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SUPPORT DETERMINATION METHODS

Eugene H. Skinner

Bureau of Mines

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ABSTRACT

The BurMines acting as agent for the Advanced Research Projects Agency (ARPA), managed a program in Rock Mechanics and Rapid Excavation. The portion of the program assigned to the Spokane Mining Research Center (SMRC) concerned analytical and empirical techniques ~ ground support with emphasis upon: (1) case history studies, (2) instrumentation, evaluation and development, (3) theoretical modeling of medium and structure interaction, and (4) field studies. No work was done by SMRC in field studies. SMRC in-house and contract work performed under case history studies covered research areas of (a) finding means of predicting rock loads, and (b) developing the methodology for determining rock loads.

Research in analysis of specific tunnel projects gathered and quantitized information on selected tunnel projects and obtained predictive techniques for support requirements. An overall operations research investigation was completed for the 7.0 mile Flathead Tunnel with a regression analysis of 78 actual tunnel sections. This analysis found nearly equal importance between the fracture density and the support density as the most important variables which affect daily rate of advance.

Research in support design methods compiled a literature bibliography of support design, and related contract effort in H0210038 and H0220075 used 190 tunnel sections and 53 separate tunnels to develop a support prediction model called the Rock Structure Rating (RSR) and the Rib Ratio (RR). Tables and figures were developed to incorporate the RSR and RR into support requirements for steel sets, rock bolts, and shotcrete for typical mining and civil tunnels between 10 and 30 feet diameter or equivalent tunnel.

Research in improved techniques for support determination was aided by use of computer methods. Contributory contract effort H0210035 was used to develop a data bank for all underground civil structures in the states of Washington and Oregon as a pilot project. An available data bank of 256 underground projects was compiled on a time-sharing computer system. The cost analysis program COHART was adopted for mining use on CDC 3200 and typical deep Coeur d'Alene mining type adit and shaft problems were run.

FINAL TECHNICAL REPORT

SUPPORT DETERMINATION METHODS

by

Eugene H. Skinner, [1/] Principal Investigator

TECHNICAL REPORT SUMMARY

The BurMines, acting as agent for the Advanced Research Projects Agency (ARPA), managed a three-year effort in Rock Mechanics and Rapid Excavation. The portion of the program assigned to the Spokane Mining Research Center (SMRC) concerned analytical and empirical techniques for ground support with emphasis upon: (1) case history studies, (2) instrumentation, evaluation and development, (3) theoretical modeling of medium and structure interaction, and (4) field studies. No work was done by SMRC in field studies. This report summarizes SMRC in-house and contract work performed under case history studies which covered research areas of (a) finding means of predicting rock loads, and (b) developing the methodology for determining rock loads. Specific research problem areas were the following:

Analysis of Specific Tunnel Projects. Research in this area was directed toward gathering and quantitizing information on selected tunnel projects and obtaining predictive techniques for support requirements. An overall operations investigation was completed for the 7.0 mile Flathead Tunnel and a regression analysis of 78 actual tunnel sections set the rate of advance as the dependent variable and the geologic and construction factors as

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the independent variable. For a composite of the 78 tunnel sections, final stepwise regression analysis found nearly equal importance between the fracture density and the support density as the most important variables which affect the rate of advance. Other construction and geologic variables were less important. An additional study was made of 19.14 miles of mine openings in Lincoln and Flathead Counties, Montana, (compiled by the Montana Bureau of Mines and Geology) and compared in terms of support to actual Flathead Tunnel support. It was shown that in each case about 77 percent of the total tunnel length required little or no support and about 23 percent definitely required support.

Determination of Support Design Methods and Modifications. Work in this problem area was directed to compiling a literature bibliography of support design. Design techniques were monitored by a design bibliography (to supplement DASA-1406) in underground design methodology. A total of about 350 publications were referenced in the subject area of underground design. Related contract effort, H0210038 and H0220075, used 190 sections from 53 separate tunnels to develop a support prediction model using the Rock Structure Rating (RSR) and the Rib Ratio (RR). Nine selected geologic variables and three construction factors were considered in an evaluation of over 200 miles of constructed tunnel ranging in size from 8 to 36 feet in diameter. Tables and figures were developed to incorporate the RSR and RR into support requirements for steel sets, rock bolts, and shotcrete for typical mining and civil tunnels between 10 and 30 feet diameter or equivalent tunnel.

Improved Techniques for Support Determination. Work in this area concentrated on improved techniques for support determination, principally aided by the use of computer methods. Contributory contract effort (H0210035) was used to develop a data bank for all underground civil structures in the states of Washington and Oregon as a pilot project. An available data bank of 256 underground projects was compiled on a time-share computer system and successfully demonstrated to the Technical Project Officer on August 2, 1971, using a telephone couplet and teletype terminal. This effort coincides with the ARPANET network linking Government and University computer centers into a nationwide computer utility. The cost analysis program, COHART, developed under contract to HARZA by the Office of High Speed Ground Transportation, Department of Transportation (DoT) was adapted for mining use on the CDC 3200 computer at SMRC. Typical Coeur d'Alene mining type adit and shaft sinking problems were run. Cost figures were compared to Deep Underground Survival System (DUSS) cost estimates. Tunnel cost figures given by the California Department of Water Resources were also compared in terms of scaled costs.

INTRODUCTION

The BurMines program developed for ARPA stressed the concept of fundamental and applied research in rock mechanics focusing on a pressing problem facing our Nation's mining, and civilian interests - Improved Excavation Technology. Seven major study areas in this ARPA program were defined by the BurMines and were arranged in relative order as appropriate for improved excavation capability in hard rock. Emphasis was directed to the balanced approach, advancing all areas concurrently, yet emphasizing the most pressing research needs. The Bureau of Mines expertise was reflected in the program framework and also within specific research topics (16,32)[2] Briefly, the individual BurMines research areas were originally developed as follows:

1. Rock and earth material disintegration.
2. Rock mechanics investigations.
3. Geologic prediction.
4. Ground support.
5. Materials handling.
6. Fundamental studies in rock mechanics.
7. System analysis and development.

The scope of work assigned to SMRC contributed to Item 4, Ground Support. The primary objective of the SMRC research topic was to develop both the empirical and analytical techniques for: (a) predicting rock loads, and (b) determining support system requirements. To achieve this objective, the following study areas were identified for SMRC investigation, namely: (1) case studies, (2) instrumentation evaluation and development; (3) theoretical modeling of medium and structure interaction, and (4) field studies (not funded). This report discusses that research conducted under case studies, Figure 1.

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2 Underlined numbers in parenthesis refer to items listed in the references.

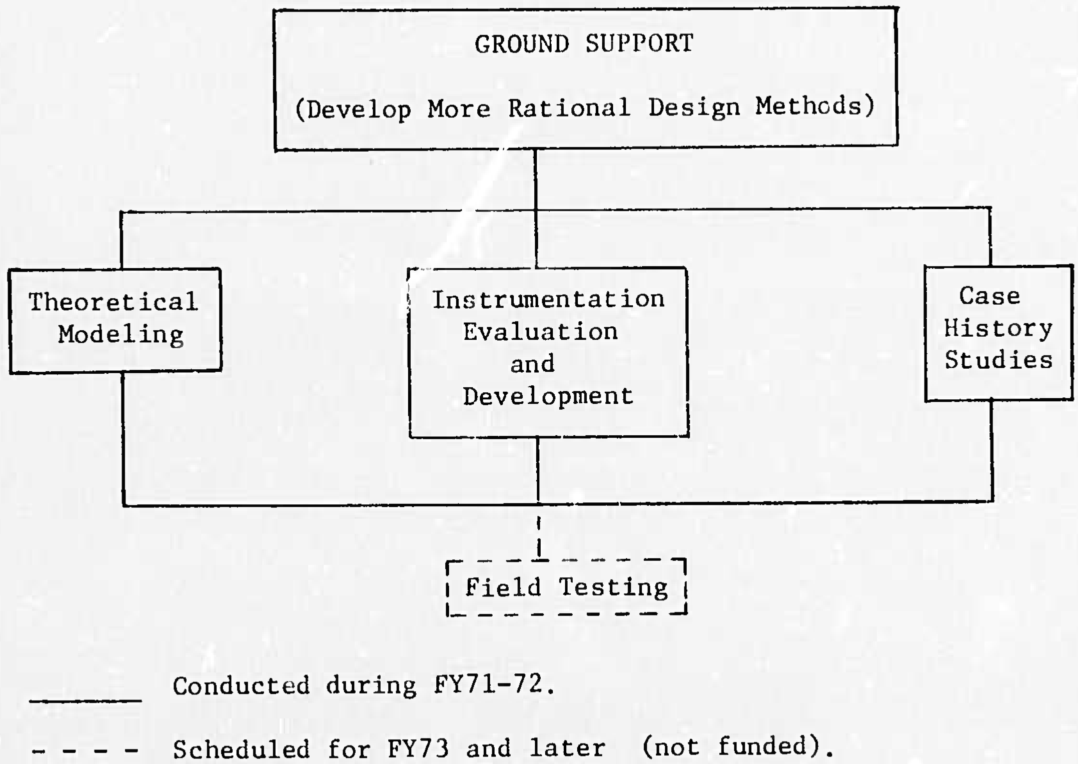


Figure 1. - Overall program of ground support research conducted by the Spokane Mining Research Center under the ARPA Rock Mechanics and Rapid Excavation Program.

RESEARCH PLAN

In recent years, many studies have been made related to the problems of tunneling. A typical conclusion from these reports (3, 13, 17) is that current mining methods (either by drill-and-blast or mechanical boring machines) are expected to continue in use for tunneling needs in the immediate future. The consensus from these reports also emphasized that those investigations conducted ahead of the tunnel face should not hold up the advance rate. Studies of advanced rock excavation techniques have been conducted; and, although several show promise, none have been field tested. As a further note, full-scale performance projections for many of these methods were extrapolated from very limited laboratory data. Therefore, it appears conclusive that unless a real breakthrough in rock excavation technology occurs, the present excavation and support systems will continue. The excavation cycle used in present systems appears nearly maximized around the feet of advance per day. Operators have empirically maximized this rate within existing technology.

An average relative cost component for various portions of the excavation cycle is as follows (15, p.27):

Table 1. - Relative Cost Components for Tunneling.

Excavation operations	22.3%
Ground control and support	16.3%
Environmental control, power, etc.	7.2%

Permanent lining	21.5%
Prime and other installed facilities	32.7%
Total	100.0%

Total support costs	
Temporary	16.3%
Permanent	21.5%
Total	37.8%

For some selected tunneling projects, support costs are estimated to easily account for 50 percent of the total project costs. Cost data, of course, are the focal point from the contractor's point of view. Therefore, using an index of relative economic value, and proportion of total costs, it is readily seen that ground support is, and will be, a very major consideration for all tunneling.

The reference reports cited previously indicate the following specific problem areas in ground support and tunnel linings: (1) the inability to successfully predict the rock loads that must be carried by the support system, and (2) inadequate methods for determining the load-carrying capacity of the various support systems. Therefore, the problem areas for this project's portion of the ARPA sponsored research at SMRC is defined by these two major problem areas of ground support: (a) to find means of predicting rock loads, and (b) to develop the methodology for determining support system design.

The research organization for the solution of these defined research needs was developed along the following problem areas:

Problem Area 1. Analysis of specific tunnel projects by the case history method. This examination was directed toward gathering and quantitizing available information on selected tunnel projects. From this information predictive operation analysis techniques for support requirements were formulated. This phase of the project also monitored the state-of-the-art in tunnel instrumentation on selected projects to assess the influence of selected variables on measured support loads and deformation. The recommendation for support requirements was compared to actual supports. This portion of the work was aided by contract research (H0210035, H0210038, and H0220075).

Problem Area 2. Determination of support design methods, including modifications at the heading face and support failure conditions. This problem documented the design assumptions made during tunnel exploration for purposes of preliminary support evaluation. The state-of-the-art for design techniques was made in conjunction with case history analysis (Problem 1)and also used contract results as necessary. Problem 2 recognized that a wide divergence in tunnel design criteria has prevailed. This problem area emphasized the pragmatic approach, as Karl Terzaghi said, "from theory to practice". The major thesis of problem 2 is that rock behavior is the key to ground control. Contract research (H0210038 and H0220075) developed the Rock Structure Rating methodology for predicting temporary support for rapid excavation based on the dependent sequence of excavation operations and various rock conditions encountered in the pre-bid project evaluation.

Problem Area 3. Improved design techniques for support determination. Using support load data, appl ed research techniques, and the assumptions and criteria for tunnel design (all obtained via the case history approach and from problem areas 1 and 2) the feasibility of a computer-based data bank was explored. This study area recognized that the technology of support design is developing fast, aided particularly by computers, with efforts made by many organizations. Data bank knowledge shall be utilized in all aspects of drill-and-blast tunnels, machine-bored tunnels, and the ARPA rapid excavation program. A powerful method for retrieval, indexing, correlation, and simulation of all known, future, and hypothetical support-load situations is possible with the computer. This research area recommended documentation by either a state-by-state or a regional data bank. A tunneling data bank from the Pacific Northwest was completed by contract H0210035.

The scope of study to assess support-load conditions in underground openings consisted of literature review, on-site examination, review of field instrumentation, and the evaluation of support-load data and design methods. Emphasis was given to the method of case history determination for support methods and modifications, particularily near the working face. The fundamental research thrust was to develop an empirical method to aid in the pre-bid determination of support requirements and through concurrent contract research, table 2.

Table 2. - Summary of tasks conducted under the case history project in ground support at SMRC.

Problem Area 1. Analysis of specific tunnel projects.

1. Gather and quantitize available construction and ground support information on selected tunnel projects.
2. Develop predictive regression equations for predicting support requirements.
3. Monitor the state-of-the-art in tunnel instrumentation for purposes of assessing the influence of the variables.

Problem Area 2. Determination of support design methods, including modifications at the heading face.

1. Compile a state-of-the-art literature bibliography in design methods for ground support.
2. Document design assumptions made during tunnel exploration for purposes of preliminary support requirements including problems of support failure in unusual situations.
3. Develop a ground support prediction model.

Problem Area 3. State-of-the-art techniques for improved support determination.

1. Document selected current tunneling projects to fulfill Problem Area 1, above.
2. Feasibility of a tunnel documentation center and data bank for all useful information.
3. Feasibility of computer based cost estimating programs.

TECHNICAL DISCUSSION

Although numerous attempts have been made by engineers to analytically "design" support systems for underground projects, the state-of-the-art has not yet reached the state of rational design, being more a process of support selection. In most instances, the basis for support selection has been past experience and visual inspection at the working face.

An objective of any design practices study would be to investigate load-transfer characteristics between rock and selected support systems and to investigate the response of these structures to ordered parameter variation of rock-support behavior characteristics. An application to the design function then is to demonstrate that currently available numerical techniques are of commercial value to the planning, design, and construction of deep underground facilities.

The need for this research effort is based on the fact that advanced numerical analysis techniques (finite element analysis) over-simplify the structural support model and its interface with the rock. Also, total material behavior characteristics are not generally available, especially before excavation. It is suggested that mechanistic structural models (which incorporate important structural geometries and linkages, together with their gross behavior characteristics) can be computer catalogued, such as by a data bank.

Predicting ground behavior as the underground opening is excavated has been, and continues to be, a perplexing problem to all phases of underground construction. Lack of predictive knowledge about (a) behavior characteristics of the medium around an opening, and (b) rock and support interaction naturally tends to lead to the use of an inappropriate support system, which increases both the tunneling costs and the safety hazards.

For most ground conditions, tunnel-support design (for usual static loading) might ultimately attain more economy and rationality through these suggested practices: (1) allowing the ground to yield slightly to the extent required for reasonable development of its strength in the ground arch; (2) utilizing initial support to preserve the ground strength; and (3) deferring final placement of permanent support until the ground arch has stabilized (for the normal case, wherein deformation rate decreases with time). Such an approach recognizes that the <u>ground itself</u> is the most efficient load-carrying member of the system. The prime function of the ground support system then becomes one of preserving the ground strength by restricting deformations to well below the start of progressive failure.

This review has furnished further insight into present underground design methods -- which at present is stated as one of engineering judgment and sometimes speculation by non-engineers. It has been said that management has in many cases abrogated design responsibility to others. However, a realistic concept of underground design must be established by some means. One obvious result of these uncertainties, due to lack of sufficient design knowledge to develop rational design criteria, is that it is necessary to rely upon large factors of safety.

The following points of view are stated concerning "exact" analytical ground support modeling:

1. Analytical modeling of the physical processes in rock-support interaction has out-stripped the availability of usable field data; both with respect to rock properties and support load behavior data.
2. Generalized analytical models are suggested as a guide to "phenominological" studies only.
3. Project construction and support installation details presently exceed the ability to mathematically model or theoretically analyze economically.
4. Most underground support systems presently appear designed by rule-of-thumb or past experience. It is suggested that the design function often has been abrogated by management and engineering.

Perhaps paradoxically, the requirements for a tunnel support system are essentially the same at great depth as at shallow depth. Once the initial excavation is created, rock accepts the stress and displacement conditions by redistribution about the opening to the surrounding material. During this process, the opening deforms and a major requirement for a support system becomes apparent. First, the support must resist initial deformation and must be resilient (elastic to plastic) to the deformation without accepting critical loading. The second major support requirement is to restrain the incompetent rock surrounding the periphery of the opening. The degree of this rock-support interaction depends on the method of excavation, the initial quality of the rock, and the nature of the stress redistribution. The final requirement of the support is its functional relation within the intended opening use and life span of the opening. As examples, a water tunnel may be under internal pressure, a civil use may require long usage and high safety, a mining operation will require only a few years actual use, and an underground hardened nuclear facility will require survival from high yield surface weapons.

The problem of optimum support selection then becomes paramount. Given the behavior specification for a support system within a specific rock structure, the designer must determine which of several support schemes fulfill these needed requirements. Based on rock structure evaluation, the support load requirements, and the intended use of the support, a cost-effectiveness study can be conducted to select the optimum support system for the specific case. Of course, consideration must be given to necessary equipment to install the support at a specified rate of advance in conjunction with a specified mining system. The concluding steps would be a total system design analysis, followed by field test and evaluation, and finally, cost-effectiveness analysis of the total system. This entire process, as described above, could be significantly aided by computer methods.

CASE STUDIES -- PROBLEM 1

The objective of this research was to examine geologic and construction variables through case history analysis and to assess their influence upon support design. A significant beginning has been made by Abel (1,2), Abel, et al (12), at the Straight Creek Pilot Bore, by Brown at the Divide Tunnel (5), and by Sharp at the Henderson Shaft Project (19). These investigators used selected construction and geologic variables along with data from instrumented steel sets, and found statistical correlation of over 90 percent between the variables and the set loads. To date, this method is the only predictive technique known for evaluating support loads using only geologic and construction variables; but any variable can easily be mathematically interrelated for any desired variable correlation through computer usage in regression analysis. The rock load on the tunnel support is the classic correlation developed by Terzaghi (24). A common criteria for support evaluation is that it be safe, efficient, and economical with the rule that the rock itself is the most efficient load carrying member (13, p.23).

The case history selected, using an operations research technique for support prediction, was made concerning the factors affecting support density on the Flathead Tunnel (the second longest railroad tunnel on the North American Continent). This 7.0 mile tunnel, constructed between 1966 and 1970, by the Corps of Engineers is typical of a modern project using drill-and-blast methods.

The main results of the operations research technique, above, which set the rate of advance as the dependent variable and the geologic and construction variables as the independent variables, is as follows: For 17 rockbolted sections, the most important variable was the fracture density, with an index of correlation , r = 0.53. No other variables were significant. For 6-inch sets, and 39 sections of tunnel, the most important variable was again the fracture density, r = 0.78, and the dip of the geologic strata, r = 0.57. Other variables were found less significant. For 8-inch sets, and 22 sections of tunnel, the most important variables were the strike, dip, fracture density, and section modulus of the support. The conclusion is that as ground conditions require increasing amounts of support, increased emphasis is placed on geologic conditions. The fracture density variable is the most important variable throughout. Finally, combining all 78 tunnel sections, for a composite of the total tunnel, the fracture density r = 0.69, and the support density r = 0.63, are the most important variables which affect the rate of tunnel progress, as measured in feet per day.

The following variables were used in the Flathead Tunnel regression analysis: support section modulus, support spacing, length of supported section, number of sets, daily rate of advance, overburden, strike, dip, and fracture spacing. The data base was obtained from the 488 daily construction reports, the complete geologic mapping by the Corps of Engineers, and the support installation details supplied by the contractor for each set installed. A BurMines Information Circular has also been prepared on the Flathead Tunnel (21).

Certainly, the above analysis follows expectations. The more support installed, the more time that must be devoted to support related activities and less time spent on actual excavation. The same intuitive relation holds for the fracture density. The greater the distance between joints, or widely spaced fractures, the greater is the expected daily rate of advance. Based on this correspondence of SMRC work with Abel's, each having similar results, it is suggested that the method has definite merit and should be applied to other projects as data becomes available.

Another critical point was examined in the use of prior case history records for tunnel ground support estimation. The particular site selected was also Northwestern Montana in the Flathead Tunnel locality where the basic data had already been collected by the Montana Bureau of Mines and Geology under financial sponsorship of the Burlington Northern Railway and the Pacific Power and Light Company. The study area comprised 9200 square miles in Lincoln, Flathead, and the northern portion of Lake County, Montana. Work by the Montana Bureau of Mines was done intermittantly between 1958 and 1970, when their final report was published (14). The report, and the preceding progress reports, were used for the data base. A total of 143 underground mining sites were identified from that study with a total length of 19.14 miles, or 2.1 miles of underground workings per thousand square miles of surface land area. These records, above, were evaluated and compared to actual ground support used on the Flathead Tunnel as follows: (1) examination of all underground mining activity within a selected nearby region; (2) classification and quantifying by rock type, length of opening, and whether the underground opening is accessible or inaccessible from the viewpoint of a prudent mine examiner; and (3) presenting selected data in a manner that breaks out ground support as related to geology, opening length, and accessible or inaccessible. Although this study (18) is the first to be applied to western metal mines, the immediate roof over coal seams has received some detailed study in western coal mines (22). Stahl cited fatality statistics wherein unfavorable geologic conditions are a contributing factor (secondary cause) in 41 percent of fatal accidents reviewed. No exact statistical significance was assigned by Stahl to rock type.

The initial Corps of Engineers estimate of ground conditions was based on available pre-construction site investigations and gave the following estimate of temporary support: (1) at least 20 percent of the total tunnel length would require heavy steel sets; (2) about 40 percent would require medium steel sets, and (3) the remaining 40 percent of the tunnel length could be supported by rock bolts. Detailed post-construction analysis showed that 22.7 percent of the tunnel required heavy steel sets; about 50 percent used 6-inch steel sets; and 27.3 percent of the tunnel length was supported with rockbolts. In all field installation of support, it was the decision at the heading by the working forces that governed choice of support used. That decision is exactly that of the prudent mine examiner--is the heading or entry safe, or not? Only the decision of the man at the face was used in both these situations. Accessible openings determined by the mine examiner were grouped with the 6-inch and rock bolt supported sections in the Flathead Tunnel. Inaccessible openings include all 8-inch and invert strut sections. A tunnel collapse occurred in ground classified as inaccessible.

Summarizing the data obtained from the pre-construction estimate of ground support through a study of mine openings as compared to actual installed supports during construction as follows, Table 3.

Table 3. - Comparison of Support Estimates, Flathead Tunnel.

Data from this study		
Accessible openings	74,887 feet	77.2%
Inaccessible openings	22,159 feet	22.8%
Total length	97,046 feet	100.0%
Actual Installed Support		
Accessible openings	27,400 feet	77.3%
Inaccessible openings	8,030 feet	22.7%
Total length	35,430 feet	100.0%

In conclusion, a remarkably coincident ground support relation was found in that both situations gave exactly the same percentages of accessible to inaccessible openings. These results, obtained from tremendous effort by field investigators and comprising nearly 26 miles of underground openings, illustrate that a thorough pre-construction surface examination and review of all sources of data bearing on ground support determinations are necessary.

DESIGN BIBLIOGRAPHY - PROBLEM 2

A project report (20) was completed to compile the state-of-the-art in design techniques for underground structures. That effort, in conjunction with the case history portion, provided expertise to assess design methodology in underground structures. The report was a bibliography search in the following three areas: (1) design as a creative process of analysis, synthesis, and optimization; (2) elasticity, with excursions as necessary into plasticity, viscoelasticity, anelasticity, fatigue, failure theories, and materials. (Only books were listed and no attempt was made to survey the entire general literature); and (3) underground design methodology. Nearly 350 publications were referenced, as well as other source listings, bringing the total list in these areas to over 1000 references. This work was directed to documenting design assumptions from actual construction and not to create theoretical design methodology. This work is a follow-on to DASA-1406, 1963 (25) which compiled a bibliography of loads on underground structures. Also, AFWL TR-66-160 (11) listed protective construction research reports. These reports have been reviewed and no duplicate references were included in present work.

GROUND SUPPORT PREDICTION MODEL - PROBLEM 2

A means of predicting rock loads, and for developing the methodology of determining rock loads was developed by joint contract research between Jacobs Associates and the BurMines (1972-1974). In addition to the background provided by the classic pioneering papers of Terzaghi and Abel (24,1,2) any unified support recommendation must require the active efforts of both geologists and engineers. The factors applied to any ground support model must enable all disciplines to reach a common understanding on common terms concerning the relative effect on support requirements from various geologic and construction conditions. This will require that certain compromises be made between those involved, but once accomplished, there would exist a standard approach to guide support determination. Those working at the heading should be able to verify or adjust actual support on the basis of previous experience as well as make periodic adjustments if encountered geologic and construction conditions are significantly different than anticipated. This aspect of the problem was also recommended by the report of the Organization for Economic Development (13).

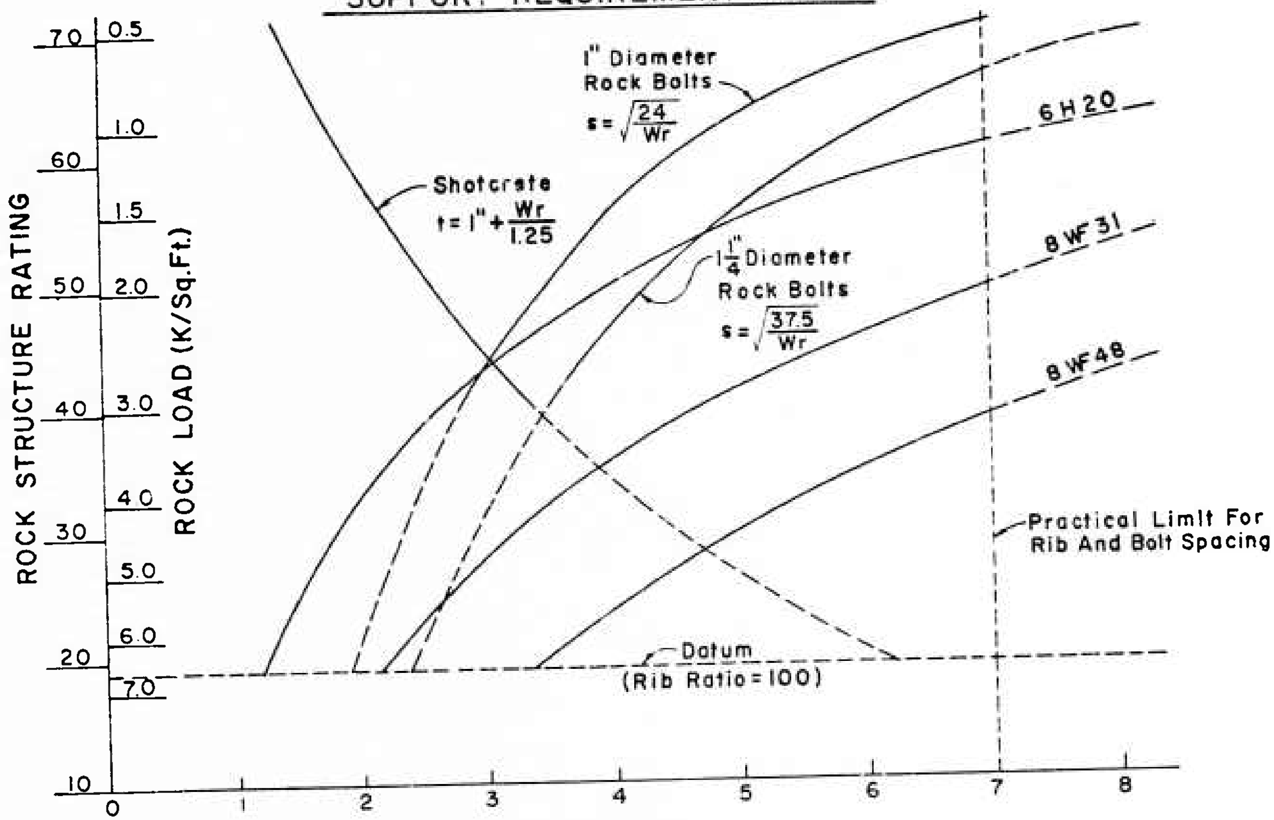
Certainly no ground support prediction model, including a rigorous mathematical or theoretical analysis can eliminate the judgment factor for those in charge of the heading as to what constitutes a safe, efficient, and economical support system at the time of construction. The goal of support prediction shall be to provide the means for making realistic appraisals of support requirements during the pre-construction period and which can be readily used, understood, and correlated with encountered construction conditions by as much of the working force as possible; including management and designers, supervisors and heading work-force leaders.

The Rock Structure Rating (RSR) and the Rib Ratio (RR) concepts provide the methodology by which support prediction can be accomplished within the existing art. The intent is not to define the need for a specific support member at a particular location but rather to allow the designer to make a general evaluation of a support system which affords the most optimum solution within the overall tunneling process. The method evolved by Jacobs Associates and the BurMines using the RSR and RR concepts is essentially an empirical approach based on historical data, the review and evaluation of findings and conclusions presented in published papers pertaining to geology, rock mechanics, theories of support determination, and, of course, the ground support practices used in actual construction. It would be impractical, if not impossible, to consider all possible combinations of all factors. Therefore, only the more important factors were grouped into two general categories: (1) geologic parameters, and (2) construction parameters, which were then broken down into individual factors.

The RSR and RR method considered: (1) rock types, (2) joint patterns, (3) dip and strike relations, (4) discontinuities, (5) faults, shears and folds, (6) ground water, (7) rock material properties, and (8) weathering and alteration. Some of these factors can be treated separately; others must be considered collectively to properly define conditions which affect ground support requirements. In some instances, it may be possible to accurately define each factor, while in others, only a general approximation can be made.

Construction parameters, as do the geologic factors, depend on ground conditions including some of the following: (1) size and geometry of tunnel shape, (2) direction of drive, and (3) method of excavation. Ground supports are often installed for reasons not related to engineering calculation, such as contract stipulations, costing procedures, and various safety regulations. These outside influences must also be considered in the final

SUPPORT REQUIREMENT CHART



20' DIAMETER TUNNEL

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support recommendation.

Space does not permit detailed discussion for each of these geologic and construction variables related to the ground support prediction model, the original reports and publications are suggested (26-31). Figure 2 further illustrates a typical support chart developed for a typical 20 foot diameter, or equivalent tunnel. Field verification of the RSR and RR concept was done in contract H0220075 for six on-going projects, seven mines and one mine haulage tunnel.

DOCUMENTATION CENTER AND DATA BANK - PROBLEM 3

For problem area 3, the feasibility of a computer based data bank was explored. Potentially, such a system could be utilized in all phases of drill-and-blast and machine bored tunnels besides the ARPA rapid excavation program. When pertinent data has been computer-stored, a powerful method for retrieval, indexing, correlation, and simulation of all known, future, and hypothetical support-load situations will be available. This problem area was attacked by contract to Foundation Sciences (9,10) in the form of a regional data bank for Washington and Oregon as a pilot project.

One of the most important tasks outlined for a national focal agency by the Organization for Economic Development (OECD) related to planning for optimum future use of the subsurface, including the recording and analysis of past and present tunneling activities (3, pg 5-10). Utilizing the contributory contract with Foundation Sciences, the BurMines demonstrated that a computer oriented data bank of pertinent tunneling information could be used for just such purposes as recommended by OECD. Specific objectives of the Foundation Sciences contract were: (a) to isolate those factors having the greatest influence on ground support, construction, economy, safety, and performance; (b) to determine whether useful relations can be established for layout and design, excavation procedures, and underground support, and (c) to identify potential areas of research for improving excavation and support methods. A detailed review was made of projects within the study area where known design and construction problems had occurred. The contract also included two case histories (methods of exploration, design, construction, and performance) for two recently completed tunneling projects in the Pacific Northwest. One was an urban highway tunnel of unusual size and the other was a large underground powerhouse chamber.

An available data bank of 256 underground projects from Oregon and Washington was assembled from 44 organizations and compiled in a time-share computer center in Seattle. A telephone couplet was used for teletype access. This method was used to further demonstrate that a data bank could be used at job-sites far from central facilities. The field demonstration at Foundation Sciences office was successfully performed on August 2, 1971.

The time-share program handled the following four programs: (1) File Maintenance Program; (2) Inquire and Print; (3) Transaction Update Program; and (4) Sort and Merge. Particular attention must be given to the last program because through this routine the user is able to create mathematical programs, call and merge the data from storage for work. The following example is illustrative (10, pg. 36):

Question: List all tunnels over 500 feet long, 15 foot in diameter, and the cost per foot.

Answer:

Blue River Dam Diversion	circular	$316
Cougar Main Diversion	arched	167
Cougar Outlet	circular	355
Green Peter Diversion	arched	781
Big Cliff Diversion	arched	428
Knowles Creek	arched	431
Sunset	arched	177
Vista Ridge West	arched	4166
Vista Ridge East	arched	4352

Question: Compute average cost for seven arched tunnels.

Answer: $1500

Question: Compute average cost for two circular tunnels.

Answer: $355

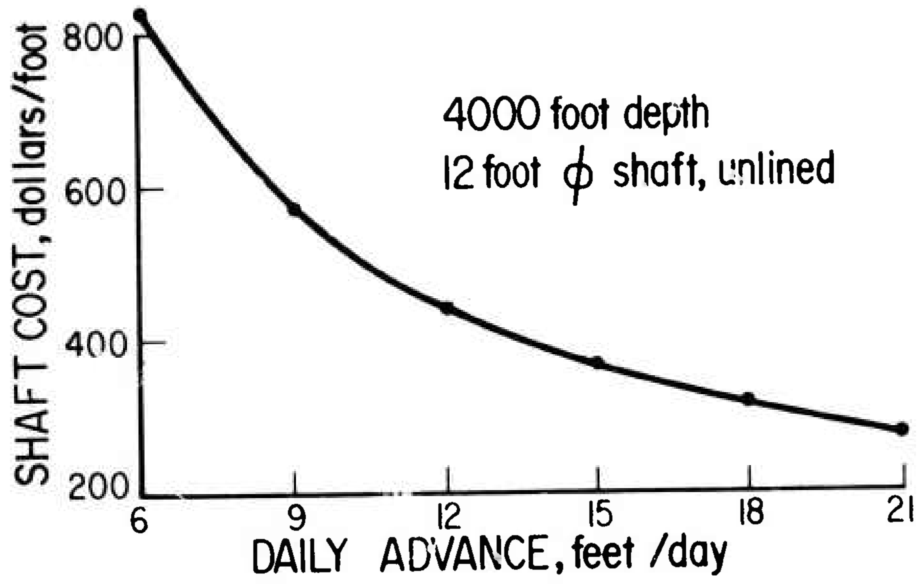
It should also be noted that the entire system can be operated by ordinary clerical staff with no special training required.

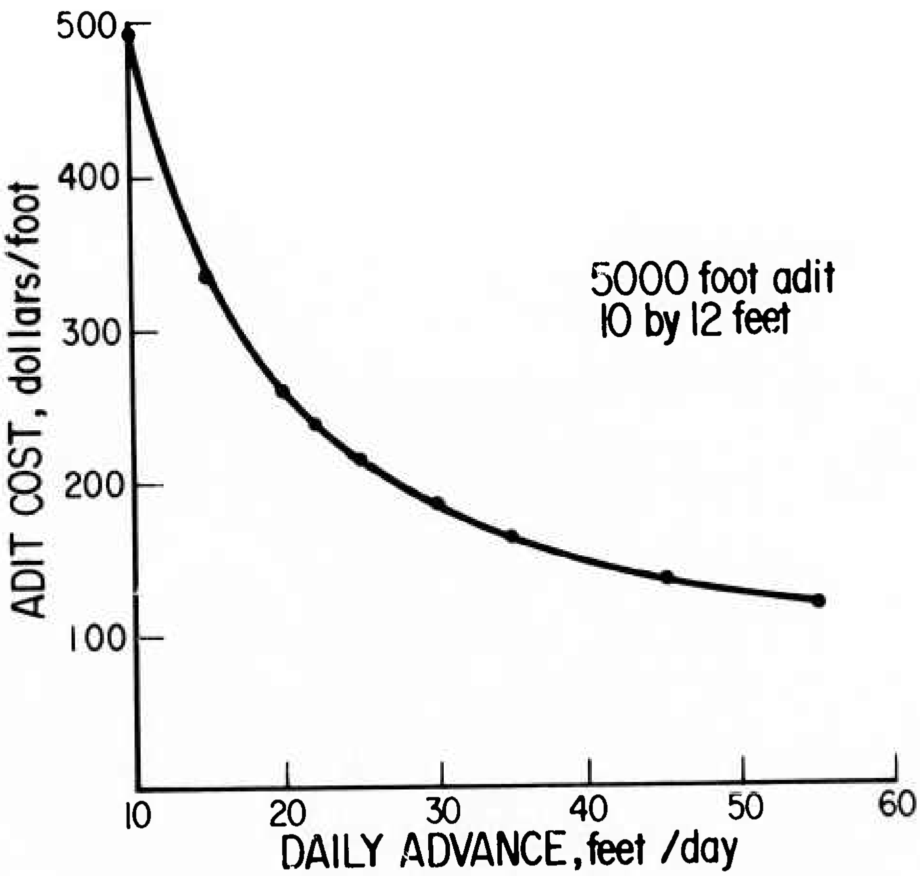
The tunneling data bank demonstrated by the BurMines could very easily be included in the ARPANET program. ARPANET is a nationwide computer network of over 25 computers began in 1969, and has been expanded by ARPA (4,23). Recently, the USGS has used the services of ARPANET to establish a nationwide geologic data bank called CRIB (7) . It is noteworthy that the International Union of Geologic Sciences, which is an outgrowth of many international conferences, has embarked on a program of International Geological Correlation Programs, called COGEODATA. To date, Canada is the first country to create a national system for the storage and retrieval of geophysical and geologic data. The NASA supported EROS program by the USGS has established a data bank of all remote sensing and satellite imagery.

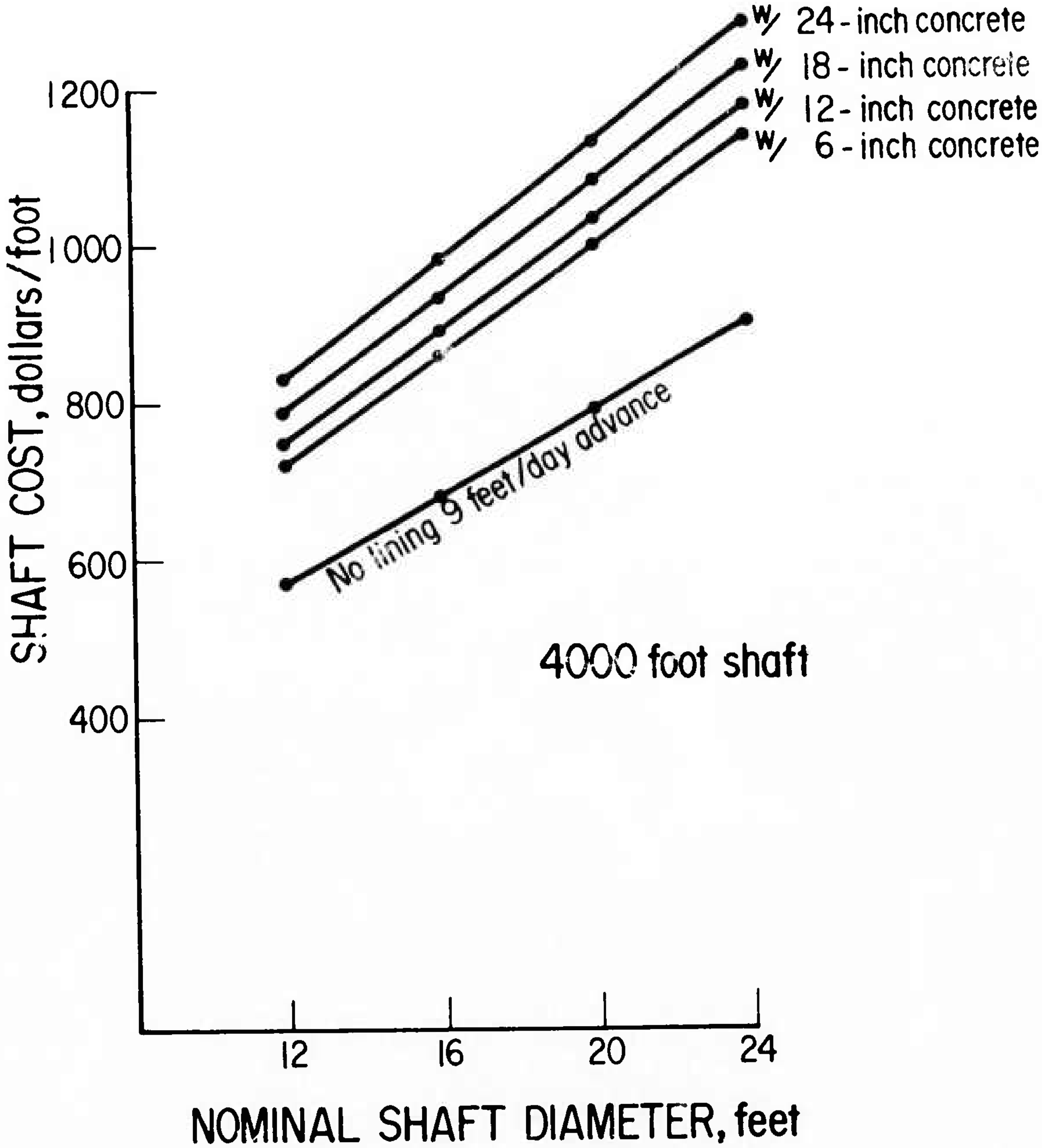
COMPUTER TUNNEL COST ESTIMATING - PROBLEM 3

A tunnel cost analysis program known as COHART was developed under contract to Harza by the Office of High Speed Ground Transportation, Department of Transportation (DoT). The reason that program was selected is because it is the only "public" program available. There are many such programs developed by private industry, but these are universally proprietary, or available at great cost. The COHART/Harza program was originally designed to have the capability to do in a single pass the entire northeast corridor rapid transit system. Up to 600 separate tunnel sections could be handled. Both tunnel sections and shaft sections can be handled simultaneously. It was originally programmed for the IBM 360; however, to make it applicable to CDC 3200 computer at SMRC considerable re-programing was required. Principally, these changes were as follows: (1) reduce the number of tunnel sections from 600 to 20; this was based on the CDC 3200 core requirements; (2) use extensive overlays for the number of calculation subroutines; and (3) to convert the entire 3308 card deck to binary coding, thus reducing the program deck to about 650 cards.

With this capability, evaluations were made on excavation and support costs. One extensive analysis was run for a 5000 foot long adit and a 4000 foot deep shaft project proposed in the Coeur d'Alenes. The parametric analysis included varying the type, thickness, and amount of support for various opening diameters. A projected cost/benefit analysis was then made using the extensive experience of mine operators. Two summary figures of typical COHART/BurMines results are shown in Figures 3 and 4. As stated, this example problem was formulated around a typical mining situation in the Coeur d'Alenes District. It was proposed that a 10 x 12 foot horseshoe adit be driven 5000 feet and then a 4000 foot shaft sunk. Typical conditions in the District were assumed, also muck was assumed simply dumped at the portal. With only 34 computer runs, averaging less than 3 minutes each, a very good definition of the project becomes available for management. Most important, the optimum rate of advance with which the adit and shaft must be sunk is clearly defined. Figure 5 shows typical shaft lining costs. The cost figures were based on no profit/overhead and with a labor cost index of 1.0. This was done to further parallel typical mining conditions. Discussion with the mine operator revealed that our costs were high, but this was believed due to the basic cost structuring differences between the


4000 foot depth
12 foot ϕ shaft, unlined
SHAFT COST, dollars/foot
800
600
400
200
6
9
12
15
18
21
DAILY ADVANCE, feet /day


5000 foot adit
10 by 12 feet
ADIT COST, dollars/foot
500
400
300
200
100
10
20
30
40
50
60
DAILY ADVANCE, feet /day



W/ 24 - inch concrete
W/ 18 - inch concrete
W/ 12 - inch concrete
W/ 6 - inch concrete
No lining 9 feet/day advance
4000 foot shaft
SHAFT COST, dollars/foot
1200
1000
800
600
400
12
16
20
24
NOMINAL SHAFT DIAMETER, feet

construction industry and the mining industry - that is, most mine construction is done by the mine operator's work force. The important conclusion is that an exceedingly high rate of advance is neither practical nor necessary. In the typical example, it is seen that for both the adit and shaft, rates of advance beyond certain limits do not cause correspondingly lower costs. This is directly due to the cost structuring of the project - labor, material, and equipment have fixed charge and write-off expense that cannot be decreased with increased rates of advance.

Costs based on the late 1960's are argued to have no relation to the present; however, the consensus is that tunneling costs have apparently been held within the general inflationary trend rather than to have grossly exceeded present inflation. Therefore, historic cost relations are generally valid but must be adjusted. COHART/BuMines tunneling cost program was also compared with shaft sinking costs for project DUSS, Deep Underground Survival Systems (8, Section 2.3.1.5, shaft costs pg. 2-108 to -112). Those cost estimates are shown in Table 4. The basis was a 6400 foot shaft sunk at 300 feet per month and in 20,25, and 35 foot diameters. Table 4 shows that COHART provides a favorable cost comparison.

A summary of tunneling costs was also published in 1959, by the California Department of Water Resources (6). That study was based on 99 tunnels in southern and northern California. In general, the cost per linear foot of a tunnel varies with the geographic location, rock conditions, length, diameter, amount of construction activity throughout the country at the time

Table 4. - Comparison of Shaft Cost Estimates, Millions $.

Source of Estimate	Shaft Diameter, feet 20	25	35	Advance Rate [1]
Cohart [2]	8.5			10 ft/day
J. S. Redpath [3]	8.0 - 9.6			10 to 13.3 ft/day
Mining Eng. Con.[5]	8.25			10 ft/day (min.)
Cohart		10.1		
Jacobs [4]		10.2		14.6 ft/day
Cohart			17.2	
Jacobs			19.4	10 ft/day

1. Based on 6400 foot shaft and 300 feet per month advance rate.

2. COHART by Harza Eng. Company, 150 South Wacker Drive, Chicago, Illinois 60606

3. J.S. Redpath, Ltd., 347 Sherbrooke St., North Bay, Ontario, Canada

4. Jacobs Associates, 500 Sansome, San Francisco, California 94111

5. Mining Eng. Consultants, Intercontinental (Pty) Ltd. of Johannesburg, South Africa

of bid, and many other factors. It is absolutely necessary to have a knowledge of the geology, and in particular the ground water conditions, in preparing cost estimates. Basically, the cost can be broken down into a size factor and a geologic factor.

The California report, based on 99 tunnels, examined tunnel sizes between 9 and 24 feet with circular and horseshoe section. Cost indices were based on 1957, with 15 percent profit and 25 percent contingencies, and proportioned as 55 percent labor, 25 percent equipment and 20 percent materials. Steel price was 25¢ pound. Steel supported tunnels cost about 25 to 60 percent more than unsupported tunnels.

SMRC reviewed the above data and a scaled cost relationship 3/ was developed from this data for diameters between 12 and 24 feet. The scaled cost relations are simply for the total cost of tunnel excavation, unlined, dry headings, as follows:

Stratified or Schistose Rock

$$\$/ft = 15.33\ (\text{diameter})^{1.073}$$

Moderately Jointed or Intact

$$\$/ft = 17.86\ (\text{diameter})^{1.070}$$

Moderately Blocky and Seamy

$$\$/ft = 15.24\ (\text{diameter})^{1.092}$$

Very Blocky and Seamy

$$\$/ft = 13.74\ (\text{diameter})^{1.140}$$

Completely Crushed and/or Unconsolidated Rock

$$\$/ft = 4.24\ (\text{diameter})^{1.750}$$

3/ A common industry practice in cost estimating is to log-log plot equipment capacity versus cost in order to obtain projected costs for larger-sized equipment. A great amount of equipment has been shown to follow the "six-tenths" law.

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