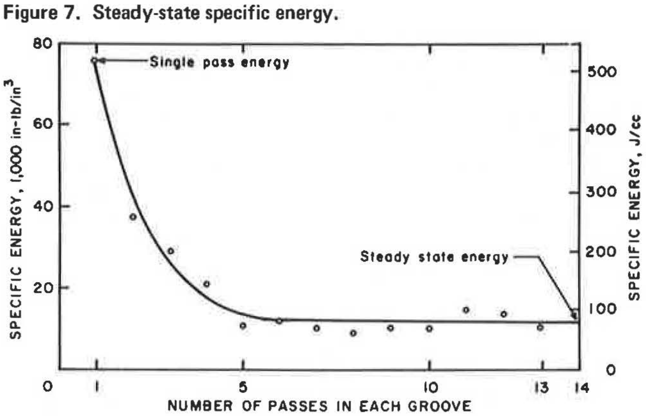
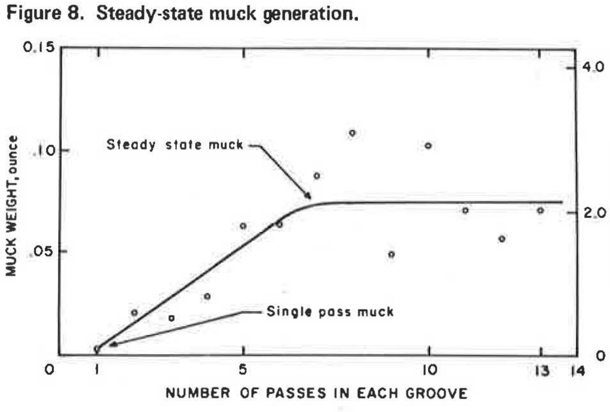


Figure 8. Steady-state muck generation.



C = cutting coefficient,
D = tunnel diameter (ft), and
F = total thrust (lbf).

Figure 9 shows the variation of specific energy with cutting coefficient for single-pass grooves at the optimum point or at the critical or minute spacings (5) and for steady-state grooves (7). The data points for a single pass represent a large set of data: 23 grooves in marble, 25 grooves in limestone, 30 grooves in granite, and 27 grooves in quartzite. The data for the steady-state mode were obtained from experiments on eight specimens from the Nast, Lawrence, and Climax tunnels. As a first approximation, the behavior in the steady-state mode can be approximated by a straight line. The behavior in the preoptimum and postoptimum regions of the single-pass experiments can be approximated by lines drawn between the conditions of critical and optimum spacing and optimum and minute spacing respectively. The behavior in the independent region is represented by the critical point because by definition the cutting characteristics of the independent grooves are the same as those of the critical groove. These approximations are confirmed by the behavior of individual data points in the interacting regions, which have been left out for the sake of clarity.

Critical specific energy, optimum specific energy, and minute-spacing specific energy decrease as the cutting coefficient increases. The single-pass data further show that, if experiments are performed in one rock type, specific energy decreases as the cutting coefficient increases while conditions change from critical to optimum. If, however, the cutting conditions continue to change in the same direction, no further increase in the cutting coefficient is realized and it begins to decrease as specific energy increases. Because the preoptimum and postoptimum segments of these variations both follow an inverse linear relation, the trend in the variation of specific energy with cutting coefficient may not be used to indicate whether the cutting conditions are preoptimum or postoptimum unless the data cover a good portion of both these regions.

Figure 10 shows the variation of specific energy with cutting coefficient for the Nast tunnel operation. Figures 8 and 9 show very close agreement between field data and laboratory data: Both show an inverse linear trend. It is interesting that the change of cutting conditions in the field was obtained by varying the forward thrust. The change in cutting-coefficient values in the field reflects an increase in the value of forward thrust rather than a decrease in the value of torque. The data points shown in Figure 7 represent torque values of 75 to 84 kN·m (102 000 to 114 000 lbf·ft), whereas the value of thrust varies from 1.78 to 2.32 MN (401 000 to 522 000 lbf).

Figure 11 shows the variation of specific energy with muck per unit length of groove for single-pass experiments. The data points represent the results obtained from over 100 grooves. For each of the three cutting modes—critical, optimum, and minute—the values of specific energy decrease as the amount of muck per unit length of groove increases. For the same rock, as muck increases from the critical to the optimum value, specific energy decreases. In the preoptimum region, however, the muck decreases and the specific energy increases. For each rock, the optimum condition is the one where the highest amount of muck is produced at the lowest value of specific energy. Because the preoptimum and postoptimum segments of these variations both follow an inverse linear relation, the trend in the variation of specific energy with muck weight may not be used to identify whether cutting conditions are preoptimum or postoptimum unless the data cover both of these performance regions.

Figure 9. Specific energy versus cutting coefficient for laboratory experiments.

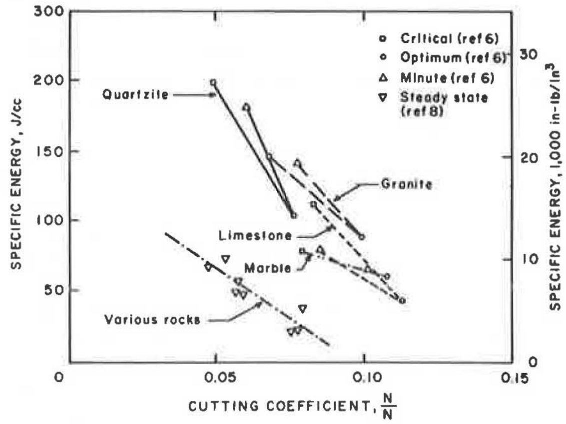


Figure 10. Specific energy versus cutting coefficient for Nast Tunnel operation.

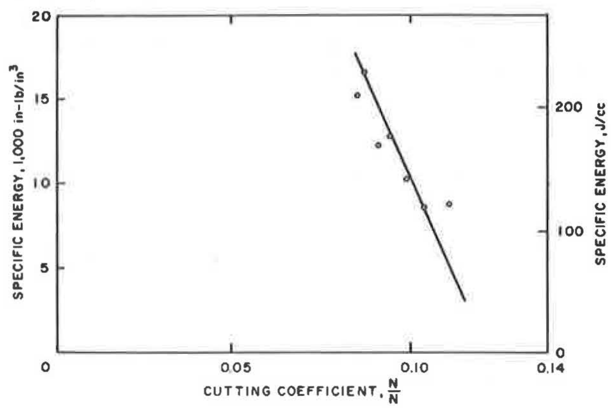


Figure 12 shows the variation of specific energy with groove depth for critical, optimum, and minute groove spacing and steady-state grooves. For each of these four cutting modes, the value of specific energy decreases as groove depth increases. The single-pass data further show that, if experiments are performed in one rock type, specific energy decreases as groove depth increases from that of independent spacing to that of optimum spacing. Specific energy increases if groove depth continues to increase in the preoptimum region. The variation of specific energy with groove depth can be used effectively to identify the mode of cutting in a given rock. Such identification is relatively simple because, for each rock, the slopes for preoptimum and postoptimum regions are positive and negative respectively.

The two major factors in muck removal in a boring-machine operation are cutter penetration and rock breakout between cutters. It can therefore be seen that advance rate in field operations corresponds with some combination of laboratory values for groove depth and muck weight. Figure 13 shows specific energy as a function of boring rate for the Nast and Lawrence Avenue tunnel operations. The material in the Lawrence Avenue tunnel is relatively uniform and—judging by values of specific energy, advance rate, and muck size distribution—the boring machine is operating in the postoptimum region. The data thus correlate well with the postoptimum segment of single-pass laboratory experiments on limestone. The material of the Nast tunnel, however, has varied significantly over the length of the tunnel so that, for the purposes of this discussion, it cannot be assumed that rock properties and rock strength stayed constant over this length. All indicators are that the Nast tunnel machine was operating in the preoptimum mode. Therefore, it appears that the variation of specific energy for the Nast tunnel can be more closely correlated with the variation of specific energy of minute spacing points plotted for various rocks.

Advance Rate

Groove depth and muck weight are the laboratory parameters that correspond to boring-machine rate (4). Figure 14 shows the variation of groove depth with cutting coefficient for single-pass and steady-state experiments. Single-pass results are given for critical, optimum, and minute groove spacing. For each of these three cutting modes, the value of groove depth increases as the cutting coefficient increases. For the same rock type, as the cutting coefficient increases from the critical value through the postoptimum region, groove depth also increases. In the postoptimum region, granite has a negative slope and other rock types have positive slopes. The variation of groove depth with cutting coefficient can be used to identify the cutting mode only if the range covers a major portion of both preoptimum and postoptimum regions. Such identification is based on the slope of the line in Figure 13 that represents the preoptimum and postoptimum regions.

Figure 15 shows the variation of muck weight per groove length with cutting coefficient for single-pass grooves, including the representative points for critical, optimum, and minute spacing. In the postoptimum region, the muck value increases with increasing cutting coefficient for the same rock. In the preoptimum region, both muck and cutting-coefficient values decrease. The variation of muck with cutting coefficient in both the preoptimum and postoptimum regions has positive slopes; therefore, it may not be a good indicator of the cutting mode because in some cases the difference in slope may not be significant.

Figure 16 shows the variation of boring rate with cutting coefficient for the Nast tunnel. This variation closely approximates a linear pattern and agrees with the laboratory data shown in Figures 13 and 14. Although other indicators point out that this machine operates in the preoptimum region, this variation cannot be used for such conclusions because the slopes of the preoptimum and postoptimum regions are both positive.

Figure 17 shows the variation in advance rate with forward thrust for the Lawrence Avenue and Nast tunnel operations. If one considers the principle that increasing thrust and decreasing spacing are analogous (4) and compares Figures 3 and 16, it becomes apparent that the Lawrence Avenue operation is in the postoptimum mode and the Nast tunnel operation is in the preoptimum mode. With increasing thrust, the rate of advance in the Nast tunnel decreases; in the Lawrence Avenue tunnel it increases. The former compares with the postoptimum region and the latter with the preoptimum region shown in Figure 3.

Muck Size Distribution

The muck obtained from single-pass or steady-state laboratory experiments may not be expected to have the same size distribution as that produced by a boring machine. It does, however, provide information that can be used to predict and analyze field situations with much more accuracy and by the help of more indicators. Generally, the material produced at the optimum spacing is substantially coarser than that obtained at the independent spacing. Plots of muck size distribution for the entire spec-

Figure 11. Specific energy versus muck weight for laboratory experiments.

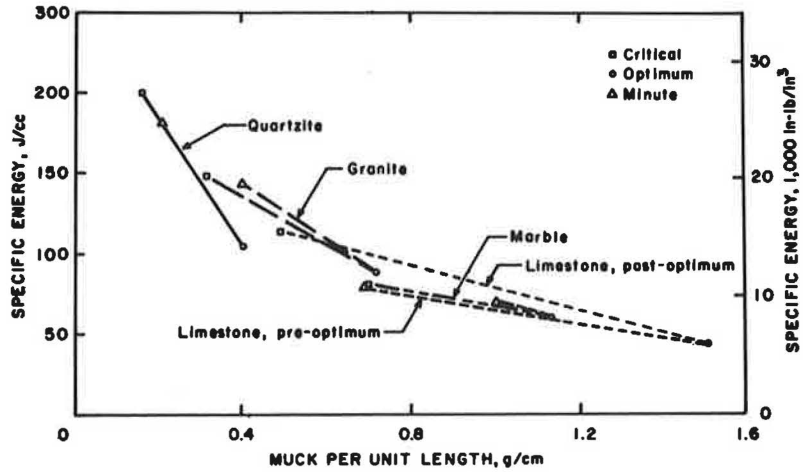


Figure 12. Specific energy versus groove depth for laboratory experiments.

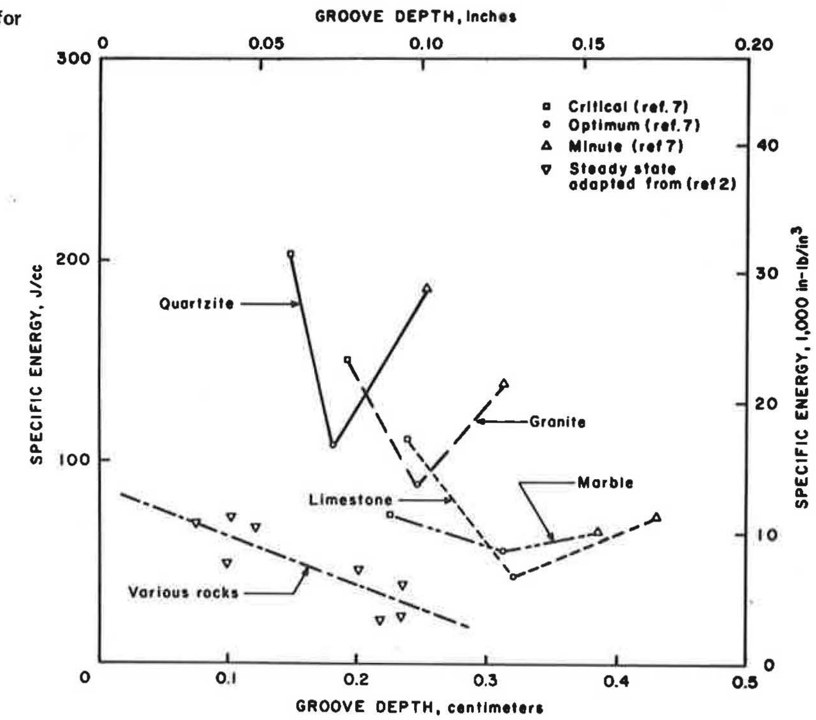
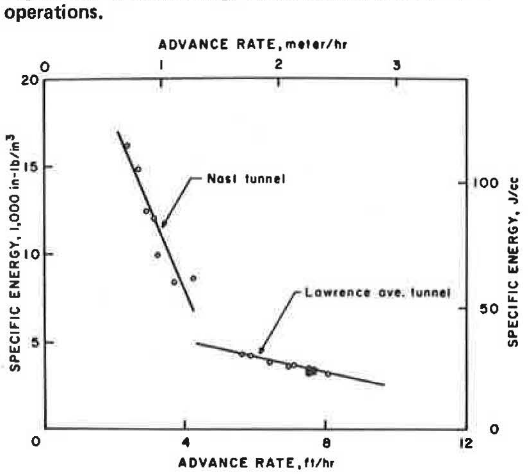


Figure 13. Specific energy versus advance rate for field operations.



trum of spacings (6) have indicated that the curves show a general coarsening of muck as the spacing is reduced from critical toward optimum (arrow a in Figure 18). If the spacing is reduced below the optimum spacing, the muck size distribution becomes fine again. For very small spacings, muck size distribution becomes similar to the distribution of muck obtained from independent grooves (arrow b in Figure 18). It has also been found that at the optimum spacing rocks of higher compressive strength produce a finer size distribution than more cuttable rocks of lower compressive strength (5). Comparison of field data and laboratory data shows that near-optimum conditions are obtained if about one-third of the pieces that compose the muck are larger than 40 percent of the distance between the neighboring grooves or the studs of the cutters (7).

Figure 19 shows the size distribution of muck obtained from the Lawrence tunnel operation and from two different locations in the Nast tunnel (the samples from the two

Figure 14. Groove depth versus cutting coefficient for laboratory experiments.

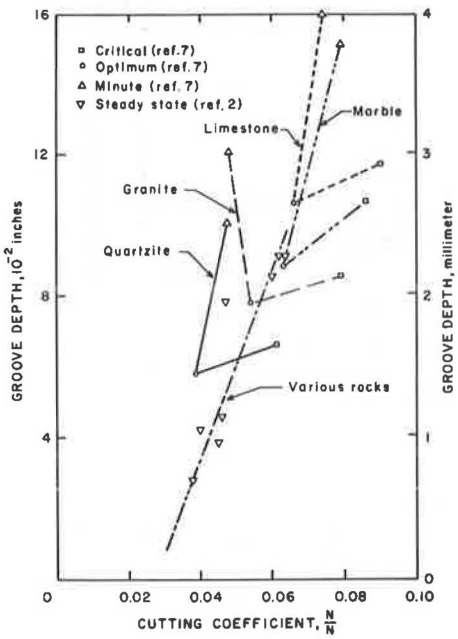


Figure 15. Muck weight versus cutting coefficient for laboratory experiments.

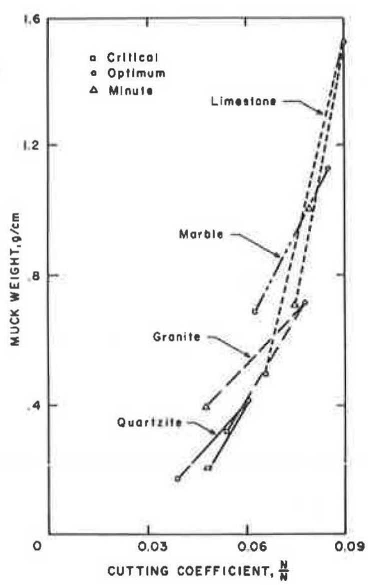


Figure 16. Advance rate versus cutting coefficient for Nast Tunnel operations.

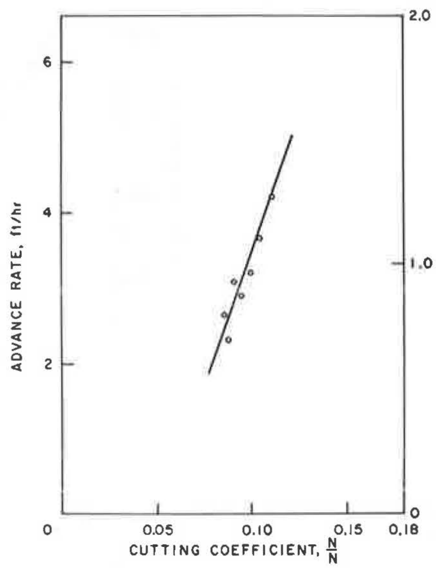
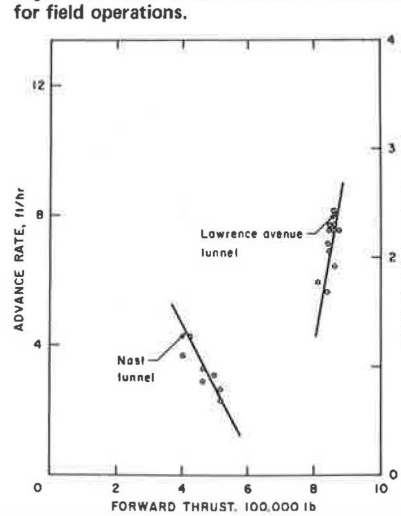


Figure 17. Advance rate versus forward thrust for field operations.



locations in the Nast tunnel are of the same rock type but of different compressive strengths). The Lawrence Avenue muck is much coarser than that from the Nast tunnel. The reason for such a difference is not immediately obvious but is probably a combination of differences in rock type and structure, thrust, cutter type, and speed of rotation.

Interestingly, the size distribution of the muck obtained from the Nast tunnel indicates that the material obtained from the stronger rock is coarser. This observation confirms other observations suggesting that the Nast tunnel boring machine is operating in the preoptimum region and as the rocks get stronger the conditions become closer to optimum and so coarser material is produced.

CONCLUSIONS

Laboratory experiments in tunnel boring conducted under the constant normal force mode or the constant penetration mode are capable of producing results that are beneficial to the design and operation of boring machines. Continuously monitoring thrust, torque, advance rate, and muck size distribution in boring machine operations will provide indicators by which the performance of the machine can be systematically assessed. The values for advance rate and cutting coefficient for boring machines can be represented in the laboratory by groove depth, muck weight, and cutting coefficient. Steady-state laboratory experiments result in values of specific energy higher than those found in field operations if the field boring conditions are postoptimum. Tunnel boring machines may be operated in either the preoptimum or postoptimum region. The former is suitable for highly variable rock whereas the latter is suitable for relatively uniform rock.

Figure 18. Variation in muck size distribution with groove spacing.

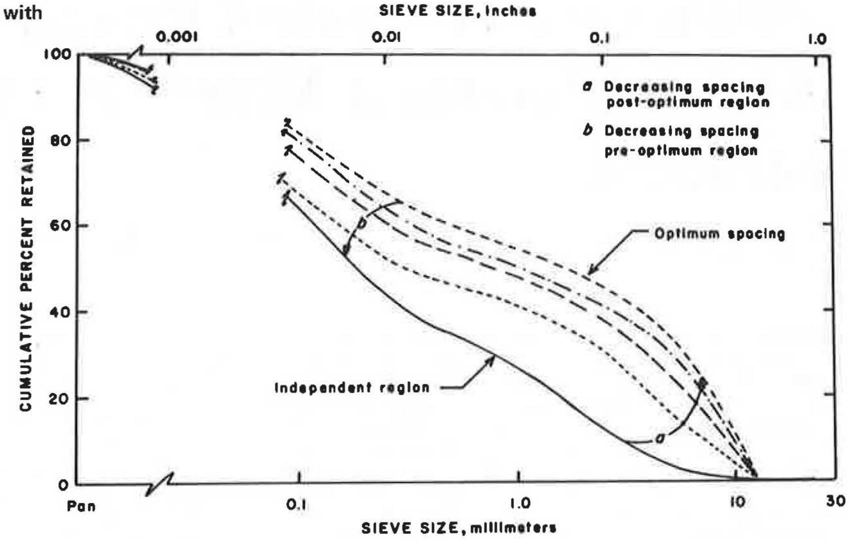
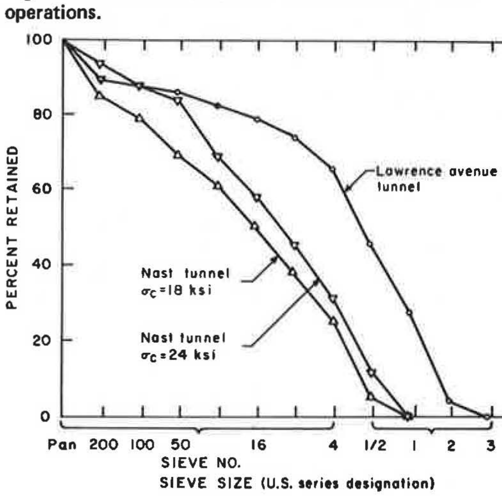


Figure 19. Size distribution of muck obtained in field operations.



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