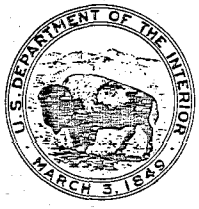
BuMines RI 7881

Report of Investigations 7881

Tunneling Machine Research

Interaction Between Disk-Cutter Grooves in Rocks

By Parviz F. Rad and Richard C. Olson
Twin Cities Mining Research Center, Twin Cities, Minn.



UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

BUREAU OF MINES
Thomas V. Falkie, Director

This publication has been cataloged as follows:

Rad, Parvis F

Tunneling machine research: interaction between disk-cutter grooves in rocks, by Parvis F. Rad and Richard C. Olson. [Washington] U.S. Bureau of Mines [1974]

21 p. illus., tables. (U.S. Bureau of Mines. Report of investigations 7881)

Includes bibliography.

1. Tunneling—Equipment and supplies. 2. Boring machinery. I. U.S. Bureau of Mines. II. Olson, Richard C., jt. auth. III. Title. (Series)

TN23.U7 no. 7881 622.06173

U.S. Dept. of the Int. Library

CONTENTS

	Page
Abstract	1
Introduction	1
Experimental procedures and equipment	3
Specimen materials	3
Cutting machine	3
Randomization of tests	5
Data collection and reduction	6
Data refinement	7
Results and discussion	8
Specific energy	9
Muck weight	9
Groove depth	12
Cutting coefficient	14
Correlation of cutting characteristics with mechanical properties	14
Field applications	18
Conclusions	20
References	21

ILLUSTRATIONS

1.	Disk cutter with tungsten carbide cutting edge	5
2.	Instrumentation schematic for linear cutter apparatus	6
3.	Optimum and critical cutter spacings	7
4.	Groove spacing classification	8
5.	Specific energy versus groove spacing	10
6.	Muck weight versus groove spacing	11
7.	Groove depth versus groove spacing	13
8.	Cutting coefficient versus groove spacing	15
9.	Groove width versus compressive strength	16
10.	Anticipated variation of advance rate with forward thrust	18
11.	Anticipated variation of cutting coefficient with forward thrust	19
12.	Anticipated variation of specific energy with forward thrust	19

TABLES

1.	Physical and mechanical properties of specimen materials	4
2.	Ratio of optimum to independent values of cutting characteristics	9
3.	Largest chip dimension	12
4.	Ratio of optimum spacing to critical spacing	12
5.	Cutting characteristics of rocks used in this study	17
6.	Correlation of cutting characteristics with physical properties	17

BIBLIOGRAPHIC DATA SHEET	1. Report No. BuMines RI 7881	2.	3. Recipient's Accession No.
4. Title and Subtitle Tunneling Machine Research Interaction Between Disk-Cutter Grooves in Rocks			5. Report Date May 1974 6. Performing Organization Code
7. Author(s) Parviz F. Rad and Richard C. Olson			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Twin Cities Mining Research Center Bureau of Mines, USDI P.O. Box 1660 Twin Cities, MN 55111			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Agency Name and Address Office of Assistant Director--Mining Bureau of Mines U.S. Department of the Interior Washington, DC 20240			13. Type of Report & Period Covered Research, FY 1973 14. Sponsoring Agency Code
15. Supplementary Notes			

16. Abstracts The Bureau of Mines conducted groove cutting experiments in marble, limestone, granite, and quartzite with a 7-in disk cutter under a normal thrust of 7,000 lb. The values of muck weight per unit length, specific energy, cutting coefficient, and groove depth for each of these rocks were determined for groove spacings ranging from 0.1 to 4 in. and from these results the values of optimum and critical spacing were computed. The results indicate that compressive strength may be used to predict some of the cutting characteristics of the independent grooves. Considering all the cutting characteristics, particularly those for the interacting grooves, shore hardness, coefficient of rock strength, and torsional velocity, correlate with cutting characteristics better than other physical properties do. Some of the field applications of the principles established in this report are also identified.

17. Key Words and Document Analysis. 17a. Descriptors

Mining
Tunneling machines
Cutting machines
Cutters

17b. Identifiers/Open-Ended Terms

Rock cutting
Boring machines

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

17c. COSATI Field/Group 08I

18. Distribution Statement	19. Security Class (This Report)	21. No. of Pages
Release unlimited by NTIS.	UNCLASSIFIED	26
	20. Security Class (This Page) UNCLASSIFIED	22. Price $3.25

INSTRUCTIONS FOR COMPLETING FORM NTIS-35 (10-70) (Bibliographic Data Sheet based on COSATI Guidelines to Format Standards for Scientific and Technical Reports Prepared by or for the Federal Government, PB-180 600).

1. **Report Number.** Each report shall carry a unique alphanumeric designation. Select one of the following types: (a) alphanumeric designation provided by the sponsoring agency, e.g., **FAA-RD-68-09;** or, if none has been assigned, (b) alphanumeric designation established by the performing organization e.g., **FASEB-NS-87;** or, if none has been established, (c) alphanumeric designation derived from contract or grant number, e.g., **PH-43-64-932-4.**

2. Leave blank.

3. **Recipient's Accession Number.** Reserved for use by each report recipient.

4. **Title and Subtitle.** Title should indicate clearly and briefly the subject coverage of the report, and be displayed prominently. Set subtitle, if used, in smaller type or otherwise subordinate it to main title. When a report is prepared in more than one volume, repeat the primary title, add volume number and include subtitle for the specific volume.

5. **Report Date.** Each report shall carry a date indicating at least month and year. Indicate the basis on which it was selected (e.g., date of issue, date of approval, date of preparation.

6. **Performing Organization Code.** Leave blank.

7. **Author(s).** Give name(s) in conventional order (e.g., John R. Doe, or J.Robert Doe). List author's affiliation if it differs from the performing organization.

8. **Performing Organization Report Number.** Insert if performing organization wishes to assign this number.

9. **Performing Organization Name and Address.** Give name, street, city, state, and zip code. List no more than two levels of an organizational hierarchy. Display the name of the organization exactly as it should appear in Government indexes such as **USGRDR-I.**

10. **Project/Task/Work Unit Number.** Use the project, task and work unit numbers under which the report was prepared.

11. **Contract/Grant Number.** Insert contract or grant number under which report was prepared.

12. **Sponsoring Agency Name and Address.** Include zip code.

13. **Type of Report and Period Covered.** Indicate interim, final, etc., and, if applicable, dates covered.

14. **Sponsoring Agency Code.** Leave blank.

15. **Supplementary Notes.** Enter information not included elsewhere but useful, such as: Prepared in cooperation with . . . Translation of . . . Presented at conference of . . . To be published in . . . Supersedes . . . Supplements . . .

16. **Abstract.** Include a brief (200 words or less) factual summary of the most significant information contained in the report. If the report contains a significant bibliography or literature survey, mention it here.

17. **Key Words and Document Analysis. (a). Descriptors.** Select from the Thesaurus of Engineering and Scientific Terms the proper authorized terms that identify the major concept of the research and are sufficiently specific and precise to be used as index entries for cataloging.
(b). Identifiers and Open-Ended Terms. Use identifiers for project names, code names, equipment designators, etc. Use open-ended terms written in descriptor form for those subjects for which no descriptor exists.
(c). COSATI Field/Group. Field and Group assignments are to be taken from the 1965 COSATI Subject Category List. Since the majority of documents are multidisciplinary in nature, the primary Field/Group assignment(s) will be the specific discipline, area of human endeavor, or type of physical object. The application(s) will be cross-referenced with secondary Field/Group assignments that will follow the primary posting(s).

18. **Distribution Statement.** Denote releasability to the public or limitation for reasons other than security for example "Release unlimited". Cite any availability to the public, with address and price.

19 & 20. **Security Classification.** Do not submit classified reports to the National Technical Information Service.

21. **Number of Pages.** Insert the total number of pages, including this one and unnumbered pages, but excluding distribution list, if any.

22. **Price.** Insert the price set by the National Technical Information Service or the Government Printing Office, if known.

TUNNELING MACHINE RESEARCH

Interaction Between Disk-Cutter Grooves in Rocks

by

Parviz F. Rad[1] and Richard C. Olson[2]

ABSTRACT

The Bureau of Mines conducted groove cutting experiments in marble, limestone, granite, and quartzite with a 7-inch disk cutter under a normal thrust of 7,000 lb. The values of muck weight per unit length, specific energy, cutting coefficient, and groove depth for each of these rocks were determined for groove spacings ranging from 0.1 to 4 inches, and from these results the values of optimum and critical spacing were computed. The results indicate that compressive strength may be used to predict some of the cutting characteristics of the independent grooves. Considering all the cutting characteristics, particularly those for the interacting grooves, Shore hardness, coefficient of rock strength, and torsional velocity correlate with cutting characteristics better than do other physical properties. Some of the field applications of the principles established in this report are identified.

INTRODUCTION

The number and size of projects that involve underground excavations are increasing steadily owing to rapid growth of the urbanization patterns and the increasing demand for excavation of mineral deposits. It has been assessed that a total of 628,800 km of tunnels will be excavated worldwide during the 1970's (9)[3] with an excavation volume of 6,031 million cubic meters. The total length of tunnels excavated in the 1970's will be 46 pct greater than those excavated in the 1960's. The excavation volume will increase by 54 pct in the 1970's. It is therefore technologically and economically advantageous to develop more efficient and more economical excavation systems.

The use of tunnel boring machines in the underground excavation operations results in minimum damage to the surrounding rock. Consequently the probabilities of roof collapse are lower in tunnels excavated with boring machines in than those excavated by explosives. The vibrations caused by

---

[1]Civil engineer (now Assistant Professor, Department of Civil Engineering, Clemson University, Clemson, S.C. 29631).

[2]Mechanical engineer.

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

boring machines are so negligible to surface structures that these machines can be conveniently operated in densely populated urban areas where explosive techniques would be objectionable. The uniform size of the muck produced by boring machines and the continuity of the operations suggest the possibility of using a continuous muck removal operation that could be more economical and more convenient than the truck or rail methods, which are cyclic in nature. Further, the size of the crew is smaller than that of the drill and blast system, thus decreasing the possibility of accidents.

The long assembly and disassembly time and high capital investment required for boring machines limit their use to long tunnels or to a project involving several tunnels. Further, owing to the scarcity of operational experience with tunnel boring machines, the unexpected geological complications occurring during the boring operations cannot, in many cases, be handled efficiently and systematically. The successful use of tunnel boring machines until recently generally has been limited to excavation in soft to medium-hard rocks such as shale, sandstone, and limestone.

In circumstances where boring machines do not perform satisfactorily, such machines are modified and developed in the field after the initial unsatisfactory performance. This procedure is costly, and in some cases, the optimum performance may not be obtained even after several field modifications. A more efficient design of boring machines will be possible if the cutting characteristics of rocks are known in relation to different cutters. The experiments described in this report are designed to provide some guidelines for an improved boring machine design procedure.

Since the mid-1960's, the Bureau's Twin Cities Mining Research Center has conducted various research projects dealing with boring machine design and performance. The experiments have been performed on the laboratory scale to develop the desirable concepts, and will be extended to the field scale to determine important operational parameters. This report describes experiments designed to determine the effects of groove spacing on cutting characteristics of marble, limestone, granite, and quartzite.

Cutting experiments in rocks can be performed either in the constant-penetration mode or the constant-normal-force mode. The constant-normal-force mode of laboratory cutting experiments simulates the field conditions more realistically because the boring machine is advanced under a constant forward force. With proper design of the hydraulic system supplying the normal force, the resultant grooves have very uniform depths of penetration. The variation of groove depths are normally less than ±6 pct about the mean depth. Further, constant-normal-force mode has several operational advantages, such as ease of selecting the length of travel, no damage to the corners of the test block, low probability of overloading the normal force system, and less stringent requirements for the surface of the test block.

Barker (1), Hustrulid (4), and Peterson (11) used constant-penetration mode for experiments with drag bits, disk cutters, and toothed cutters, respectively. To a limit defined by the difference in experimental procedures, there is agreement between the results obtained by these investigators and those obtained from the work performed by the Bureau.

Barker (1) investigated the relative efficiency of the deep-cut principle and found that for each penetration depth there exists an optimum spacing at which material is removed with highest efficiency. The material obtained at this spacing was coarser than that obtained at other spacings. Barker also found that at constant penetration the means of normal and cutting forces increased with increasing depth or with increasing groove spacing.

Teale (13); Morrell, Bruce, and Larson (7); and Rad and McGarry (12) used constant-force mode for experiments with rolling cutters. Very close agreement is obtained between these earlier results and those given in this report.

Teale (13) investigated the cutting characteristics of rocks using toothed cutters under various normal forces and found that increasing the normal force increases the depth of penetration, volume of muck, and coarseness of muck.

Morrell, Bruce, and Larson (7) investigated the relation between thrust, muck, and specific energy and developed prediction equations for some of the cutting characteristics. Rad and McGarry (12) investigated the effects of disk diameter, groove spacing, thrust, and speed on specific energy and muck.

EXPERIMENTAL PROCEDURES AND EQUIPMENT

The experiments described in this report were performed to determine the values of optimum and critical spacings, as well as other cutting characteristics for four different rock types. The results were correlated with physical and mechanical properties and then guidelines for better design and usage of tunnel boring machines were developed. The experiments were performed with a 7-inch disk cutter and with a normal force of 7,000 lb. The relative rock-cutter speed for all the cutting experiments was 3 inches per second (ips). The length of the groove was approximately 18 inches for all tests.

Specimen Materials

The rocks used in this study were marble, limestone, granite, and quartzite. Table 1 shows the physical properties of these rocks as determined by Property Determination Research Support and Fabric Analysis Research Laboratories of the Bureau's Twin Cities Mining Research Center (6). The specimens were approximately 24 by 24 by 8 inches and the surfaces were smooth to the touch, although they were not polished.

Cutting Machine

The rolling disk cutter used in these experiments was 1 inch thick and 7 inches in diameter. It was made of hardened steel with 36 wedge-shaped pieces of tungsten carbide having a 90° included angle inserted at the edge of the cutter as shown in figure 1. Thus, for all practical purposes, it would be assumed that the cutting was done with a tungsten carbide cutter having a 90° included angle.

TABLE 1. - Physical and mechanical properties of specimen materials

Property	Property index	Rock type			
		Marble[1]	Limestone[2]	Granite[3]	Quartzite[4]
Apparent density.....g/cm^3..	P_1	2.688	2.553	2.724	2.637
Compressive strength.....MN/m^2..	P_2	71.4	108.4	183.4	559.2
Do.....psi..	P_2	10,360	15,720	26,600	81,100
Tensile strength.....MN/m^2..	P_3	5.59	3.78	11.00	8.91
Shore hardness.....scleroscope units..	P_4	49.5	56.2	84.4	89.1
Impact strength index.....	P_5	0.69	0.61	1.28	1.04
Compression modulus.....GN/m^2..	P_6	19.92	20.20	29.91	45.74
Tensile modulus.....GN/m^2..	P_7	49.47	8.62	70.13	23.33
Dynamic Young's modulus.....GN/m^2..	P_8	55.05	37.96	79.31	59.80
Pulse velocity.....km/sec..	P_9	4.962	3.984	5.858	4.760
Bar velocity.....km/sec..	P_{10}	4.526	3.856	5.396	4.762
Torsional velocity.....km/sec..	P_{11}	2.935	2.619	3.463	3.517
Poisson's ratio.....	P_{12}	0.251	0.162	0.240	0.038
Fracture surface energy.....10^{-3}J/cm^2..	P_{13}	4.20	6.86	8.90	12.90
Grain size.....mm..	P_{14}	0.48	0.03	0.17	0.27
Microcrack area.....mm^2/mm^3..	P_{15}	2.00	28.60	5.06	7.80

[1]Geologic description: Holston Limestone; commercial name: Tennessee marble; location: Knoxville, Tenn.

[2]Geologic description: Cordell Dolomite Member, Manistique Formation; commercial name: Valders white rock; location: Valders, Wis.

[3]Geologic description: St. Cloud Gray Granodiorite; commercial name: Charcoal granite; location: St. Cloud, Minn.

[4]Geologic description: Sioux Quartzite; commercial name: Jasper quartzite; location: Jasper, Minn.

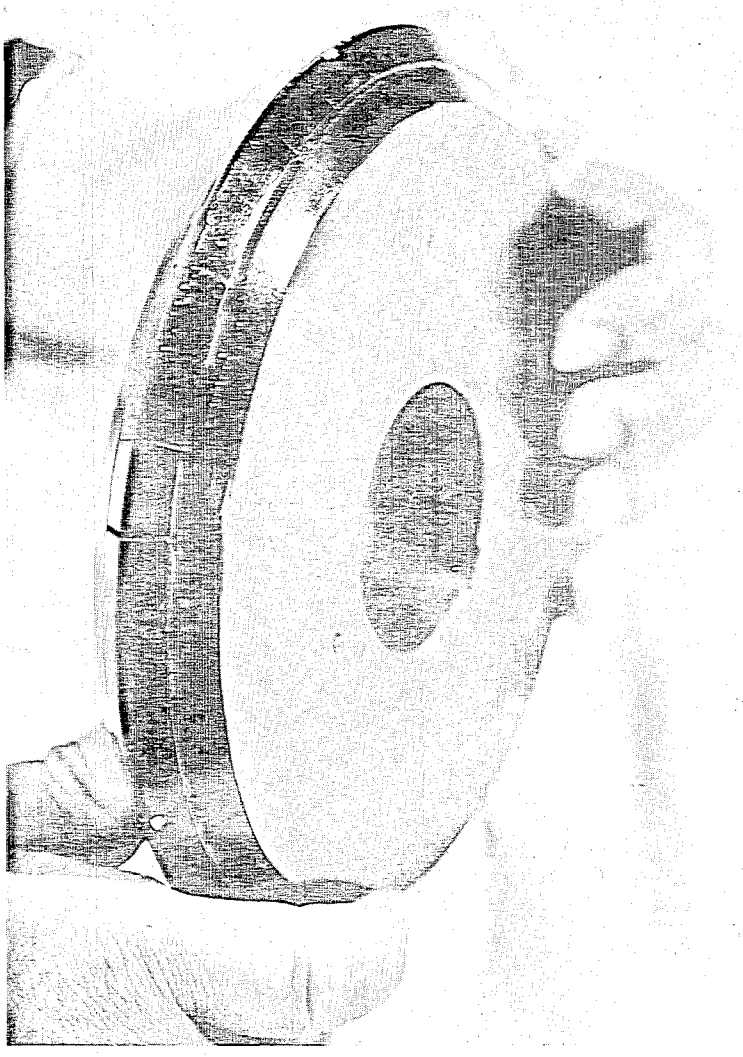


FIGURE 1. - Disk cutter with tungsten carbide cutting edge.

During the design process of these experiments, a technique was developed for measuring the wear of cutters with particular application to those that have tungsten carbide inserts. This technique uses the value of the circumference and an index for damage severity as bases of comparison for various stages of cutter wear. The cutter used in these experiments was examined before initiation of the testing phase and after the tests were completed. The results show that the circumference stayed essentially the same and the damage severity was very slight.

The disk cutter was mounted on a specially designed cutting machine called a linear cutting apparatus (LCA). The normal force and cutting force of the cutter were provided by the pistons of two hydraulic cylinders. Details of the structure and capabilities of this apparatus are given in RI 7410 (7).

Randomization of Tests

The order by which these rocks were tested was determined by a statistically random process. To minimize the effects of cutter wear on the results, the rocks were tested again, in the reverse order. The order of spacing arrangements for the series was also reversed for the same reason.

Experiments were performed on all rocks for nominal spacings of 1/4, 3/8, 1/2, 5/8, 3/4, 7/8, 1, 1-1/8, 1-1/4, 1-1/2, 1-3/4, 2, and 4 inches. The order by which these spacings were used was randomized for the first half of all experiments. The reverse of this order was used in the second half of the experiments. The actual spacing between two neighboring grooves was determined later using a precision caliper.

Data Collection and Reduction

The cutting force and normal force were measured by two strain gage bridges properly alined and calibrated for this purpose. The bridges were activated by a dc power supply and their output was monitored and recorded by a multichannel strip chart recorder. The recorder was equipped with two integrators to facilitate calculation of averages for the forces as well as the total work required for cutting of each groove. The averages for normal force and cutting force were conveniently obtained from the integrators of the strip chart recorders. The cutting force recorded by the strip chart recorder is the force measured at the cutter shaft (fig. 2). In order to obtain the force applied at the cutter-rock interface, these values were corrected by the ratio of the cutter shaft lever arm and interface lever arm: 12/15.4. The corrected horizontal force was used to calculate cutting coefficient and specific energy given in this report.

For each groove, the value of cutting coefficient was obtained by dividing the cutting force by the normal force. Generally, the variation of the normal force was approximately ±5 pct about the mean value, although the variation of cutting force had no established pattern.

After cutting the groove, the length of the cutter travel was measured, to the nearest 1/8 inch, and the muck was collected with a hand-held vacuum cleaner. The muck was then weighed to the nearest 0.01 gram on a precision balance. The depth of the grooves was measured with a micrometer depth gage at every inch of travel and then averaged over the entire length of the groove. The center-to-center spacing between two neighboring grooves was measured at

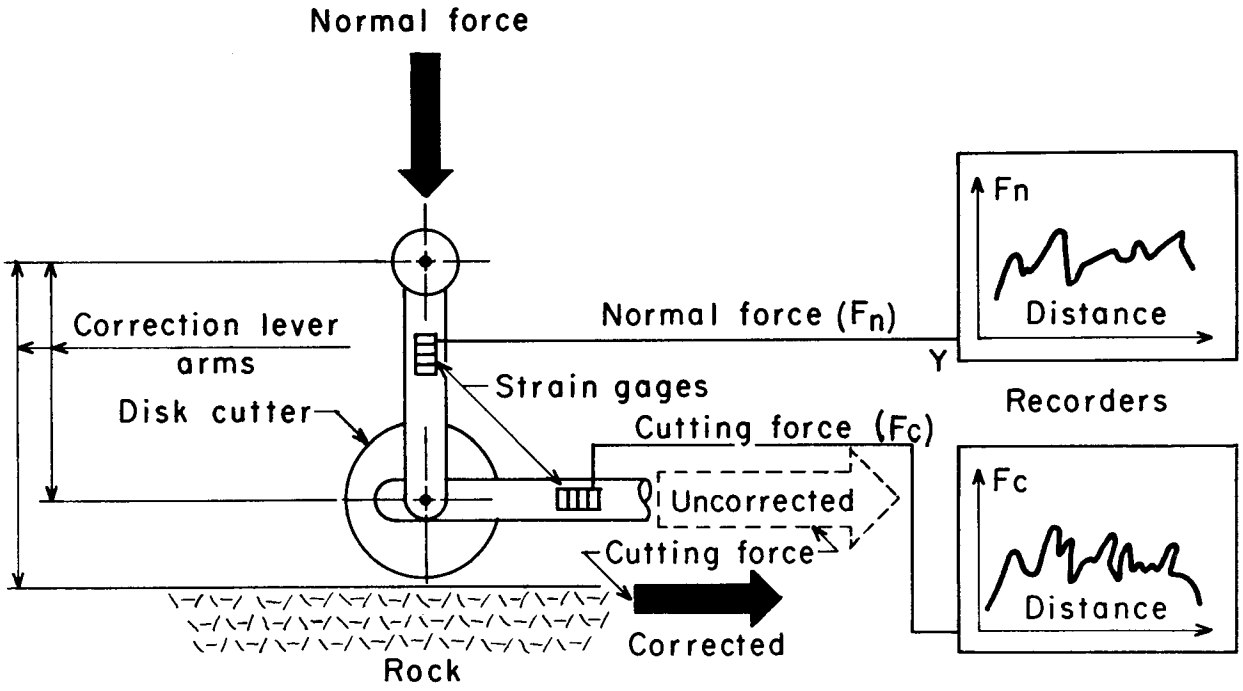


FIGURE 2. - Instrumentation schematic for linear cutter apparatus.

every inch of travel with a dial gage caliper and was averaged over the entire length. The weight of muck from each groove was divided by the travel length of the cutter to get a uniform value for comparison purposes. The total work done by the cutting force was divided by the volume of the total muck to obtain the value of specific energy for each groove. The work done by the normal force was not entered into these calculations, because it was generally about 5 pct of the work done by the cutting force. Further, percentile contribution of the normal force to specific energy is a function of groove length and becomes less than 1 pct for grooves longer than 50 inches. In field operations, the groove length is varied and relatively long. The groove lengths of the disk cutters on a 20-ft-diameter boring machine are from 62 inches to 754 inches for each revolution of the cutter head.

Data Refinement

Previous studies (1, 12) have indicated the existence of critical spacing and optimum spacing between two neighboring parallel grooves cut in rocks. Critical spacing is equal to the largest distance between two neighboring parallel grooves at which there is interaction between grooves (fig. 3). At spacings greater than the critical spacing, the grooves become independent and at closer spacings there is chipping between adjacent grooves. The chips, formed by breakout between the interacting grooves, are considerably larger than those produced by independent grooves. In the interacting region, the amount of muck is greater than independent grooves and the value of specific energy is smaller than independent specific energy. By definition, the values of specific energy and muck weight at critical spacing are the same as those for all independent grooves with greater spacings.

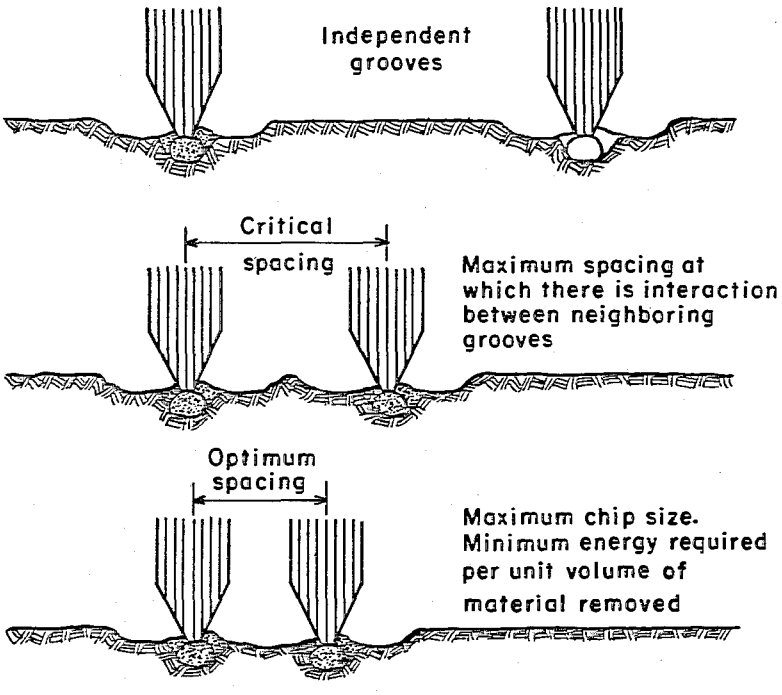


FIGURE 3. - Optimum and critical cutter spacings.

For each set of cutting conditions, there also exists an optimum spacing at which the highest amount of muck with the lowest value of specific energy is obtained. Any decrease or increase in groove spacing from the optimum spacing will result in reduction in efficiency of cutting as measured by muck weight and specific energy.

During the course of the work at the Bureau of Mines, a computer routine was developed to estimate the values of optimum and critical spacings for functions that have optimum and critical points in their variation. This routine uses a

multiple-regression technique and a simple iterative optimization technique to define a three-line combination that best fits the data. The three lines signify the variation of data in the independent region where the neighboring grooves do not interact, and the variation of data in interaction regions, called pre-optimum and post-optimum, where neighboring grooves do interact as shown in figure 4. It was found that many of the cutting characteristics of the rocks used in this study can be defined by the three-line combination described above. Thus, using this computer routine, estimation of optimum and critical spacing can be made based on the values of cutting characteristics very systematically. This program will be made available to interested parties on request from the Bureau of Mines, Twin Cities Mining Research Center, P.O. Box 1660, Twin Cities, Minn. 55111.

Increasing the normal force or decreasing the cutter diameter will result (12) in values for optimum and critical spacing different from those obtained under conditions of present experiments. Under the same cutting conditions, however, similar results are expected.

RESULTS AND DISCUSSION

For each of the four rock types, the variation of four parameters was determined with varying groove spacing. The parameters were specific energy, muck weight, groove depth, and cutting coefficient. Values of optimum and critical spacings were calculated for each parameter using the computer routine. These values were then correlated to the physical and mechanical properties of the rocks in order to determine the properties of rocks that correlate with their cutting characteristics. Cutting characteristics are defined as the output variables of the cutting experiments. The input variables are the rock properties and the cutting conditions.

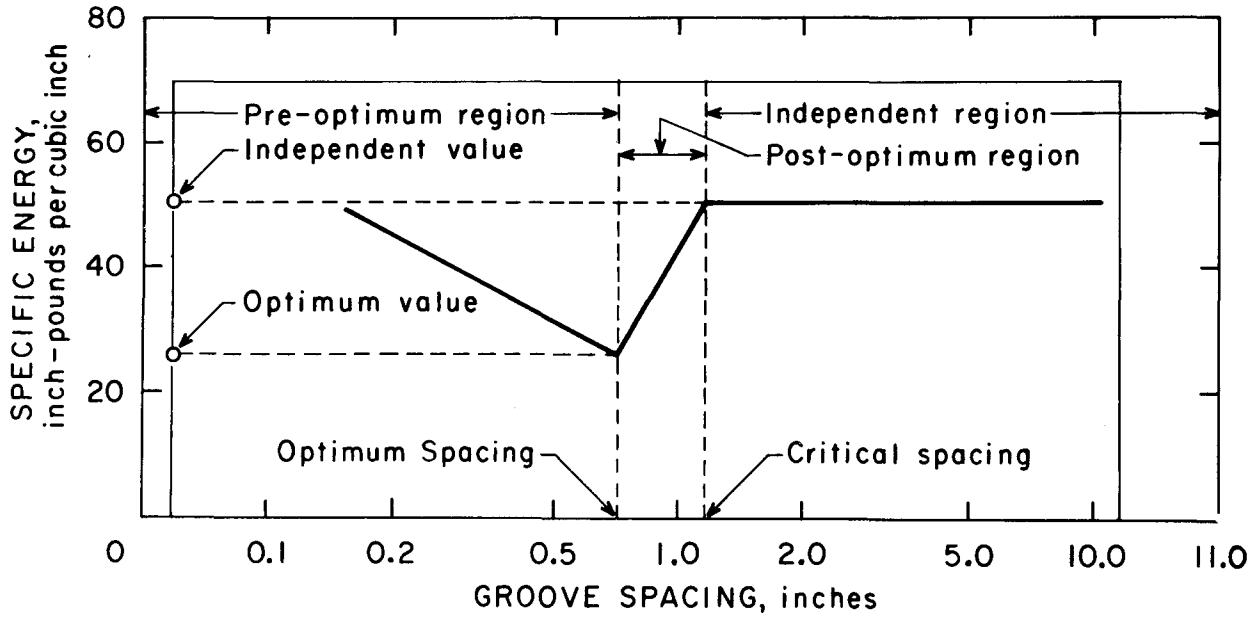


FIGURE 4. - Groove spacing classification.

Specific Energy

Figure 5 shows the variation of specific energy with groove spacing for marble, limestone, granite, and quartzite. The value of independent specific energy of marble was the lowest of all four rock types used in these experiments. The value of critical spacing for grooves in limestone was, however, the largest. The value of compressive strength for all rock types was found to have reasonable correlation with specific energy of independent grooves, although such correlation was not found to exist with specific energy at optimum spacing. This observation indicates that although the value of compressive strength may be a good tool for estimation of specific energy of independent grooves, it does not provide any useful information regarding many other cutting characteristics.

The value of specific energy is reduced from that of independent grooves when the groove spacing is reduced from the critical spacing. The lowest value of specific energy is obtained at the optimum spacing--this represents an improvement of 25 to 60 pct from the independent value. Table 2 shows the ratio of optimum to critical specific energies as defined in figure 3. The best improvement is obtained for limestone grooves and the worst for marble grooves. This observation leads to the conclusion that since substantial improvements are made in limestone grooves by setting the distance to optimum, in field practice care should be taken to achieve the optimum condition very accurately. Setting the optimum distance for neighboring grooves of marble is less critical because deviations from the optimum value will result in smaller penalties in values of muck and specific energy (table 2).

TABLE 2. - Ratio of optimum to independent values of cutting characteristics

Cutting characteristic	Rock type			
	Marble	Limestone	Granite	Quartzite
Muck weight.....	1.7	3.0	2.3	2.5
Cutting coefficient.....	1.5	1.5	1.3	1.5
Specific energy.....	.75	.40	.60	.50

When the spacing is further reduced below the optimum spacing, the value of specific energy increases. Such increase in the value of specific energy in the pre-optimum region, viewed together with an increase in the fineness of the muck, confirms that an inverse relation exists between the fineness and the specific energy.

The ratio of optimum to critical spacing (fig. 3) as obtained by specific energy, varied between 0.43 - 0.78 (table 4) without any apparent trend.

Muck Weight

Figure 6 shows the variation of muck weight with groove spacing for marble, limestone, granite, and quartzite. The grooves whose distance from their neighboring groove is larger than the critical spacing can be considered to be behaving independently. The size distribution of muck from independent grooves was essentially the same for each rock. Comparing the four rocks of this study, independent grooves in quartzite produced the finest muck and independent grooves in marble produced the coarsest muck.

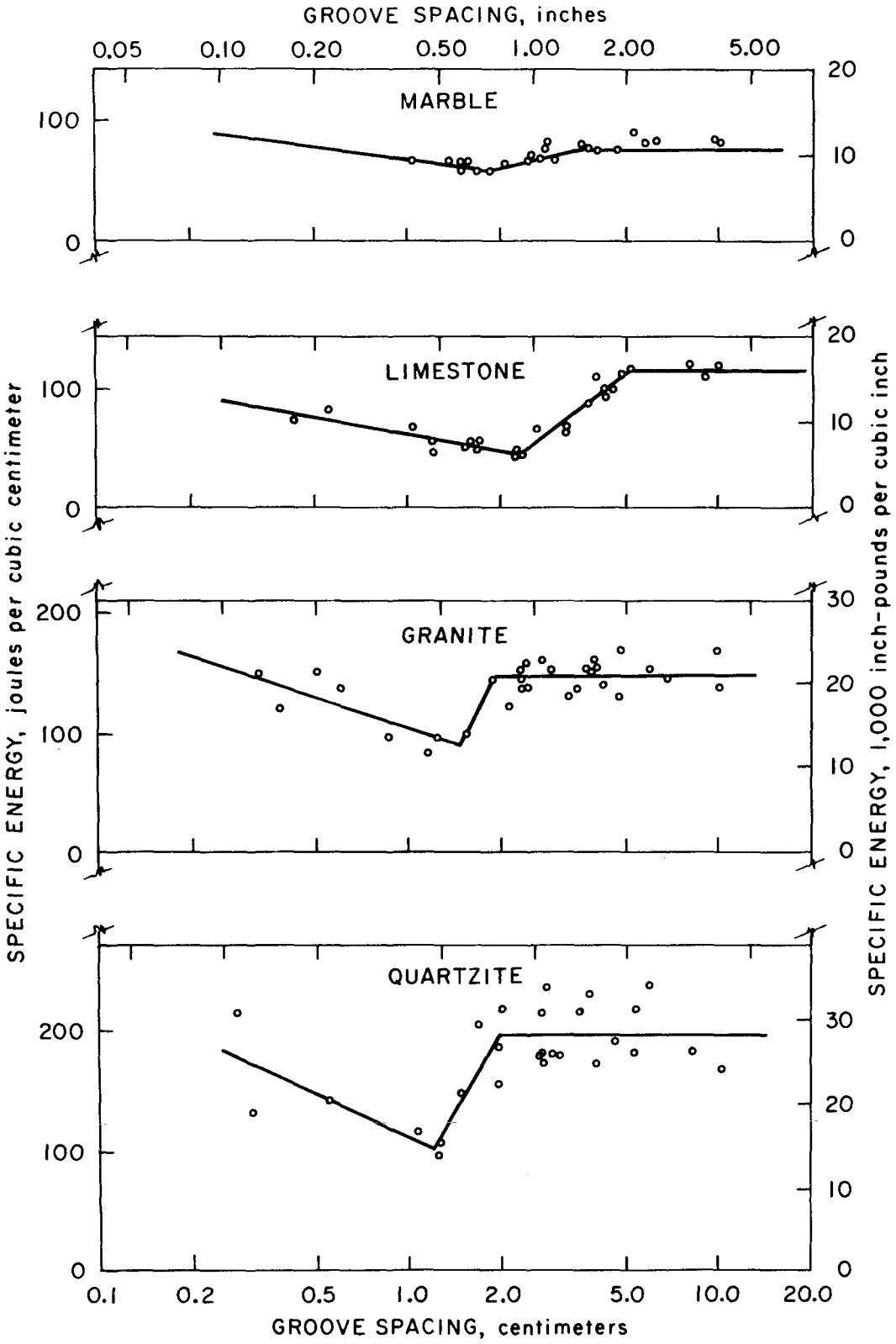


FIGURE 5. - Specific energy versus groove spacing.

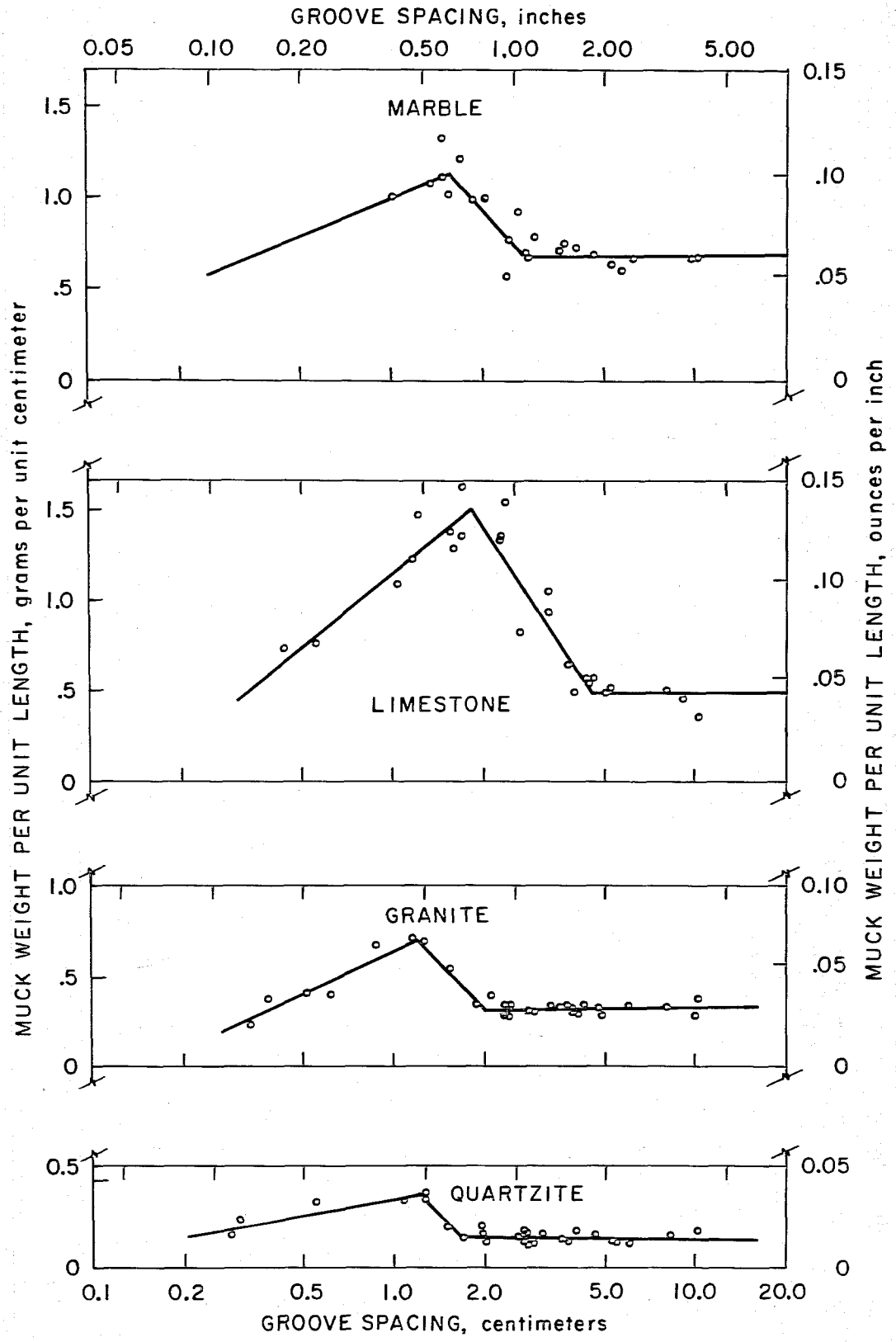


FIGURE 6. - Muck weight versus groove spacing.

Grooves with spacings smaller than the critical spacing interact and thus produce larger chips. In the post-optimum spacing region, the highest interaction is developed and the largest muck weight is produced when the groove spacing is reduced to the optimum spacing. Table 2 shows the improvement in the muck weight when the spacing is reduced from critical to optimum. The highest improvement is shown in limestone grooves and the lowest in marble grooves. Since the improvement in muck weight is very substantial in limestone, accurate determination of the optimum conditions are extremely important for operations in limestone. By comparison, determining the optimum conditions for marble is not as important because the reduction in muck weight due to a near optimum spacing may be negligible. Table 3 shows the largest chip dimension for independent and optimum grooves. Limestone grooves produce the largest chip obtained at the optimum spacing and therefore, based on muck weight, limestone is the most cuttable rock type of these four.

TABLE 3. - Largest chip dimension, inches

Region	Rock type			
	Marble	Limestone	Granite	Quartzite
Independent	0.9	0.8	0.5	0.4
Optimum....	1.7	2.0	1.0	.9

If the spacing is further reduced below the optimum spacing, the amount of muck is reduced and the size distribution is shifted toward finer muck particles. In the pre-optimum spacing region, the muck weight and largest chip dimension are reduced as the groove spacing is reduced. The value of muck weight for groove spacings in the pre-optimum region is similar to the muck weight for grooves in the post-optimum region. For practical purposes, however, it is desirable to keep the spacing larger than the optimum. For the spacings in the post-optimum region, the cutter is subjected to less severe lateral forces while producing larger chips than in the pre-optimum region. If the cutting apparatus is not properly constructed, these lateral forces result in waviness of the groove that should be straight. The ratio of optimum to critical spacing as obtained by muck weight varied between 0.4 to 0.73 without indications of any apparent trend (table 4). The value of compressive strength of these rocks was found to have a reasonable correlation, with independent muck weight, and with the largest chip dimension obtained from the independent grooves.

TABLE 4. - Ratio of optimum spacing to critical spacing

Cutting characteristic	Rock type			
	Marble	Limestone	Granite	Quartzite
Muck weight.....	0.60	0.40	0.62	0.73
Specific energy....	.49	.43	.78	.61
Cutting coefficient	.74	.58	.39	.26
Average.....	.61	.47	.57	.52

Groove Depth

Figure 7 shows the variation of groove depth with groove spacing for marble, limestone, granite, and quartzite. Although the variation of groove

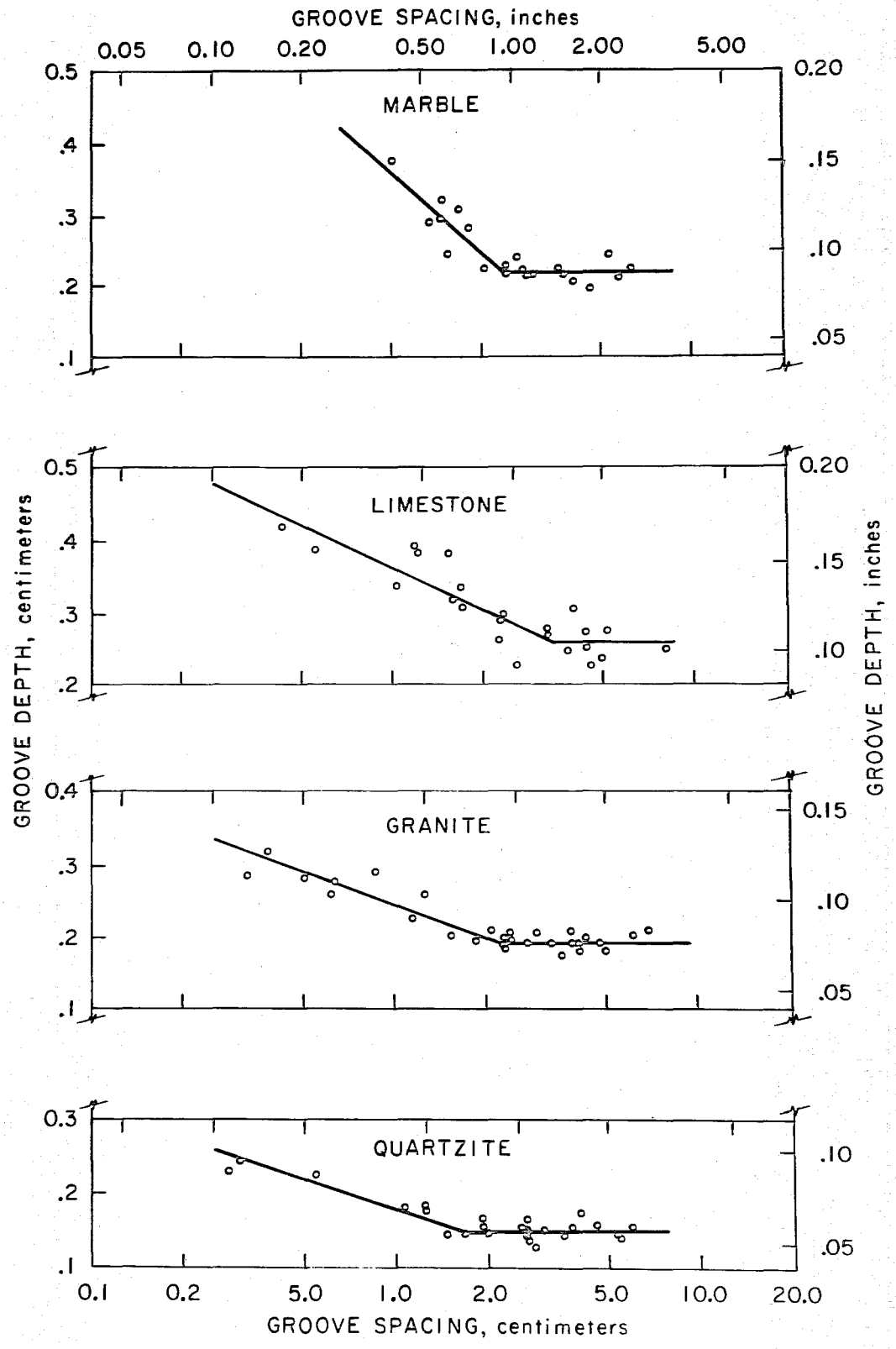


FIGURE 7. - Groove depth versus groove spacing.

depth with spacing did yield critical spacing for all four rock types, it did not indicate any optimum spacing for any of them. The values of critical spacing obtained from groove depth for all four rocks, however, agree with those obtained from muck weight and specific energy. The groove depth increases as the spacing is decreased below the critical spacing. Independent grooves of limestone were the deepest grooves and the independent grooves in quartzite were the shallowest of all independent grooves. The rate by which the groove depth increases with decreasing spacing below the critical spacing is essentially the same for limestone, granite, and quartzite and slightly higher for marble. Although the independent groove depth for marble is lower than that of limestone, the depth increases so rapidly in the interacting region of the groove spacing that at 0.4-inch spacing, the same depth is obtained in both rocks.

Cutting Coefficient

Figure 8 shows the variation of cutting coefficient with groove spacing for marble, limestone, granite, and quartzite. The highest value of independent cutting coefficients is obtained for limestone, and the lowest independent cutting coefficient for quartzite. The critical and optimum spacings obtained from cutting coefficient values agree with those obtained from other parameters. The percentile improvement obtained in the value of cutting coefficient is essentially the same for all rocks (table 2). Therefore, in comparison with the other three rocks, at optimum spacing and independent spacing, grooves in limestone require the highest cutting coefficient. Although at optimum spacing limestone is highly cuttable, based on values of muck weight and specific energy, at the independent spacing it is much less cuttable than marble. This observation leads to the conclusion that the value of cutting coefficient alone may not be taken as a measure of cuttability. The ratio of optimum spacing to critical spacing as obtained from the cutting coefficient is shown in table 4. Although general agreement is obtained between ratios of optimum to critical spacing obtained for each rock, cutting coefficient seems to result in high ratios for marble and limestone and low ratios for granite and quartzite. This is primarily due to variations in the critical spacing for the cutting coefficient values.

Correlation of Cutting Characteristics With Mechanical Properties

The materials removal process involved in disk cutting of rocks includes the penetration of the disk tip into the rock surface, thus creating microfractures, macrofractures, and crushed material under the cutter tip (3, 9, 12). Some of the cracks that are initiated extend to the rock surface, thus creating chips. The entire crushing, fracture initiation, and fracture propagation processes are developed as a result of the stress fields developed in the rock by the disk cutter. These stresses are combinations of tensile, compressive, and shear stresses.

The behavior of rock under three simple stresses--tension, compression, and shear--can easily be determined (6). The behavior of rock under a combined stress state can be determined from the behavior of rock under the single stresses and from factors defining any interaction between these

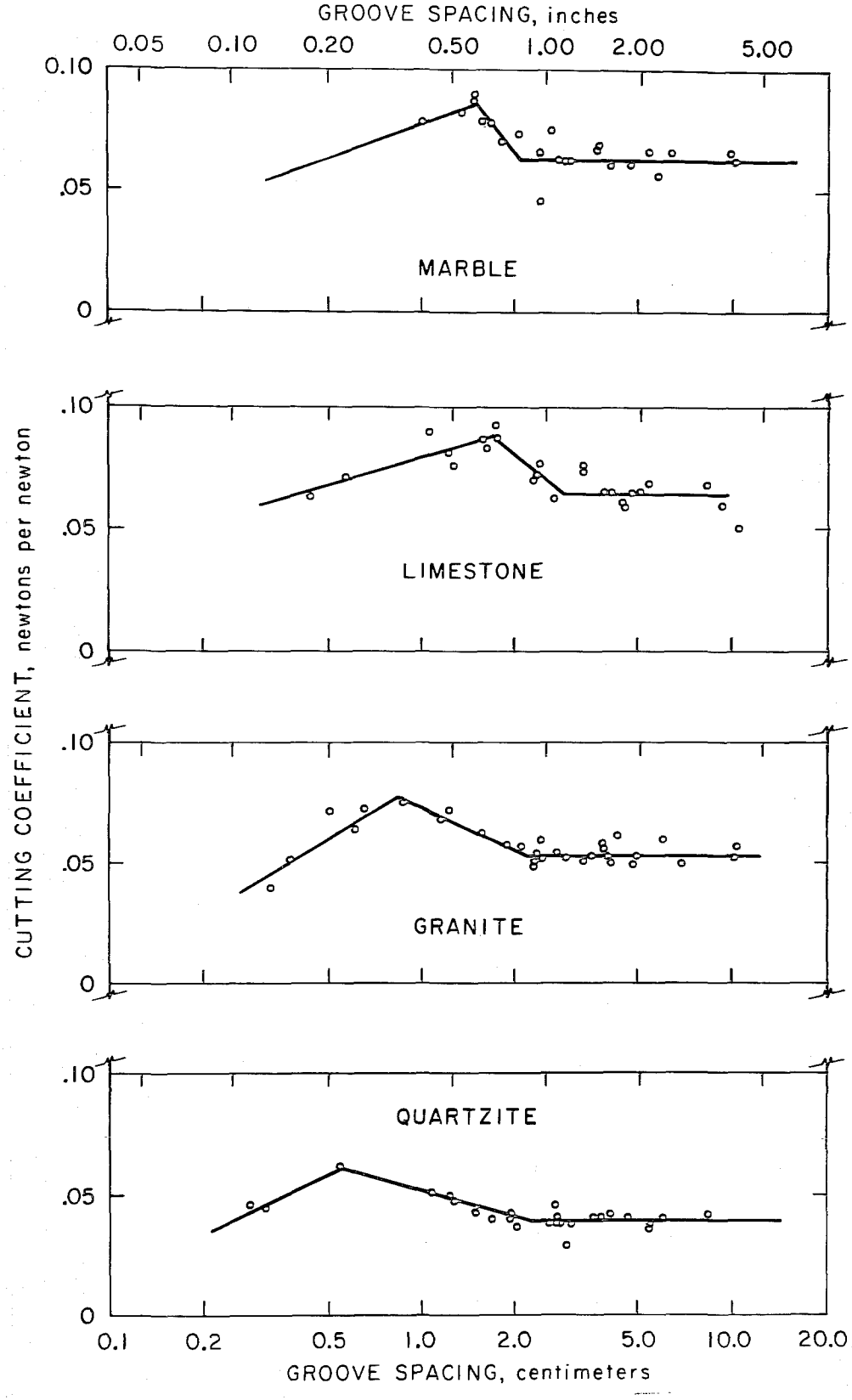


FIGURE 8. - Cutting coefficient versus groove spacing.

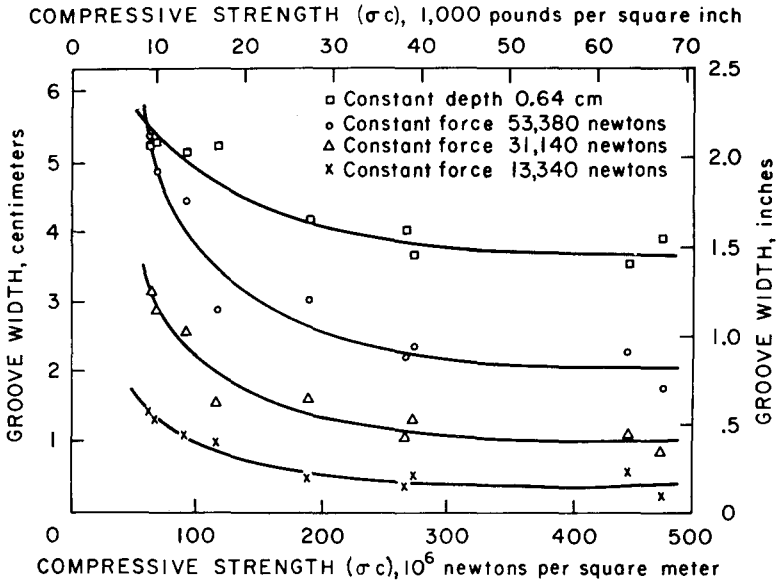


FIGURE 9. - Groove width versus compressive strength.

stresses that might be operating at the complex stress level (12). Other properties of rocks, such as drillability and cuttability, can be inferred from tests that determine more complex indices, such as Shore hardness and coefficient of rock strength (4-5). It therefore seems reasonable to assume that some combination of the rock strength indices will describe the various cutting characteristics of rocks.

Traditionally, compression test has been used to determine strength, deformation, and fracture characteristics of rocks. For many applications, including excavation, rocks can be classified fairly satisfactorily according to their compressive strength.

Figure 9 shows the relation between the compressive strength and groove width for constant normal force and constant penetration modes of laboratory cutting experiments.

Although there is an appreciable amount of scatter in the data, there is a general correlation between the groove width and the value of compressive strength. Therefore, the width of independent grooves for a given disk cutter can be inferred from the normal force and from the value of compressive strength. Values of muck weight and specific energy for independent grooves obtained during the course of this work also correlate closely with the compressive strength.

Table 5 shows the values of cutting characteristics determined for these four rock types from the results of this study. Since the number of rocks used in this study was four and thus did not lend themselves to a detailed statistical search of the desired correlations, only visual observations were used to determine which properties correlated closer than other physical properties with each cutting characteristic.

By plotting the cutting characteristics against the physical properties of these rocks and by noting the best correlation in the plotted data, three physical properties were chosen for each cutting characteristic. This does not imply that the other properties are believed to have no effect on that property. It does indicate that based on the results of this study, the most important properties are the four chosen by this process. Table 6 shows the physical properties chosen with this technique for each cutting characteristic.

TABLE 5. - Cutting characteristics of rocks used in this study

Cutting characteristic	Characteristic index	Rock type			
		Marble	Limestone	Granite	Quartzite
Average optimum spacing.....mm..	C_1	16.41	19.51	11.66	9.83
Average critical spacing.....m..	C_2	27.08	39.93	20.30	18.75
Optimum muck.....g/cm..	C_3	1.124	1.519	0.713	0.408
Independent muck.....g/cm..	C_4	0.678	0.493	0.315	0.166
Optimum specific energy.....J/cm^3..	C_5	59.60	43.43	88.24	103.09
Independent specific energy.....J/cm^3..	C_6	76.18	111.98	145.92	197.69
Optimum cutting coefficient.....N/N..	C_7	0.086	0.090	0.079	0.061
Independent cutting coefficient.....N/N..	C_8	0.063	0.066	0.054	0.039
Independent groove depth.....m..	C_9	2.235	2.667	1.956	1.473

TABLE 6. - Correlation of cutting characteristics with physical properties

Physical property characteristic[1]	Cutting characteristic[2]								
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
P_1	-	-	-	-	-	-	-	-	-
P_2	-	-	-	x	-	x	-	-	-
P_3	-	-	-	-	-	-	-	-	-
P_4	x	x	x	x	x	x	x	x	-
P_5	x	x	x	x	x	-	x	x	x
P_6	-	-	-	x	-	-	x	x	x
P_7	-	-	-	-	-	-	-	-	-
P_8	-	-	-	-	-	-	-	-	-
P_9	-	-	-	-	-	-	-	-	-
P_{10}	-	-	-	-	-	-	-	-	-
P_{11}	x	x	x	-	x	x	-	-	x
P_{12}	-	-	-	-	-	-	-	-	-
P_{13}	-	-	-	-	-	-	-	-	-
P_{14}	-	-	-	-	-	-	-	-	-
P_{15}	-	-	-	-	-	-	-	-	-

[1]See table 1 for explanation of individual physical property characteristics.

[2]See table 5 for explanation of individual cutting characteristics.

It becomes apparent that the value of compressive strength can be used to predict the values of muck and specific energy of independent grooves. The cutting characteristics of independent grooves may also be predicted from values of Shore hardness, coefficient of rock strength, and torsional velocity. The optimum values of the cutting characteristics correlate with Shore hardness, coefficient of rock strength, and torsional velocity.

The results of this study show that the estimation of values of optimum and critical spacing can best be done with Shore hardness, coefficient of rock strength, and torsional velocity.

Field Applications

The concepts developed and observations made during the course of this study may be of practical use toward the optimum design and usage of tunnel boring machines, even though the numerical data may not be presently directly applicable to the field operations of boring machines.

The results of this study show that under constant normal force, optimal muck removal is achieved when the spacing between the cutters is set to the optimum value. Previous rock cutting studies have shown that increasing the normal force affects the cutting conditions with the same trend as does decreasing the groove spacing (12). Thus for constant spacing the optimum conditions can be achieved by setting the normal force to the optimum value. Since the forward force is controllable in almost all boring machines, it may be possible to obtain optimum cutting conditions using the data developed through the Bureau's work and previous related works.

It is expected that the variation of advance rate will resemble the curve shown in figure 10.

For a constant arrangement of the cutters, if the applied normal force is not high enough, the grooves will behave almost independently and very little or no interaction will be developed, resulting in very small or no advance rate. As the normal force is increased above the critical value in the post-optimum region (fig. 3), the interaction between grooves increases, causing higher advance rates. At optimum thrust, a near-maximum amount of muck is removed from between two neighboring grooves. Therefore, very little improvement in advance rate is obtained by increasing the normal force beyond the optimum value and into the pre-optimum region. The reason the advance rate

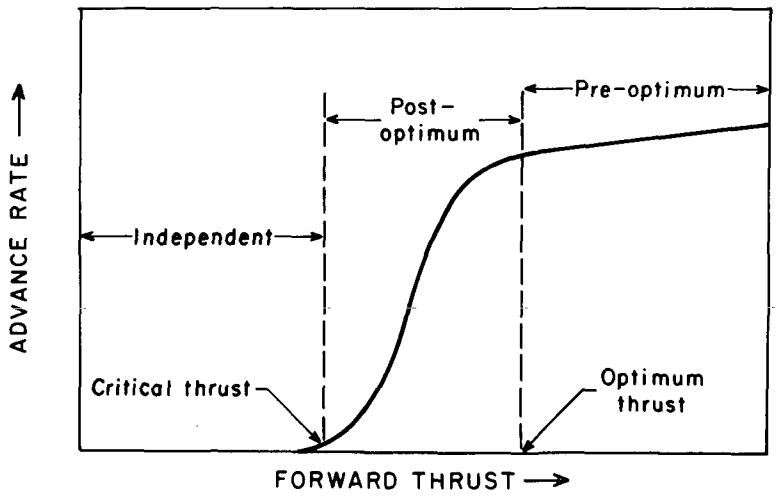


FIGURE 10. - Anticipated variation of advance rate with forward thrust.

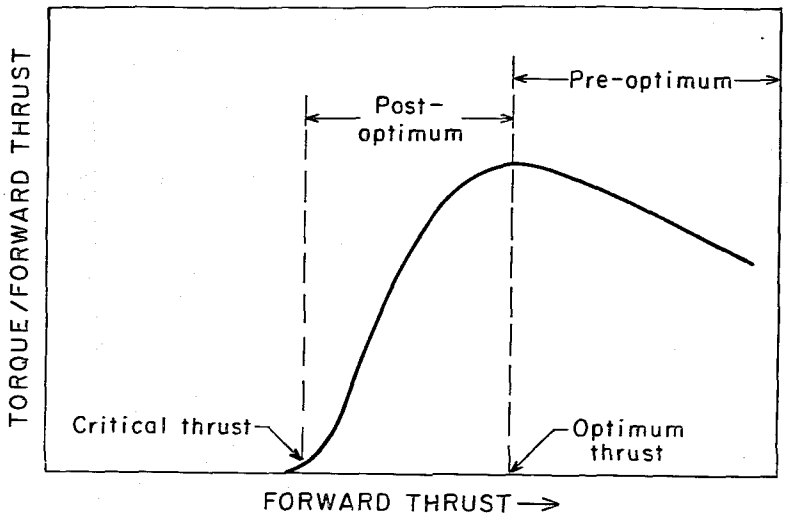


FIGURE 11. - Anticipated variation of cutting coefficient with forward thrust.

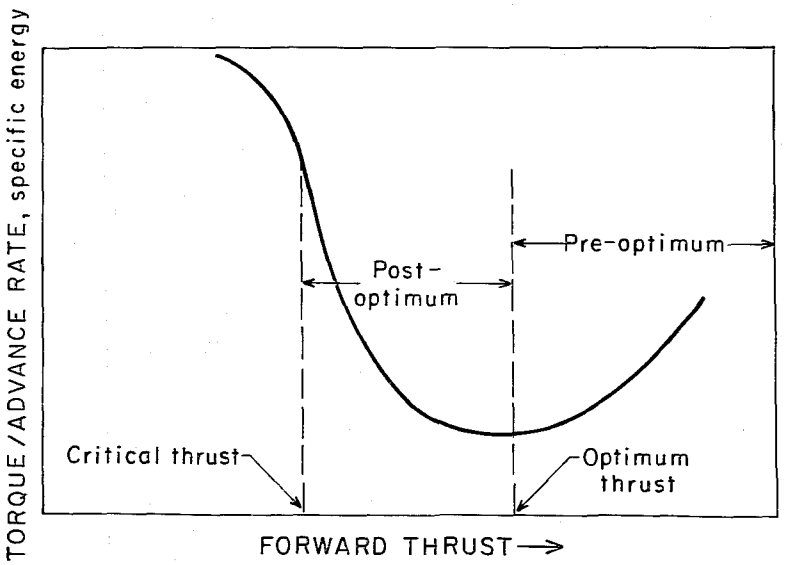


FIGURE 12. - Anticipated variation of specific energy with forward thrust.

is not expected to decrease in the pre-optimum region is that it is affected by the groove depth, which increases (fig. 7), and muck, which decreases (fig. 5), in this region.

If the value of torque/forward thrust is plotted, it is expected to vary as shown in figure 11. The main difference between figures 9 and 10 is in the pre-optimum region, where the slopes are expected to be positive and negative, respectively. Although the advance rate is expected to increase slightly in the pre-optimum region (fig. 9), the relative benefit of increased thrust in this region is expected to decrease (fig. 11).

To optimize the forward thrust, first the boring machine is driven forward with a variety of forward thrust settings, including the value believed to be the optimum. For each of these cases either the advance rate or the average torque of the machine is determined.

The results of this study indicate that, for a given boring machine operating in marble and limestone formations, the optimum thrust will be lower in limestone than in marble. A boring machine operating in granite and quartzite should preferably have smaller spacing between the cutters, otherwise extremely high normal forces will be required to attain optimum conditions. The results of this study show that although the optimum thrust levels for quartzite and granite will be similar, the optimum thrust for quartzite will be slightly higher than that for granite.

The forward thrust corresponding to the optimum advance rate and torque should be used to obtain optimum performance of the machine. If possible, the

thrust should be set such that cutters operate at the optimum spacing. Otherwise, they should operate in the post-optimum region. The observations made during the course of this study have shown that operation in pre-optimum region will subject the cutter assemblies to unusually high lateral forces.

If the machine operates in very hard rock or with large spacing between cutters, the advance rate might continue to increase with increasing forward force and yet never reach the optimum force depicted in figure 10. For such a condition, the most desirable results will obviously be obtained by setting the forward force to maximum thrust based on maximum allowable load per cutter.

The ratio of torque to advance rate is believed to be proportional to the value of specific energy (fig. 6), because torque corresponds to the cutting force and advance rate corresponds to muck weight and groove depth. Therefore, if values of torque and advance rate are available, the variation of their ratio with forward thrust will follow the pattern shown in figure 12, from which the values of optimum and critical thrust can be determined.

Monitoring the torque and advance rate can also be used as an aid for detecting changes in rock strength and changes in cutter tip conditions. The results of this study have shown that for the same normal force, the cutting coefficient is higher for more cuttable rocks. Since cutting coefficient is represented by the torque on the boring machine, an abrupt change in torque will indicate a change in rock type, rock strength, or a mechanical failure such as a bearing failure. A gradual decrease in the value of torque or advance rate, while the rock type and rock strength is the same, will indicate a degradation in the cutting capability of the cutters and an inspection of the cutterhead may be in order.

CONCLUSIONS

Laboratory groove cutting experiments in marble, limestone, granite, and quartzite have demonstrated that all these rock types possess optimum and critical values for the spacing of neighboring grooves. The values of optimum and critical spacing can be obtained from determination of variation of muck weight, specific energy, groove depth, and cutting coefficient with groove spacing. The value of unconfined compressive strength can be used to predict some of the cutting characteristics of independent grooves. To predict cutting characteristics of rocks in their interacting regions of groove spacing, however, a set of physical properties will be required. The value of Shore hardness, coefficient of rock strength, and torsional velocity correlate more closely with cutting characteristics than other physical properties tested. Extensive experimentation is required to define the various cutting characteristics of rocks accurately as a function of their strength indices and cutting conditions.

The results obtained and observations made during the course of this study were used to construct guidelines for the optimal usage of tunnel boring machines. Implementation of these guidelines is expected to encourage design of cutterheads of boring machines that will operate in the post-optimum thrust region with near-optimum spacing for that machine's specific operating conditions.

REFERENCES

1. Barker, J. S. A Laboratory Investigation of Rock Cutting Using Large Picks. Internat. J. Rock Mech. and Min. Sci., v. 1, No. 4, October 1964, pp. 519-534.

2. Gaye, F. Efficient Excavation. Tunnels and Tunneling, v. 4, No. 1, No. 1, January 1972, pp. 39-48; v. 4, No. 2, March 1972, pp. 135-142.

3. Hartman, L. H. The Simulation of Percussion Drilling in the Laboratory by Indexed Blow Studies. Pres. at First Conf. on Drilling and Rock Mech., Austin, Tex., Jan. 23-24, 1963, Soc. Petrol. Eng., AIME, SPE Preprint 500, 8 pp.

4. Hustrulid, W. H. Development of a Tunnel Boreability Index. Part II. Use of Linear Cutter for Prediction of Tunnel Boreability. Rept. on Contract No. 14-06-D-6849, Bureau of Reclamation, November 1970, 136 pp.

5. Kraatz, P. Rockwell Hardness as an Index Property of Rocks. M.S. Thesis, Univ. Ill., Urbana, Ill., 1964, 67 pp.

6. Lewis, W., and S. Tandanand. Bureau of Mines Test Procedures for Rocks. BuMines IC 8628, 1974.

7. Morrell, R. J., W. E. Bruce, and D. A. Larson. Tunnel Boring Technology. Disk Cutter Experiments in Sedimentary and Metamorphic Rocks. BuMines RI 7410, 1970, 32 pp.

8. Musselman, J. A. An Experimental Investigation of Index Indentation of Rock. M.S. Thesis, Rice Univ., Houston, Tex., May 1967, 134 pp.

9. Nishamatsu, Y. The Mechanics of Rock Cutting. Internat. J. Rock Mech. and Min. Sci., v. 9, No. 2, March 1972, pp. 261-270.

10. Orski, K. Presentation of the Report on Tunneling Demand. Proc. Advisory Conf. on Tunneling, Organization for Economic Cooperation and Development, Washington, D.C., June 22-26, 1970, No. DAS/CSI/T/70.76, p. 39.

11. Peterson, C. R. Rolling Cutter Forces. Pres. at Fourth Conf. on Drilling and Rock Mech., Austin, Tex., Jan. 14-15, 1969, Soc. Petrol. Eng., AIME, SPE Preprint 2393, 10 pp.

12. Rad, P. F., and F. J. McGarry. Thermally Assisted Cutting of Granite. Proc. 12th Symp. on Rock Mech., University of Missouri--Rolla, Nov. 16-18, 1970, Society of Mining Engineers of AIME, New York, 1971, pp. 721-757.

13. Teale, R. The Mechanical Excavation of Rock--Experiments With Roller Cutters. Internat. J. Rock Mech. and Min. Sci., v. 1, No. 1, January 1964, pp. 63-78.

* U.S. GPO: 1974—705-590/606

INT.-BU.OF MINES,PGH.,PA. 19167