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ROCK CLASSIFICATION AND ROCK PROPERTY LISTING

Warren W. Krech

Bureau of Mines

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Bureau of Mines In-House Research
Rock Classification and Rock Property Listing

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The Bureau of Mines conducted a project for the Advanced Research Projects Agency (ARPA) Rock Mechanics and Rapid Excavation program to investigate rock classification as one means to improve rapid excavation technology. A standard rock suite was established, tested for standard properties, and distributed to contractors on request in the form of 1 cubic foot blocks. An extensive listing of ten physical-mechanical rock properties was compiled from Bureau and outside literature sources and is being presented in a Bureau of Mines Information Circular. A new technique for direct laboratory measurement of rock fracture energy was established. The requirements that must be met to build and to use a comprehensive rock classification system for predicting rapid excavation advance rate are discussed.

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TECHNICAL REPORT SUMMARY

The subject of rock classification is of extreme interest to most researchers and designers in the field of rock mechanics. Most of these people are looking for a simple, easily obtainable, and brief set of rock properties--index values--by which to predict all responses of rock to man-initiated disturbances. The purpose of this project was to provide a classification, along with a rock property listing, that would fit the needs presented.

Early project background investigations showed that sufficient field information was not present in a useable form to build a meaningful classification system. Indeed, most reported prior investigations did not seem to recognize or ignored the importance of "total observation" while acquiring even the extremely limited field data reported.

As a result of early project redefinition, an additional task was defined; the establishment of a standard rock suite (eight rock types) for rapid excavation research. These eight rock types were obtained in quantity and made available to ARPA contractors in 1 cubic-foot blocks. Standard property tests were conducted on a representative portion of the blocks and the results made available to the contractors.

An extensive listing of ten physical-mechanical rock properties potentially useful to researchers and designers was compiled and will be published as a Bureau of Mines Information Circular.

In the search for more meaningful laboratory measures of intact rock strength, new techniques for direct rock fracture energy measurements were

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developed at the Twin Cities Mining Research Center of the Bureau of Mines. The concept of direct laboratory measurement of energy requirements will likely prove valuable for describing behavior of jointed rock as well as for intact rock.

As a result of studies under the "Rock Classification and Rock Property Listing," the Bureau of Mines attempts in the report to define what a classification must accomplish, how a series of functional classifications must be generated, how these classifications are likely to interact, and what information must be obtained and assimilated in order to build and utilize a classification system.

The main goal of the report is to establish in the reader's mind the degree of complexity required to establish meaningful classifications of rock behavior (engineering classifications).

No conclusions based on measured parameters are presented. An evaluation of the information presented in the report should lead the reader to an understanding of many of the performance aspects of a rapid excavation system that influence advance rate.

Further research and investigation toward development of engineering classifications should be approached with restraint. The true advantages of the availability of a classification system measured in terms of advance rate increase or cost decrease should be weighed against the cost to develop such a classification system. Also, the progress in advance-of-face exploration should be such that information necessary to utilize a classification system may be available.

ROCK CLASSIFICATION AND ROCK PROPERTY LISTING

by

Warren W. Krech

ABSTRACT

The Bureau of Mines conducted a project for the Advanced Research Projects Agency (ARPA) Rock Mechanics and Rapid Excavation program to investigate rock classification as one means to improve rapid excavation technology. A standard rock suite was established, tested for standard properties, and distributed to contractors on request in the form of 1 cubic foot blocks. An extensive listing of ten physical-mechanical rock properties was compiled from Bureau and outside literature sources and is being presented in a Bureau of Mines Information Circular. A new technique for direct laboratory measurement of rock fracture energy was established. The requirements that must be met to build and to use a comprehensive rock classification system for predicting rapid excavation advance rate are discussed.

INTRODUCTION

One of the difficulties facing engineers desiring to improve rapid excavation technology is the lack of universal engineering systems of classifying rock present at an excavation site. The misunderstandings that arise can lead to complete work disruption during excavation operations caused by use of improper equipment, inadequate problem anticipation, or poor cost analysis. An engineering classification of rocks, along with an extensive listing of mechanical and physical rock properties, would establish a uniform reference system that would promote more accurate advance planning in mining and excavation operations. The need for engineering classification is especially great for input into a systems approach to the design of such operations.

Project Objective

Development of a basis for a predictive rock classification for rapid underground excavation operations, particularly for horizontal underground boring application, was the aim of the research initiated under the general title "Rock Classification and Rock Property Index." The work reported in this final report is a result of efforts on the following specific tasks: (1) maintain a suite of standard rock types and supply blocks from the suite to ARPA investigators, (2) complete a listing of rock properties obtained from published and unpublished research data, (3) determine a program for gathering rock property data for developing a definitive classification of rock for each fragmentation system, and (4) complete a preliminary classification of rock for horizontal boring purposes based on rock mass properties and currently available horizontal boring data.

Project Justification

It is of great advantage for researchers to use test specimens from a carefully selected group of rocks because correlation among results of various research projects will be much more meaningful and beneficial to all concerned. The determination of standard properties of a representative portion of the rock by the distributing group, such that they can supply that information along with requests for the rock, can save much costly duplication of effort.

A comprehensive listing of rock properties useful to excavation designers and researchers was not available. The publication of such a single source listing can save much costly duplication of search effort. It may provide information that would not otherwise be sought from the general literature, leading to better advance planning.

Rock classification can form the basis of systems analysis for the advance prediction of excavation performance and the effects of the excavation. Such prediction could lead to one or both of shorter project duration or less costly construction. The need for classification of rock for horizontal underground boring application is great because of the high time and dollar costs of equipment mobilization -- demobilization.

Project History

Among early goals of the project was the development of a series of related rock classifications based on a computer analysis of a large number of laboratory test data obtained from the literature often adjusted to "standard" conditions by "mathematical formulas." The new classification system(s) would be developed by reviewing past efforts and modifying them or improvising as necessary. The resultant classification was to establish a uniform system to promote accurate advance planning such to prevent improper equipment specification, inadequate problem anticipation, or poor cost analysis.

Literature studies early in the project pointed out the lack of any format valuable to a quantitative rock classification. The availability of meaningful field data, with which to tie the laboratory data and the field performance of any mining system was found totally lacking. Effort on classification was narrowed to the examination of literature useful to horizontal underground boring only. No progress was possible because the narrower search did not yield a format or any significant field data.

The majority of the effort on rock classification was not undertaken because of a technical manpower shortage due to vacancies and a hiring freeze. No quantitative data could be obtained from either direct field observation or from construction project files. Rather, a definition of what a classification should entail, how it could be used, and what data must be acquired to attain a classification for horizontal boring application consumed the majority of project effort on classification. The result of this effort should lead to a greatly improved base from which to launch any further classification work.

The need for a standard rock suite to be utilized by the various researchers in the ARPA program was recognized early, and a suite of eight rocks was acquired, tested for standard properties, and distributed to contractors as 1 cubic foot blocks upon contractor request.

Efforts toward compilation of an extensive listing of rock properties potentially useful to designers in rapid excavation continued over the duration of the project.

Efforts toward definition of "standard" rock properties led to the development of techniques to measure the fracture energy requirements for rock under various laboratory test configurations. Results of this preliminary work are encouraging.

Previous and Background Work

No publication on the development of a comprehensive and quantitative rock classification for horizontal boring application could be located in the technical literature. Examination of the general classification literature shows a lack of any quantitative measure by which to predict any sort of excavation system response with rock mass properties (2, 3, 4, 5, 11).

A major reason for lack of a quantitative classification given in the majority of publications on "attempts" to classify rock is the lack of sufficient field data on which to base a classification. The cost and magnitude of development of generally applicable classifications is such that no particular equipment manufacturer, contractor, or mining company can justify the expense of such a development.

In order to assess the desirability of a government agency developing such classifications, an evaluation of the costs necessary to accomplish the classification relative to the benefits derived from the classification must be made. Such an analysis for a given classification type is in itself expensive.

Under ARPA sponsorship, an examination of a rock classification for horizontal boring application was undertaken by the Bureau as an in-house project. The question of a comprehensive rock property listing was addressed, as well as the desirability of the establishment of a standard rock suite for correlation of laboratory and field test results obtained by the many researchers attacking a variety of related excavation problems. A basis for analysis of the cost of building rock classification can be found in an analysis of what must be accomplished in an effort to define and obtain the necessary background information necessary for a classification. If upon examination the cost of the building of a series of rock classifications is justified, then the framework or basis for the classifications are available as a guide for gathering of field data useful to each classification.

Relationship to Other Bureau Programs

Various efforts in rock fragmentation, materials handling, and ground support are underway within the Bureau. An effort to classify rock response to the various aspects of an excavation system, if successful, could yield an integrated package of research results in a form useful to the field engineer. Rock classifications are only of value when the data necessary for their use is obtained in advance of the working face. Other projects within the Bureau are examining methods to determine rock properties in advance of a working face.

Interest in standardization of test methods and in correlation of studies between various Bureau projects concerned with problems of utilizing lunar surface materials led to the establishment of a NASA rock suite. The ARPA rock suite (Standard Rock Suite for Rapid Excavation Research) expands the rock types available for such standardization and correlation work.

The work reported herein was carried out at the Twin Cities Mining Research Center of the U.S. Bureau of Mines, Minneapolis, Minnesota. Government restrictions placed on manpower during the course of the work severely limited the progress of the work toward the original goals set prior to the project startup.

ROCK PROPERTY LISTING

Summary

An extensive listing of physical and mechanical rock properties has been lacking in modern rock mechanics literature. Ten physical and mechanical properties were selected for listing during this project. Bureau of Mines and outside literature sources were used to obtain property data, with as many of the ten properties as possible obtained for each rock type. A bibliography of additional papers containing reference to rock property measurement was constructed to be an aid to those investigators that require rock property data in addition to that tabulated.

Rock Property Listing

The listing was set up in a format useful to researchers seeking a rock type for a specialized experiment or to designers encountering a rock type new to their experience. The information presented is that most likely to be useful to designers who feel that standard physical and/or mechanical properties may allow prediction of advance rate with rapid excavation methods. Those parameters should be useful to researchers and designers in many other areas of rock mechanics.

The data taken from the literature sources was converted to the set of standard units selected for the table listing. No factors were applied to the literature source data to correct or adjust to "standard" test conditions. For example, some compressive strength data presented is for other than 2:1 height-to-diameter specimens; and tensile strength data presented is from several different test techniques.

Direct use of values presented for final design purposes should be done with great caution. The original source should always be obtained and studied prior to the use of a particular value. It is of special significance to note that extremely few rock types have had all of the selected properties determined by an investigator on a single source rock sample.

Publication

The complete listing of over 1,000 entries, along with an extensive bibliographic section is reported in a Bureau of Mines Information Circular presently in draft, entitled "A Listing of Physical and Mechanical Rock Properties" (10).

STANDARD ROCK SUITE

Summary

The need for rock property data over a wide range of parameters for a given rock type is present, but such information is generally not available. Likewise, different rock types for use by various groups in rapid excavation research have not been available from a single source. Standard rock suites available from central sources can answer this need.

The expense of conducting a wide range of tests on a rock type is usually too great in time and monies for any one group to justify. The availability of rock blocks of sufficient size and quantity to be useful, having standard mechanical properties documented, can lead to the establishment of a wide range of test results for a given rock type at very little extra expense if groups doing specialized research can draw on these standard rock supplies. Available data on that rock saves researchers expending redundant effort, and the specialized information can be added to a central file for that rock type. The new information can be made available to the scientific community as general information and for distribution with further rock blocks. Overall correlation between various research projects is better facilitated by the wide range of test results available.

Rock Suite

A suite of eight rock types was selected for a standard suite to be used in the Advanced Research Projects Agency (ARPA) program in Rock Mechanics and Rapid Excavation. The suite was selected based on the availability of rock in large and fairly homogeneous lots and on the likely pertinence of the properties to the ARPA program requirements. Table 1 gives a listing of the rock types and their source location. The eight rock types that comprise the rock suite are Barre Granite, Berea Sandstone, Dresser basalt, Holston Limestone (Tennessee marble), Salem Limestone (Indiana Limestone), Sioux Quartzite, St. Cloud Gray Granodiorite (Charcoal granite), and Westerly Granite. Geologic, petrographic, physical property, and standard static and dynamic test data were obtained for each rock type.

TABLE 1. - Suite of rocks

Rock Type	Geologic Name	Location
Granodiorite	Barre Granite	Barre, Vt.
Feldspathic Sandstone	Berea Sandstone	Amherst, Ohio
Hornblend Biotite	Dresser basalt	Dresser, Wis.
Bioclastic Limestone	Holston Limestone (Tennessee marble)	Friendsville, Tenn.
Brecciated Limestone	Salem (Indiana) Limestone	Bedford, Ind.
Quartzite	Sioux Quartzite	Jasper, Minn.
Granodiorite	St. Cloud Gray Granodiorite (Charcoal granite)	Cold Spring, Minn.
Granodiorite	Westerly Granite	Westerly, R. I.

The information is the first step in the building of a comprehensive property listing for the eight rock types.

Publication

The geologic, petrographic, physical property, and standard static and dynamic test data are reported in a Bureau of Mines Information Circular presently in review, entitled "A Standard Rock Suite for Rapid Excavation Research" (9).

NEW TECHNIQUES FOR ROCK FRACTURE ENERGY MEASUREMENTS

Summary

The need to determine better means to characterize rock fragmentation is becoming increasingly apparent to researchers in all fields of rock mechanics. Many drilling researchers utilize "specific energy" (compressive energy/unit volume) measurements in their analysis of rock behavior but such measurements combine rock characteristics and rock/tool interaction into a single measured value (14). A rock fragmentation characterization that eliminates rock/machine interaction effects must be developed in order to understand and improve fragmentation systems. Researchers are becoming more aware of the importance of fracture energy (i.e., all energy consumed in creating a unit area of new rock surface) in the analysis of rock failure. Drilling and hydraulic fracturing are examples of load applications where fracture energy is required for proper rock fragmentation analysis (7, 12).

Efforts made during this project have resulted in successful direct measurements of rock fracture energy. The direct measurements of the energy required to fail rock under laboratory conditions are now possible for

several different test configurations and stress regimes through the use of closed-loop, servo-controlled test systems. The test methods provide energy measurements for uniaxial tensile, torsional, direct shear, and uniaxial compressive failures.

Background

Griffith (6) introduced the concept of energy balance as a hypothesis to his theory on rupture. Griffith's energy balance hypothesis was that a crack will extend as long as the potential energy available to the crack is greater than the surface energy required to extend the crack (generate a surface) in that system.

The energy consumed in rock fragmentation was directly measured by conducting laboratory tests in such a manner that cracks can grow under stable conditions, that is, for conditions where the potential energy within the test system is controlled so as to incrementally supply energy necessary to create new rock surface. For such conditions, a complete load-deformation history of a specimen loaded to failure can be obtained. The work done on the specimen can directly be found from the load-deformation history.

The term "fracture energy" was adopted as a broad term that includes surface energy and all other dissipative energies associated with and necessary for the generation of a unit area of new rock surface.

Significance

The direct measurement of work done to fracture or fragment is basic in that it does not require the determination of stresses or strains within a specimen, but rather only the external forces applied to the specimen and the displacement of those forces.

It is proposed that the energy balance concept holds for rock loaded to failure in any manner, that fracture energy is a basic rock property that can be measured in the laboratory, and that the characterization of rock and the analytical solution of field problems will be greatly advanced by the application of fracture energy concepts.

Publication

Further detail of test procedure, analysis, and results for tests on three rock types are presented in a preprint of a paper presented to the 47th Annual Meeting of the Society of Petroleum Engineers of the AIME, entitled "New Techniques for Rock Fracture Energy Measurements" (8).

ENGINEERING CLASSIFICATION

Need for Classification

To classify rock as it influences the various functions of excavation in rock is to define separated responses of a rock to an induced disturbance based on measurable properties of the rock. Thus, a classification will allow prediction of rock response in terms of measured rock properties. Because of the great complexity of mining or excavating systems, it is necessary to separate classifications in terms of various tasks or functions such as fragmentation-mechanical, fragmentation-explosive, ground support, materials handling, and other such areas. The interaction of the various functions of a mining or excavating system, and the different induced disturbances - response patterns of the various functions do not allow the construction of a general engineering rock classification of any usefulness.

The need for classification of rock for horizontal underground boring application is great because of the high cost of equipment mobilization - demobilization. There is no present method by which to predict boring performance based on advance information of the engineering-geological properties of the in-place rock.

Many different measures of rock response can be utilized within a classification. It is important to predict the average daily advance rate, with normal operating procedure and normal crew for the range of machines and methods (singly or in combination), through each basic rock type as defined in advance of a project--or in advance of a working face a sufficient amount so as to provide alternatives to route or methods.

Literature

Examination of the classification literature shows a lack of quantitative description in the various classifications (1, 2, 5, 15). Of those few that attempt to describe any portion of rock quantitatively (3, 4, 11), none have relationships that directly correlate with any excavation subsystem. The general classification by Coates and Parsons (2) has the best basis for qualitative description of rock as it relates to excavation systems. Deere (3) has the most accepted "quantitative" classification used in this country, but extreme care must be exercised by the user in order to prevent negative value resulting from the use of the classification.

Limitations in Building a Quantitative Classification

The interrelationships at work during an underground excavation operation are so great as to require a series of classifications related to each normal work function of an excavation sequence before classification can become a useful tool.

The primary classification in the series is that classification that directly deals with the work function of interest. Choosing the performance of a horizontal underground boring machine as the work function of interest, it can be seen that there are other factors that effect machine performance as measured by advance rate. Such other factors include the type of machine, machine condition, cutter type, cutter condition, size and shape of opening, support or lining requirements, materials handling requirements, crew efficiency, and management efficiency.

The choice of machine and cutters, and a definition of machine and cutter condition can probably be related to excavation performance by a secondary classification relationship based on past performance of the machine. This could be accomplished in a manner not totally dissimilar from present practice. The effect of size and shape of the opening would interrelate with the discontinuities present, and would affect working conditions as it relates to the size of men and machines. Support or lining requirements are almost exclusively dependent upon the relationship of the ground conditions to the support system design, although contractural requirements and real or imaginary safety problems can significantly influence requirements. The relationship of support or lining requirements to excavation performance is tied together if materials handling systems or support crews keep pace with the excavation system to the extent necessary for a maximum time or distance limitation between support and face. The materials handling system capacity is dependent upon the rock being removed from the face, and the type of machine breaking the rock, in combination with the particular handling system design. The maintenance of the materials handling system is of significant note relative to the dependability of that system.

Crew and management efficiency is of extreme importance for two reasons; first is that machine tunnel boring is extremely dependent upon man and machine performance, with the particular detailed character of the rock of secondary importance, and second is that the crew and management efficiency is very difficult to evaluate.

The many variations possible in man/machine performance, along with the great magnitude of their impact may mask all but the greatest differences in rock properties from rock zone to rock zone.

Rock Classification

The general rock classification presented in Table 2 does not meet the requirements of a useful design classification. It only points out the important factors that must be considered in building or using a quantitative classification.

Framework for a Quantitative Horizontal Boring Classification

The requirements for building a useful quantitative horizontal boring classification are different from those necessary to use such an available classification. A definition of terms is required because of the use of many non-standardized terms in excavating and mining practice.

Advance rate is divided into three general classes, instantaneous, average, and production. Normal is the term reserved for the standard

TABLE 2. - General rock classification

Dominant nature	Pertinent properties and parameters	Potential behavior of excavation system
Intact-massive	Energy-strength-hardness Abrasiveness Anisotropy or bedding Joint spacing Water In situ state-of-stress	Rate dependent on thrust, rpm, cutter life - is, primarily machine dependent
Jointed	Joint spacing and orientation Water Abrasiveness Energy-strength-hardness In situ state-of-stress Time Size and shape of opening	Rate primarily water dependent
Faulted	Orientation of opening through discontinuities In situ state-of-stress Water Gouge material Joint spacing and orientation Abrasiveness Energy-strength-hardness Time Size and shape of opening	Rate primarily dependent upon opening stability

crew basis and standard machine. Actual is the term reserved for the particular crew basis and particular machine being used. An average advance rate of particular interest is the optimum normal. This is the average rate attainable under optimized operating conditions with the standard machine. The instantaneous advance rate directly observed is the unadjusted instantaneous advance rate.

For the greatest simplicity, both average and instantaneous advance rates are for the time the machine is in operation. Scheduled and non-scheduled machine downtime are accounted for external to the advance rate classification and are applied to the actual average advance rate to gain a production advance rate. Production advance rate is the final measure of the performance of an excavation system, the calendar days required to complete an excavation of a given length. Table 3 shows a tabulation of these advance rate definitions.

In order to utilize an advance rate/rock classification for a standard crew and machine, auxilliary classifications for machine downtime/rock classification, crew efficiency/rock classification, and system efficiency/rock classification are needed. The building of a quantitative horizontal boring (advance rate) classification requires the acquisition of this same information for purposes of adjustment of the directly observed instantaneous rates to average normal advance rates.

The steps in building an advance rate classification are:

1. Observe and record the unadjusted instantaneous advance rate. The time increment must be small enough to insure that there are no changes in either the excavation system or the rock encountered during the measurement interval.

TABLE 2. - Definition of advance rate

Class	Type	Characteristic
Instantaneous	Maximum Peak	Maximum possible over given short time period
	Optimum Peak	Maximum possible while maintaining over longer time period
	Unadjusted	Directly observed
Average*	Optimum Normal	Normal system
	Actual	Actual system
Production	Production	Actual system including scheduled and non-scheduled machine downtime, excepting that caused by delays in other system component breakdowns

*Over operating period only

2. Observe and record all machine operating conditions, wear (condition of equipment), crew efficiency, and total system efficiency.

3. Observe and record all scheduled and non-scheduled downtime not related to total system efficiency.

4. Observe and record management efficiency.

5. Measure and record rock properties and acquire rock samples for laboratory testing.

6. Convert instantaneous advance rate to average actual advance rate.

7. Compare actual system to normal system.

8. Convert average actual advance rate to average normal advance rate.

9. Relate average normal advance rate to rock properties.

10. Relate boring machine downtime to rock properties.

11. Relate crew efficiency to rock properties. This will require evaluation of crew efficiency and adjustment of the results to a normal crew efficiency prior to relating to rock properties.

12. Relate system efficiency to rock properties. This will require evaluation of system efficiency and adjustment of the results to a normal system efficiency prior to relating to rock properties.

The relationships of average normal advance rate, downtime, crew efficiency, and system efficiency to rock properties can best be accomplished by choosing the measurable or observable rock properties that most effect the particular aspect being classified. A matrix presentation of the most important quantities can be set up, with numerical values inserted for the various combinations of factors. An equation with weighting factors for all combinations of factors would yield a single numerical value for a given rock type.

The steps in using an advance rate classification are:

1. Determine measurable or observable rock properties at as many points along proposed alignments(s) as is economically possible.

2. Determine the average normal advance rate at each point.

3. Determine all other operating factors at each point.

4. Determine the actual average advance rate at each point.

5. Determine and plot the production advance rate at each point. Calculate the average production advance rate.

6. Compare results from steps 1-5 for each potential route with each machine type or strategy available.

With average production advance rates and the unit costs associated with the attainment of those rates, the incremental project cost may be determined for each project alternative.

Use of the classification can be made in an identical manner in order to optimize remedial action based on the more detailed data that becomes available just in advance of a working face.

Because of the interaction of rock properties on the many different aspects of the excavation system, and because of the desireability of utilizing similar classifications for use with materials handling and ground support, it is likely that computer analysis of input data will be a necessity.

Figure 1 shows the flow of information from rock property data through project cost. This flow must be traced for each set of assumptions for crew-machine-management at each change in rock type along the excavation route, and the summation of the incremental project costs minimized.

If the dominant cost is the excavation cost, then all costs associated with the overall excavation project including such items as materials handling, and ground support could be included as "support" in Figure 1, with the resultant project cost being the total for all parts of the excavation system.

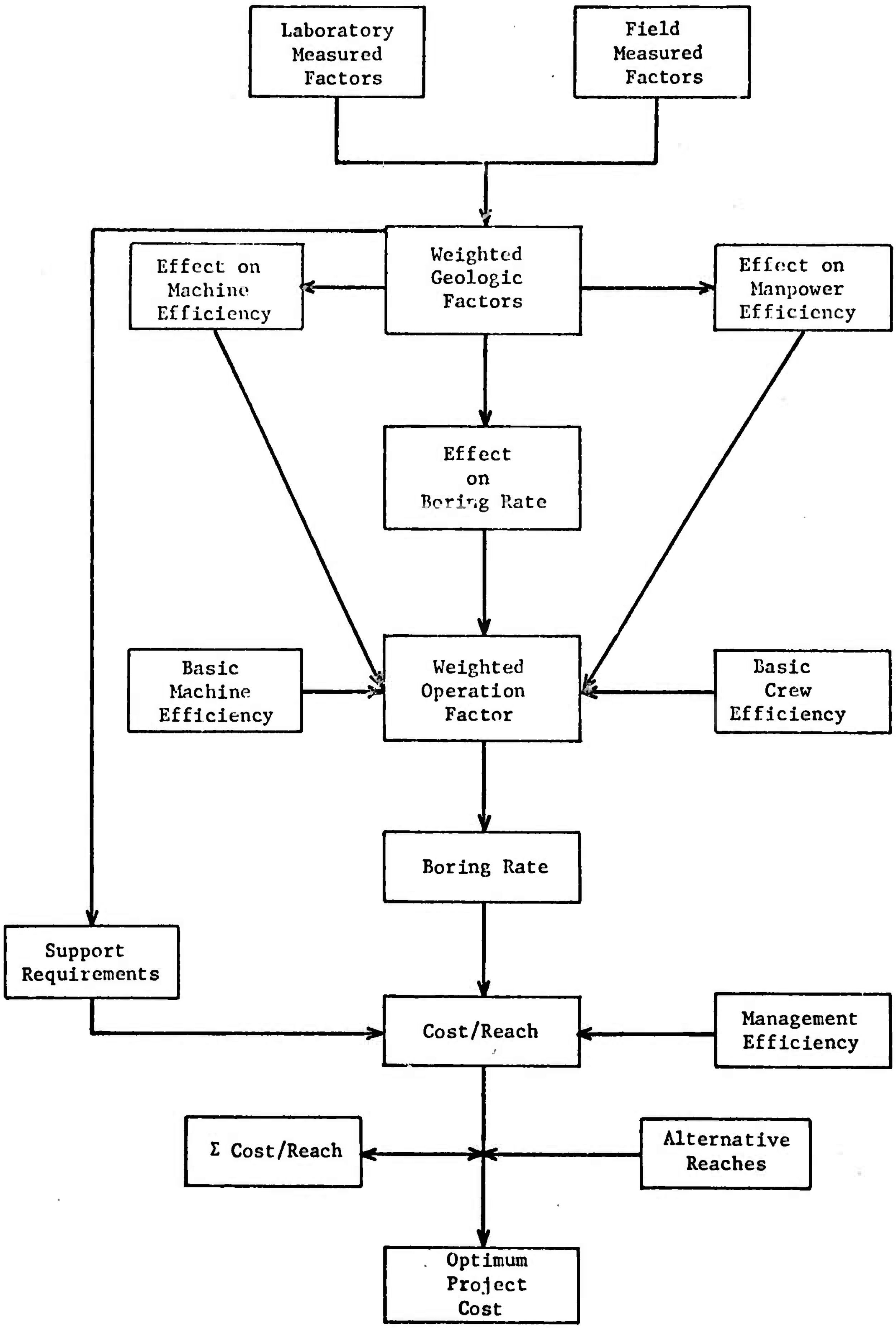
If the dominant cost is that for the ground support installation, then an analysis similar to that shown in Figure 1 would be handled as part of the ground support analysis, and "support" would include the costs associated with the boring machine function.

A further refinement would be to attain incremental project costs for each primary function, and to optimize the summation of the incremental project costs both for the combination of system alternatives and for the route alternatives.

Requirements to Obtain Data and Build Data Bank of Sufficient Nature to Build an Engineering Classification of Horizontal Boring in Rock in Terms of Rock Properties

A unique situation exists in the gathering of data for the purposes of analysis such to build a rock classification for the prediction of excavation functions. It is required that simultaneous, complete, and accurate sets of data must be taken at a sufficient frequency to yield data for analysis.

FIGURE 1. - Project cost optimization



"Simultaneous" means over such a time period that all factors remain essentially constant during the measurement period. "Complete" means all aspects of the operating system as well as the rock properties and system performance. "Accurate" means, for the most part, to a degree greater than is normally taken under production conditions only. "Sufficient frequency" means at every opportunity available because of a change in operating conditions or rock conditions. The accomplishment of this type of data acquisition cannot be done as part of a production routine. Additional instrumentation and data acquisition equipment, along with a special team of engineers and technicians, must be continuously available during data acquisition periods.

Thus, grabbing a random rock sample and running to a laboratory to conduct a simple test is <u>not</u> sufficient effort to correlate tunnel boring machine performance with rock properties. Crew and machine efficiencies vary greatly between crew-machine-contractor-job-time due to many complex and interrelated factors. These factors must be analyzed and properly interpreted, then separated out from gross observations of "advance rate" in order to determine rock/system interaction on a quantitative basis. Such detailed analysis demands that measurements of all factors be made over many short time periods to insure a statistical basis for their use. Averages or averaging techniques prior to tabulation of data are not acceptable. Classifications cannot be built on data taken where averaging (particularly that due to the effects of long sampling periods) has occurred.

The primary reason for the uniqueness and the care necessary in obtaining classification data is that factors other than all but the greatest variations in rock properties dominate the control of advance rates in excavation systems. These "other factors" must be normalized if the variations in rock properties are to be related to excavation system performance.

In general, five types of observations or measurements must be made to obtain a simultaneous data set. These are industrial engineering measurements necessary to determine crew efficiency, measurements of system efficiency, general observations on management efficiency, machine parameter measurements, and rock mass properties.

Industrial Engineering Measurements

Great care in acquisition of data on the performance of men and machines must be exercised. In order to accomplish a meaningful classification, and to utilize a classification, adjustments must be made to productivities of men and machines to or from a standard basis. Industrial engineering techniques must be utilized to establish standard times for activity units from observations of element times, and to account for productivity different from standard productivity.

It is of particular importance to emphasize the tendency of production units to have higher productivity during short observation periods, or to explain system breakdowns as "unusual." Only with careful and measured observations of all work units can a proper assessment of normal productivity be made of all aspects of an excavation system.

Another part of the industrial engineer measurements is all aspects of equipment performance parameters. The thrust, operating speed, and cutter conditions are of primary importance in a given machine configuration. It is not satisfactory to use a manufacturer's rating or a production foreman's guess; equipment must be instrumented and operating data continuously recorded. Instantaneous penetration rates and operating speed (rpm) for a series of torque limited and thrust limited situations must be made for each rock situation encountered. Sufficient data of this type will allow the derivation of a relationship defining a normal advance rate in terms of machine operating parameters and rock type for each machine type and cutter type combination. The effects of cutter condition on the relationship must be defined, as well as the effects of operating parameters on machine and cutter life.

Geological and Rock Property Measurements

Rock mass properties can be defined by two types of measurements and observations; laboratory and field. Examples of important types of laboratory measurements are strength, fracture energy, density, hardness, abrasiveness (silica content), and joint properties (stiffness and strength). In some cases other standard physical mechanical intact rock properties such as permeability and dynamic wave velocities may be useful.

In the field, joint patterns and spacing, fault zones, overburden and in situ stresses, fault zones, and ground water are of great importance. In some cases other geologic factors such as bedding orientation, seismic velocities, or rock temperature may be of importance.

Laboratory testing requires a representative sample in order to yield a meaningful measure of a field property (13). The care taken in setting up the background geologic description of the source area, and the effort to obtain samples on a systematic basis must be great to yield meaningful laboratory test results. Decisions must be made on number, location, and orientation of samples; sample extraction, recovery, and preservation techniques; specimen preparation techniques; and specimen testing techniques. The relationship of the sampling techniques the geology must be defined.

Further definition of in-place rock is possible with in situ test methods on a limited basis. Primary advance testing is done by means of vertical boreholes, and in some limited cases by horizontal pilot boreholes. General geologic observation yields the remaining available advance information. Of particular importance in field observation are bedding, joint, and fault orientation and ground water conditions.

DISCUSSION

The need for rock classification for predicting underground excavation system performance is present. A cursory examination of the requirements that must be met to build such a classification indicates that the cost of obtaining the required information and building the classification system may be prohibitive. The entire question of obtaining the information necessary to use a predictive classification in advance of an excavation has been addressed by the ARPA Rapid Excavation and Rock Mechanics program in a general manner. The possibility of obtaining sufficient information in advance of excavation is not high with present or foreseen techniques.

The possibility of obtaining new types of measures of in situ rock that are also descriptive of how the rock influences an excavation system seem very remote. The writer feels that any further rock classification for horizontal boring application is premature; rather, effort should be expended on defining efficient operation techniques for existing excavation systems such to maximize the potential of those existing systems.

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