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13. ABSTRACT

A method of predicting subsurface conditions for future tunnel construction is developed. It describes and rates the rock structure on basis of its need for support in close proximity to the working face. The concept, designated the rock structure rating (RSR) utilizes geologic data and information which could be made available for consideration in the pre-construction period. Methods and techniques used in making geological investigations for tunnel construction are discussed.

Correlation between predicted RSR values and actual support installation was accomplished by researching 33 case history tunnel projects. A method, called the rib ratio (RR) concept, was developed by which actual steel rib support installations could be compared on a common basis. Numerical relationships between RSR values, RR's, steel rib support and rock loads are established. The RR concept is expanded to include rock bolt and shotcrete support. Support Requirement Charts are presented which identifies appropriate support systems for different sized tunnels driven through various types of rock structures.

New concepts of ground support are investigated and evaluations made as to most likely candidates for improving rapid excavation technology.

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RESEARCH IN GROUND SUPPORT AND ITS EVALUATION FOR COORDINATION WITH RAPID EXCAVATION

by

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PREFACE

This report on various aspects of ground support determinations for rock tunnels has been prepared by Jacobs Associates in accordance with terms of Contract No. H0210038 dated February 1971 with the Bureau of Mines, Department of the Interior.

It is part of ARPA's Military Geophysics program directed toward research and study of the relationship between methods of predicting ground support requirements and the actual installation of support in proximity of the face during tunnel construction. All concepts and methodologies are considered with respect to advancement of "Rapid Excavation" technology.

The Contracting Officer is Mr. Alan Granruth of the Bureau of Mines, Denver Federal Center, and the Project Officer is Mr. E. H. Skinner, Spokane Mining Research Laboratory. Their cooperation was most helpful in conducting the research effort. Appreciation is also expressed to different government and private agencies who provided historical data and records used in developing the methods and procedures proposed herein.

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INTRODUCTION

The need to improve underground excavation techniques has been the subject of discussion for many years, but only recently have specific requirements and goals been defined. One such instance is the National Academy of Sciences' publication "Rapid Excavation-Significance-Needs-Opportunities" submitted in 1968. It sets forth various goals, recommendations and guide lines for continued research which could materially improve the art of tunneling. Two general areas of concern outlined in that report are 1) Development of geological techniques for determining rock and ground-water conditions prior to excavation operations and 2) Improvement of processes for producing temporary support, in a wide range of rock-mass conditions, at speeds compatible with advance tunneling machines.

The research effort performed and discussed in this report is directed toward the development and improvement of methods and procedures pertinent to the above two problem areas. The report includes consideration of 1) Geologic and ground support data pertaining to selected previous tunnel construction; 2) Methods of predicting subsurface conditions; 3) Correlation of geologic predictions and ground support systems; 4) New ground support concepts and 5) Various cost evaluations of the overall tunneling process. Developed methodologies, comments and remarks are oriented toward the practical aspects of present day tunnel construction.

SUMMARY

A method of predicting subsurface conditions based on pre-construction geologic data is developed. This prediction method, referred to as the Rock Structure Rating (RSR), is subsequently related to different support systems which would satisfy the ground support requirements for most rock tunnels. This correlation is made by use of the Rib Ratio (RR) concept which compares and relates various support systems to a common datum or support requirement. New support concepts are investigated on basis of their adaptability to underground rapid excavation. Economic evaluations are made for several tunneling situations using either conventional or innovative support systems.

FACTORS AFFECTING GROUND SUPPORT

The first section of the report deals with various geologic and construction factors which affect the rock structure and which are usually or could be made available for consideration in the pre-construction period. The different factors are identified and their individual or combined relative effect on support requirements indicated. Existing techniques or methods used to obtain geologic information for tunnel construction are discussed and comments made as to their sufficiency and reliability.

ROCK STRUCTURE RATING

Ground support requirements are dependent on the condition or quality of the rock structure through which a tunnel is driven. Using geologic factors previously defined, an empirical prediction method (RSR) is developed by which a rock structure can be rated with respect to its need for support. This concept, which reflects requirements of the several involved disciplines and historical data pertaining to tunnel construction, is adaptable to modification

as may be determined from continued research or future experience.

CASE HISTROY STUDIES

Records and data of 33 previously constructed tunnels were studied. The chosen case history projects included various tunnel sizes, support systems and methods of excavation. Emphasis was placed on obtaining information pertaining to both pre-construction and as-built geology and actual support installations. An RSR value was determined for each case history tunnel or portion thereof which could be analyzed as a separate geological section.

CORRELATION OF ROCK STRUCTURE RATING AND GROUND SUPPORT

The primary support member used in most of the case histroy projects was the steel rib. To correlate the actual support installation with RSR values, it was necessary to develop a common basis of comparison. This was accomplished by the rib ratio (RR) concept which relates the actual installation to a theoretical rib spacing which would have been required if used in a soft ground tunnel section (datum condition). The concept considers Terzaghi's empirical equations, rock loads etc.

RSR values and corresponding rib ratios were determined and plotted for approximately 100 case history sample tunnel sections. An equation for the average curve of all plotted points was used to establish the numerical relationship between rock structure ratings, steel rib support and rock loads. The concept was expanded to include rock bolt and shotcrete support systems.

Support Requirement Charts were prepared which identifies those systems that would satisfy the support requirement for different sized tunnels driven through various types of rock structures.

GEOLOGIC INVESTIGATIONS - AREAS OF IMPROVEMENT

The current state-of-the-art for making geologic investigations is discussed and potential areas of improvement are suggested. Many recent improvements are due to efforts of the mining and petroleum industries. Most of their developed techniques are fairly specialized and oriented toward the delineation of mineral deposits rather than rock structural properties for design purposes. Seismic investigation from both bore holes and tunnel headings have possible, though limited, present potential. Improved techniques in long hole horizontal drilling can add a new dimension to borings. The greatest potential for improvement seems to be in the area of increased awareness of the need for standardization and definition of terms, methods and goals; of acquiring, storing and disseminating geologic data needed for the prediction of ground support requirements.

DETERMINATION OF SUPPORT REQUIREMENTS FOR HYPOTHETICAL TUNNEL

A hypothetical tunnel situation is used to illustrate the RSR concept in predicting ground support requirements. The simulated tunnel covers a wide range of rock conditions from hard massive granite to soft, water bearing sandstone. Appropriate support systems for each rock condition are identified from Support Requirement Charts. The model is used also to demonstrate the type of geologic data needed to make RSR evaluations. Both drill and blast and boring machine methods of excavation are considered.

NEW CONCEPTS OF GROUND SUPPORT

Sixteen new concepts of ground support are described and illustrated. Some have been conceived by others, some are parallel or similar to ideas being developed by others, and several are a direct outgrowth of the research study. The basic requirement or consideration in developing the support concepts was their potentiality of fulfilling the need of an optimum support system compatible with current and anticipated rapid rates of underground excavation. Some of the concepts could be used today, others would require considerable development and research. They include support systems using new materials; new uses for existing materials; mechanical supports and new mechanical methods for placing or installation. In all instances, the support is considered placed as close as possible to the tunnel face. The concepts do not involve permanent lining except those where the initial ground support serves a dual purpose.

The concepts were evaluated and compared with respect to eight basic parameters which reflect requirements of the overall tunneling system. Advantages and disadvantages are discussed. An economic analysis considering the total tunneling process was subsequently made for five of the most promising concepts.

COST EVALUATION OF SUPPORT SYSTEMS

The relative effect and dependency of different tunneling sub-systems, cost components, daily rates of advance and costs per lineal foot of tunnel are discussed. Economic evaluations, based on costing procedures used in the construction industry, are given for several tunneling situations. Each support situation reflects a different rock structure and the use of either a conventional or innovative support system which would satisfy the support requirement. Both drill and blast and boring machine methods of excavation are considered. The evaluations identify the support system which would provide most optimum solution of the tunneling process with respect to the predicted rock structure rating.

SPECIAL COMMENTS

The research effort consisted primarily of an investigation and study of 33 previously constructed tunnel projects and a general review of current literature and methods dealing with tunnel geology and ground support determinations. Within the limit of present-day technologies, prediction of subsurface geologic conditions and subsequent determination of adequate support systems depends to a large extent on personal judgement and empirical evaluations of various geologic and construction factors which affect ground support requirements. A major problem in this respect is the lack of pertinent historical data which can be used to define and relate predicted geology with actual support installations. This particular problem will continue unless definite efforts are made to: 1) standardize requirements or criteria to be used in obtaining, recording and interpreting geological information for future tunnel construction and 2) establish a uniform as-built format to be used in recording actual construction conditions. The findings and results of the research effort; the RSR and RR concepts, provide the methodology by which this could be accomplished. Effective implementation will require the cooperation and general acceptance of the methods by the several disciplines involved in tunnel construction. Existing techniques used in making tunnel site geological investigations must have improved capability to give more reliable information pertaining to the overall predominate rock structure as opposed to isolated locations along the tunnel alignment.

Considered one of the most promising candidates in this respect is the development of long-hole horizontal drilling techniques. At the present time there appears to be no new support material or member which would fulfill the requirement of an optimum support system. Movable mechanical supports or automated mechanical concepts utilizing rock bolts or shotcrete have the largest potential of improving the tunneling process. Data obtained from in situ testing or laboratory expirements must be realistically correlated with some method of geologic prediction to be of help in the development of underground rapid excavation.

ARPA RECOMMENDATIONS

Achieving the ARPA goals of underground rapid excavation requires the development of 1) a more reliable method of predicting subsurface conditions and 2) an adequate ground support system which can be installed with little or no reduction in the anticipated heading advance rate which could be achieved in an unsupported tunnel. It is recommended that additional studies be undertaken to expand and verify the RSR and RR concepts of determining ground support requirements based on geologic predictions. The effort must be directed toward ultimate acceptance by the tunnel construction industry of a uniform and practical approach to the problem of support determinations. It is also recommended that several of the developed new concepts of ground support be further evaluated with respect to their adaptability to rapid excavation.

SECTION I

FACTORS AFFECTING GROUND SUPPORT

1.1 INTRODUCTION

Predicting the need, and providing adequate and economical ground support systems for tunnels, is one of the main problems in achieving the goal of underground rapid excavation. Although this problem has been faced in the construction of every tunnel, no specific or even general solution has been advanced which might be applicable to all. Individual solutions have been reached, either with respect to specific ground conditions encountered or predicted during tunnel excavation or with respect to applicable contract stipulations and construction requirements. There is no question that in many instances certain geological factors and work conditions, common to many, were similarly evaluated in arriving at the individual solutions.

The purpose of this section is to define and/or specify those factors which are most relevant to the determination of ground support requirements and which are usually, or could be made available for consideration in the planning of future tunnel projects. These factors will be used in subsequent sections of this report to describe the rock structure through which a tunnel is to be driven and which in turn is related to support requirements.

Factors pertinent to ground support determinations can be grouped into two general categories:

1. Geologic Parameters
2. Construction Parameters

It would be impractical, if not impossible, to consider all possible combinations of the two. Consequently, this section is directed toward the general identification of ground support factors related to typical civil works, single bore tunnels driven through fair to good rock structures. This classification will include the vast majority of future tunnels in which ground support would present a problem. Tunnels driven through soft ground formations can generally be assumed to require continuous support throughout. Very little or no support would be expected for tunnels driven through "excellent rock" structures. Both conventional drill and blast and boring machine methods of excavation are considered in this report. The term "ground support" implies rock support and/or reinforcement placed in close proximity of the working face.

1.2 GEOLOGIC PARAMETERS

As used herein, geologic parameters pertain to those factors affecting the quality or condition of the rock structure which could be ascertained by present day methods of geological investigations or laboratory testing procedures. No attempt is made to delve into the science of either geology or rock mechanics, but rather, only to use and relate such knowledge to the prediction of ground support in terms compatible with tunnel construction. Any new method or proposed standard procedure of identifying or predicting subsurface conditions by means of designated parameters must depend to a large extent on the personal judgement, experience and evaluation of those involved in tunnel construction and engineering geology. The validity or modification of any such method would be determined by results obtained from actual experience and use of the method.

Geologic factors considered in this study are discussed breifly in the following paragraphs. All have been extensively analyzed and evaluated with respect to ground support requirements in many previously published technical documents and books. (See appendix for references). The factors are:

1. Rock types
2. Joint pattern (spacing and condition)
3. Dip and strike
4. Discontinuities
5. Faults, shears, folds, etc.
6. Ground water
7. Rock material properties
8 Weathering or alteration
9. Overburden depth

Some of the factors can be treated separately; others must be considered collectively to properly define a condition which would affect ground support requirements. The list could be expanded or condensed to reflect the rock structure properties for a particular project. In some instances, it would be possible to accurately define the factors; in others, only general approximations can be made.

1.2.1 Rock Types

Probably the most generally used single descriptor of a rock structure has been "rock type". This term embraces a wide variety of geological factors ranging from basic rock formations; igneous, sedimentary and metamorphic, to specific properties such as texture and structure, mineralogical composition, chemical composition, age and origin, anisotropy, degree of alterations, hardness etc. Predicting rock behavoir during tunnel excavation requires fundamental knowledge and evaluation of the physical occurrence and relative mix of these factors. Unfortunately, such evaluations can only be approximated in the pre-construction period. Ground support determinations made from appraisal of cores or drillers logs are not necessarily typical of the overall rock mass; nor in some cases, even indicative of the rock's behavior in a large tunnel opening. As-built geology or in-situ testing data provide useful information which can be used in associating rock types with support requirements for future work but is of little help in the initial planning or driving of the tunnel.

Regardless of the limitations and obvious discrepancies in evaluation, the combined relative effect of many different rock properties has often been categorized and used as a basis for classifying "rock types" with respect to support requirements. The general terms of "good", "fair", or "poor" tunneling ground are typical examples. They are applicable to all rock types and in general infer similar support requirements. A tunnel driven through either "good" granite or "good" sandstone would probably require little or no support.

Different mechanical or engineering properties of rock material, such as compressive strength and modulus of elasticity can also be grouped or approximated by rock types. Although these properties usually reflect the mechanical behavior of homogeneous specimens obtained in the laboratory, they are indicative and helpful in the overall determination of tunnel supports. Mechanical properties of rock are usually described in relative terms such as "hard", "medium" or "soft", each implying a general range of values and conditions depending on rock type. The compressive strength of a "hard" quartzite may be over 30,000 psi, that of a "hard" sandstone only 18,000 psi. In either case, supports may or may not be required depending on other geologic factors affecting the rock structure. The feasibility of using present day boring machines is directly related to the compressive strength, hardness and other properties of the rock material to be cut. This will be discussed later in conjunction with construction parameters.

1.2.2 Discontinuities

Any structural or geological feature that changes or alters the homogeneity of a rock mass can be considered as a discontinuity. There are many different types or classes of discontinuities, any one or all of which could be critical in determining ground support requirements. As used herein the term is applied to faults, shears, bedding and foliation surfaces or other similar surfaces caused by movement or displacement. Associated strikes, dips and joint patterns are discussed in paragraph 1.2.3.

The effect on the surrounding rock masses due to these localized discontinuities varies considerably over any given region depending on the origin or formation of the particular structure. In most cases it is possible to at least approximate the extent and degree of geologic disturbance by review of historical data or surface geology. Some regions, such as the Coastal Range in California, are intensely folded or faulted; others like the Sierra Nevada foothills are usually massive in structure. General terms such as massive, intensely folded, etc. can be used to help describe the overall rock structure through which a tunnel is to be driven.

A massive formation may be cut by one or more major fault zones, each varying in width from a few feet to several hundreds of feet. Support would probably be required in those sections of a tunnel passing through or near the fault zones, while the remainder of the tunnel may require little or no support. In other cases a tunnel may be driven through various types of discontinuities with no apparent change in either the rock's behavior or support requirements.

1.2.3 Joint Pattern

All tunnels will be driven through a rock structure which has been fractured to some degree by discontinuities and/or internal stresses within the rock mass. This condition can be described in terms of average spacing (or size) and orientation (dip and strike) of individual blocks of rock caused by the fracturing process. It is commonly referred to as the "joint pattern" and is the most difficult and probably the most critical factor to appraise with respect to predicting support requirements.

Some evaluation or description of the joint pattern is used in most technical analysis of tunnel support and to a certain extent in the determination of actual installation of support during tunnel construction. Factors considered range from experimentally obtained values or parameters derived from theoretical mechanisms of deformation and failure of jointed rock masses to empirical evaluations obtained from construction of tunnels in similar rock structures. In addition to defining the geometric dimensions of the joint pattern, it is necessary also to evaluate jointing with respect to the condition of the joint surfaces, tunnel size, direction of drive and method of excavation. Each of the many combinations of these factors, might dictate individually different support requirements.

1.2.4 Ground Water

The effect of ground water on support requirements and tunnel construction varies with respect to other geologic conditions such as weathering or alteration of the rock structure, joint filler or condition of joint surfaces and depth of cover. Probably the most difficult support situation which can be experienced in tunnel driving occurs where heavy inflows under high pressures are encountered in conjunction with adverse rock properties. Many tunnels however, have penetrated heavy inflow formations with little difficulty with respect to ground support. Potential ground water sources or inflows can be estimated from surface hydrology, topographic maps, ground water studies, drawn down curves for local wells and vegetation. In some areas consideration should be made of seasonal rainfalls.

1.3 SOURCES OF GEOLOGIC INFORMATION

There are usually several sources and types of geological investigations which would provide information pertinent to the problem of identifying and describing different geologic factors. The quantity and quality of such information varies for each particular project and to a certain extent with repsect to general policies of the contracting agency or owner. All geologic data pertaining to the area should be considered in making predicitions of ground support requirements. Typical sources are discussed in the following paragraphs.

1.3.1 Historical Geology

An overall appraisal of subsurface conditions can be made by review of the historical geology for the region. Most areas in which tunnels within the continental United States are driven will probably have been mapped or investigated in some detail by the U.S. Geological Survey or other governmental or private agencies or individuals. Previous underground construction or well-drilling data may also be available and should be considered. Types of information likely to be included are the following:

1. Origin and sequence of geological formations.
2. Lithology of predominant rock types.
3. Extent and degree of various discontinuities-faults, shears, etc.
4. Weathering or alteration.
5. Hydrology.

For some projects, historical geology is the primary source of information on which to base predictions of ground support requirements. Reliability depends upon the extent and detail of information provided for the particular region. All interpretations made from historical data require an estimate of the probability of encountering different rock formations during the tunnel construction. Bledsoe (Reference 1) has indicated a procedure which may help. He relates a hypothetical probability of geological occurrence with expected duration or increments of length of different rock types which may be anticipated along the tunnel alignment. A similar analysis could be developed for specific regions and used in conjunction with available geological data. Indications of potential ground water inflows and hydrostatic pressures can usually be approximated from study of historical geology.

1.3.2 Surface Geology

The most reliable and complete source of information on which to base support predictions is surface geology or mapping in the vicinity of the tunnel alignment. Some form or degree of surface geology must be provided for all projects, either prepared by the owner or the individual contractor. The extent of detail is usually limited by economics and/or physical conditions of the site such as topography and ground cover. Although aerial photography and other recent techniques are being used to expand and compliment surface geologic information, the basic responsibility still rests with the engineering geologist who makes the survey. Both quantitative and qualitative information of all geologic factors could be provided or indicated by a thorough surface investigation. Due to various legal and other considerations, extrapolating surface features to tunnel grade is often left to the contractor. In certain areas, this extrapolation is fairly straightforward, in others, very complicated. Borings, outcrops, surface cuts, rock cliffs and other topographic features will all help in making projections to grade. Tunnel support requirements are usually determined with respect to a geological profile along the tunnel line which has been developed from surface geology.

Evaluations of subsurface conditions made by the individual contractor during his site investigation are based on, or are related to, data contained in the surface geology report.

1.3.3 Borings

Physical or visual evaluation of subsurface conditions can only be made from core samples obtained from borings. The many restrictions or limitations, both as to economics and interpretations of core logs, are well known. Improved techniques of long-hole horizontal drilling may greatly increase the scope and value of bore-hole information which could be provided for future tunnels.

Many vertical borings are made to verify the projection of localized major discontinuities to tunnel grade. Although this practice helps to determine the extent and type of support which might be required for a particular stretch of tunnel, (oftentimes only a very small percent of the total length) it seldom provides information which could be used in making a comprehensive overall evaluation of predominant rock structure. Borings made in the vicinity of the portals are useful but not greatly beneficial with respect to the overall project. In predicting ground supports it is generally assumed that the first several hundred feet of tunnel from the portals would need support. This assumption would not materially affect the total support requirement. The above discussion is not intended to minimize the value of borings, but rather to indicate the potential advantages and disadvantages in using different criteria to determine bore hole locations.

A visual inspection or analysis of a core enables the contractor to better correlate geological definitions and terminology used to describe the rock structure with respect to physical properties and conditions of the rock. This correlation is essential due to large discrepancies in interpretation and meaning of typical geological information. A "friable sandstone" could be described in many ways, none of which would be as meaningful as appraisals made from a physical examination of a typical core sample.

1.3.4 Laboratory Testing

Some recent tunnel site investigations have included results of laboratory analysis of different physical-mechanical properties of the rock. This type of lab test information is more important in considering the overall feasibility of using a boring machine than it is to the actual determination of ground support requirements. It does, however, provide indications of possible rock behavior during tunnel construction.

As the science of jointed rock mechanics improves, it is likely that more pertinent ground support information can be provided by laboratory or in-situ analysis of rock properties.

1.3.5 Other Investigations

Various geoplysical methods such as seismic, electrical resistivity, magnetometers and gravimeters have been and are being used in tunnel site investigations. However, with the exception of determining depth of overburden or top of rock, present methods have limited applications with respect to prediciting subsurface conditions for tunnel support along the tunnel profile.

A potential goal would be to develop a geophysical technique, either seismic or sonic, by which it would be possible to rate or evaluate rock structure at grade between bore holes located at one or two mile intervals along the tunnel line. Even if the ratings were only of a relative nature, such as "as good as" or "worse than", they would be helpful in predicting ground supports. Standard of comparison could be the rock encountered in the respective bore holes or other common datum. Correlation of test data with actual ground conditions encountered during construction may eventually provide a reasonable basis of measure. Similar techniques have been recently used in successfully determining the rippability of rock.

1.4 CONSTRUCTION PARAMETERS

The effect of most geologic factors on support requirements depends also on construction conditions or parameters including the following:

1. Size of tunnel
2. Direction of drive
3. Method of excavation

Considerations of stress relief or stand-up time are not included in the scope of this study. All supports are assumed to be installed immediately after the excavation or behind the boring machine. The effect of contract stipulations and safety requirements are treated spearately.

The purpose and general location of the tunnel, specified by the owner or designer, dictate the size and usually the direction of drive. Method of excavation, either conventional drill and blast or boring machine, depends primarily on the physical properties of the rock material. Economic limitations imposed on the use of boring machines, either due to size or length of tunnel are becoming less significant with recent improvements in machine design and adaptability.

1.4.1 Size of Tunnel

The most important construction parameter is the size of tunnel opening. A small tunnel driven through fairly poor quality rock may require little or no support whereas a large size tunnel driven through the same rock structure may require heavy support.

All determinations of ground support requirements must take into account the size of the tunnel opening. How these determinations are made depends on the discipline involved. The designer might base his conclusions on a theoretical analysis of such factors as the ratio of joint spacing to tunnel diameter, the anticipated arching action of the rock, or rock load; the constructor's decision might be strictly a rule-of-thumb evaluation wherein nothing less than a 6" WF rib would be used in, say, a 12-foot tunnel. Both solutions or approaches have been used and probably each could be substantiated by reference to a specific type of rock structure and tunnel size.

Although it may be possible to make detailed analysis applicable to small increments of size, this study considers tunnels in the general range of 10, 14, 20, 24 and 30 foot diameters. This is due to the fact that pre-construction geology is usually so general in nature that it would be impractical to try to differentiate support requirements for small variations in tunnel size.

1.4.2 Direction of Drive

Direction of drive can be described with respect to both tunnel grade and the strike and dip of the rock structure. Although driving up or down grade does not in itself alter support requirements, it does influence the overall tunneling process, especially in areas of heavy ground water inflows. Such a condition should be considered in tunnel construction, but for purposes of this study, direction of drive will relate only to the strike and dip of the rock structure. Formations with strikes parallel or sub-parallel to the longitudinal axis of the tunnel are not affected as much by direction of drive as are those which are perpendicular to the axis. In both instances, it is necessary to consider the corresponding dip and joint pattern of the rock. The evaluation of the combined relative effect of strike, dip, joint pattern and direction of drive is probably the most critical decision to be made with respect to support determinations for any particular size tunnel. General approximations, such as the "best" or "worst" condition, can be made with respect to direction of drive by considering different combinations of these factors within certain limits of measure. For example, steeply dipping joints (60° - 90°) which lie parallel to the tunnel axis would have a more adverse effect on support requirements than parallel joints dipping at say 30°, regardless of direction of drive. On the other hand, the condition caused by rocks dipping at 45° and lying perpendicular to the axis would vary with respect to direction of drive, either against or with the dip. In the first instance, the rock would have a tendency to fall into the tunnel opeining, in the latter, the face would confine the rock. Eight different combinations of strike, dip and direction of drive are considered in this study, each with respect to various joint spacings. (See Figure 2.3)

1.4.3 Method of Excavation

Any method used to excavate a tunnel will cause some disturbance of the surrounding rock structure which, in turn, will affect support requirements. A measure of this disturbance might be made in terms of either the actual physical damage to the rock or by various stress relief calculations. In either case, it would be very difficult to distinguish between the "before" and "after" conditions which may or may not have had an effect on ground support. The actual loosening and fracturing of rock caused by blasting is more often reflected as "overbreak" than in additional support requirements. Some formations that appear to be stable after initial penetration by either conventional or machine methods may subsequently require support.

It is generally concluded that a machine driven tunnel will require less support than one driven by conventional methods. As more tunnels are constructed by use of the boring machine, it may be possible to make an empirical evaluation of different support requirements occasioned by the two methods of excavation. Such an evaluation could indicate either the increased amount of support required when using drill and blast method or could relate to the increased stability or quality of the surrounding rock structure resulting from use of a boring machine. The latter possibility has been considered for this study.

1.4.4 Contract and Safety Requirements

The difficulty of predicting ground support requirements is further complicated by the more or less intangible effects of various contract stipulations and safety regulations. Current practices have evolved over a period of years and presently are reflected as integral and important aspects of the competitive bid process by which most tunnels are constructed. Although there is no "standard" contract document, the general trend has been to try and limit, insofar as possible, excessive use of supports over and above the given bid quantity. This is usually expressed in various "responsibility clauses" and "price stipulations" which assume that the given bid quantity does in fact represent the actual support need. The effect of these contract requirements or the question as to whether or not supports are required, is most critical for those tunnels driven through fair to good rock structures. Many decisions regarding this matter are based more on considerations of actual or potential safety hazards than on engineering analysis of rock properties. This is especially true in larger size tunnels where minor spalling or slacking of the rock could have serious consequences.

The designer of any structure is charged with the responsibility of providing an appropriate solution at the least possible expense. Unfortunately, tunnel supports do not lend themselves to specific determinations normally needed to fulfill this assignment, but rather must be evaluated with respect to the total tunneling process including consideration of 1) material cost of the support member, 2) cost of installation, and 3) possible reductions in optimum advance rates. The relative effect or evaluation of these factors is constantly changing due to ever-increasing labor costs and improvements in tunneling techniques.

Optimum advance rates in either supported or unsupported tunnel sections require a continuous, repetitive sequence of all necessary operations. Frequent change in operations or cycles, in an effort to reduce total quantities of support or to adapt a specific support member to a particular rock condition, have been found to often lead to greater cost without materially improving the tunnel structure.

In light of the above, it may be advisable to reconsider present rationale of trying to limit actual quantities of support. For example, a specified continuous support system, even though over-designed for portions of the tunnel, but which could be installed with little or no reduction in optimum advance rates, might well prove to be most advantageous. In such case, the bid documents might specify the maximum quantity of support (continuous support) and possibly provide for incentives or bonuses for any reduction experienced during construction.

These comments will not resolve the problem of contract stipulations regarding support requirements but may indicate possible alternatives for consideration. No special allowance for this factor is made in this study other than to recognize its possible influence when correlating geology and actual support installations discussed in subsequent sections.

1.5 CONCLUSIONS

Predicting ground support requirements for future tunnels involves the consideration of many factors. Although they can be categorized in general terms, it is obvious that final determinations depend to a large extent on empirical and personal evaluations of their combined relative effect on the rock structure. This is due not only to the infinite variations of possible occurrence and extent of geologic factors but also to the limitations imposed by present day techniques of making geological investigations. The problem is further complicated by contract ural and safety requirements pertaining to tunnel construction.

The various factors and considerations discussed in the preceding paragraphs are not all-inclusive and probably are somewhat different than those which might be specified by other disciplines. However, they do relate to those basic evaluations which must be made in predicting ground support requirements. In general they can be determined or appraised by use of present-day methods of geological investigations.

SECTION 2

ROCK STRUCTURE RATING

2.1 INTRODUCTION

Various geological factors considered in making predictions of ground support requirements are discussed in Section 1. They basically describe the quality of a "rock structure" which in turn dictates the need for ground support. With respect to tunneling, general evaluations of those factors range from such descriptive words as "good" or "bad" to fairly detailed technical descriptions based on geological and experimental analysis. Many seemingly discrepancies in both terminology and meaning can be attributed to different disciplines involved in tunnel construction, i.e. the contractor, the engineer and the geologist. Each discipline offers significant contributions to the overall solution of the support problem and in many instances, similar answers are obtained even though different approaches to the problem may have been used. Relating qualitative descriptions of different geologic factors and properties to a common criteria has posed a problem for many years. Terzaghi's Rock Classification System and more recently, the RQD index proposed by Deere are examples of such classifications. Descriptive terms as used in Terzaghi's classification have different meanings to both engineers and geologists. The RQD index qualifies, by means of numerical ratings, a specific geological factor as observed from core analysis. In one form or other, these and other methods of appraising geologic factors have been used by individuals responsible for predicting ground support for all tunnels.

This section of the report develops a methodology by which a rock structure can be rated with respect to its need for ground support. It is referred to as the Rock Structure Rating (RSR) and is determined by evaluating and weighting, within certain limits of measure and engineering judgement, the relative effect on support requirements of pertinent geologic factors.

The nature of the problem and the type of data available for consideration requires an approach which must be general in scope yet specific enough to provide realistic solutions. It must relate to the overall rock structure as opposed to isolated locations along the tunnel line and must be capable of conveying the same meaning to different disciplines. The intent is not to define the need for a specific support member but rather to make a general appraisal of a support system which would afford most optimum solution to the tunneling process.

It is realized that in some instances supports have been installed for reasons not directly related to ground conditions. The effect of this and other construction parameters are discussed in Section 4.

2.2 ROCK STRUCTURE RATING

All geologic factors contribute to or affect the description and condition of the rock structure. Each can be considered individually within a range of possible occurrence and collectively with respect to their relative effect on each other. For instance, a rock may be described in terms of hardness: such as compressive strength, Mohs scale or other analogies and also in terms of various joint or fracture patterns. An overall evaluation must consider both conditions and the relative mix of each. By assigning reasonable limits of measure and rating each factor by a weighted numerical value, it is possible to define and rank the rock structure with respect to support requirements. This could be accomplished in many ways, depending on individual preferences and judgments, method of approach and ultimate goals. Within limits of present-day technologies, a more-or-less empirical approach would be required in all cases.

Two basic methods and variations thereof were considered in this study. In method #1, the geologic factors were treated individually; method #2 combined the same factors into general parameters for evaluation. Both provide a numerical RSR value by evaluating and ranking the relative effect on ground support requirements of those factors likely to be available for consideration in the pre-construction period. The final RSR rating being the sum of weighted values determined for the individual factors or parameters. The higher numbers reflecting "good" ground conditions wherein little or no support would be required, the lower numbers indicating various degrees of heavier support requirements. Figure 2.1 is a graphic presentation of the two methods and variations considered. It illustrates the empirical approach to the problem and shows how method #2 evolved from original concepts.

Formats, limits of measure and weighted values assigned to applicable factors were established for the different methods and used in analyzing, recording and evaluating geologic data obtained from case history studies. In some instances, pre-construction geology was either not available or of such a general nature that it was not possible to make reasonable evaluations. In other instances, detailed as-built geology was available and therefore was used in determining the RSR values. As the study progressed, the original formats and assigned values were revised to more nearly reflect the data and findings of the research effort. RSR values as determined by the several methods were compared and subsequently correlated with actual ground support used in the respective tunnels. These comparisons and evaluation of results, in conjunction with other information obtained from case studies, were used in finalizing RSR method #2 which is proposed in this study.

The general procedure and concept followed in determining rock structure ratings by the two different methods is discussed below. Method #1 is included

DEVELOPMENT OF

ROCK STRUCTURE RATING CONCEPT

RT - Rock Type

CA - Core Analysis

SV - Seismic Velocity Ratio (Reference 2)

JO - Joint Orientation (Dip & Strike)

RF - Rock Mass Folding & Discontinuities

MF - Major Faults

JS - Joint Seal

CT - Cover Over Tunnel

WF - Water Flow

RM - Rock Modulus Ratio (Reference 2)

RH - Rock Hardness

JP - Joint Pattern (Spacing)

RSR #1

PARAMETERS	MAX. VALUE
RT ←→ CA	30
+ RT ←→ SV	13
+ RT ←→ JO	9
+ RT ←→ RF	14
+ RT ←→ MF	13
+ RT ←→ JS	3
+ RT ←→ CT	2
+ RT ←→ WF	4
+ RT ←→ RM	12
RSR#1	100

RSR #1A

PARAMETERS	MAX. VALUE
RT ←→ CA	35
+ RT ←→ JO	15
+ RT ←→ RF	15
+ RT ←→ JS	10
+ RT ←→ WF	10
+ RH ←→ RM	15
RSR #1A	100

Figure 2.1

DEVELOPMENT OF

ROCK STRUCTURE RATING CONCEPT (Cont'd)

RSR #2

PARAMETERS	MAX. VALUE	
RT ↔ RH ↔ RF	("A")	20
+		
JP ↔ JO	("B")	30
↓ +		
WF ↔ JS	("C")	30
Σ ↔ CA	("D")	(Var.)
=		
RSR #2		100

RSR #2A

PARAMETERS	MAX. VALUE	
RT ↔ RH ↔ RF	("A")	30
+		
JP ↔ JO	("B")	20
↓ +		
WF ↔ JS	("C")	30
Σ_s ↔ CA	("D")	(Var.)
=		
RSR #2A		100

RSR #2B

PARAMETERS	MAX. VALUE	
RT ↔ RH ↔ RF	("A")	25
+		
JP ↔ JO	("B")	40
↓ +		
WF ↔ JS	("C")	25
Σ_s ↔ CA	("D")	(Var.)
=		
RSR #2B		100

RSR #2C*

PARAMETERS	MAX. VALUE	
RT ↔ RF	("A")	30
↓ +		
JP ↔ JO	("B")	50
↓ +		
WF ↔ JS	("C")	20
RSR #2C		100

* Letter suffix of RSR indicates progressive stages of development. RSR #2C is the final resultant method developed by this study and is used to determine structure ratings for the remainder of the report.

Figure 2.1 (continued)

primarily for purposes of illustrating the procedures; method #2 (indicated as RSR #2C on Figure 2.1) reflecting the results and conclusions of the research effort. Details of case history studies and correlation with actual support installations are discussed in Sections 3 and 4.

2.2.1 RSR Method #1

A review was made of various books and technical papers dealing with different aspects of the overall ground support problem (References 1 through 18). This was done primarily to avoid unnecessary duplication of previously published works and to delineate factors, methods or technologies which might contribute to the solution. Pertinent data was listed and grouped in accordance with general subject matter such as methods of geological investigations, rock mechanics, and support determinations. This information was analyzed by members of the research team on the basis of their combined experiences with engineering geology, ground support determinations, and background in underground construction. Consideration was made of the following:

1. Typical geologic information available in the pre-construction period.
2. Types of geological investigations used and reliability of developed data.
3. Most important geologic factors to be considered with respect to effect on rock structure.
4. Methods of measuring the qualitative and quantitative properties of each factor.
5. Relative effect on support determinations.
6. Developing a general method or procedure of rating the rock structure.

This review and analysis resulted in the development of method #1, which considered thirteen basic rock types in conjunction with nine geologic factors. It was found that this approach, although desirable, was too specific with respect to available data. Consequently, the format, factors and weighted values were modified as shown on Figure 2.1. In essence, method #1 rated the rock structure as the numerical sum obtained by adding the weighted values assigned to each designated factor. An example as to how the values were determined is illustrated in Figure 2.2, Evaluation of Core Analysis. The maximum weighted value to be assigned to this factor is 35. Lesser values are indicated depending on an overall evaluation of the core with respect to three basic rock types: igneous, sedimentary and metamorphic. Five limits of measure are shown for each of three possible ways of evaluating or appraising the core: 1) the RQD index, 2) fracture frequency or 3) visual inspection. For example, a value of 30 would be assigned to this factor if the core sample was igneous and had an RQD index of 75-90% or had been appraised by visual inspection as being "good". Core analysis information provided in case study records was evaluated with respect to most applicable combination of conditions indicated by the table. The corresponding weighted value was assigned to this factor. Other factors were considered accordingly, using available geologic data to determine limits of measure, physical qualities, etc.

2.2.2 <u>RSR Method #2</u>

Method #2, which is illustrated as Figure 2.3, presents a somewhat more general approach of rating the rock structure. It does, however, more nearly reflect the interdependency of the different factors. The same general procedure was used in establishing the format and values as previously discussed for method #1. The method #2 concept rates the relative effect on ground support requirements of three parameters each with respect to several

RSR METHOD #1

EXAMPLE

GEOLOGIC FACTOR NO. 1 - CORE ANALYSIS **MAX. VALUE 35**

ROCK TYPE	ROCK QUALITY DESIGNATION (RQD)				
	0-25%	25-50%	50-75%	75-90%	90-100%
	FRACTURE FREQUENCY (fractures/ft.)				
	> 4.5	3-4.5	2-3	1-2	< 1
	VISUAL INSPECTION				
	VERY POOR	POOR	FAIR	GOOD	VERY GOOD
IGNEOUS	6	16	24	30	35
SEDIMENTARY	4	10	16	24	35
METAMORPHIC	5	12	18	27	35

RQD = Deere's evaluation

Fracture frequency = fractures per foot of core

Visual inspection = individual judgment

Figure 2.2

ROCK STRUCTURE RATING
PARAMETER "A"
GENERAL AREA GEOLOGY

BASIC ROCK TYPE	GEOLOGICAL STRUCTURE			
	MASSIVE	SLIGHTLY FAULTED OR FOLDED	MODERATELY FAULTED OR FOLDED	INTENSELY FAULTED OR FOLDED
IGNEOUS	30	26	15	10
SEDIMENTARY	24	20	12	8
METAMORPHIC	27	22	14	9

Figure 2.3

ROCK STRUCTURE RATING
PARAMETER "B"
JOINT PATTERN
DIRECTION OF DRIVE

AVERAGE JOINT SPACING FEET	STRIKE ⊥ TO AXIS					STRIKE ∥ TO AXIS		
	DIRECTION OF DRIVE					DIRECTION OF DRIVE		
	BOTH	WITH DIP		AGAINST DIP		BOTH		
	DIP OF PROMINENT JOINTS					DIP OF PROMINENT JOINTS		
	FLAT	DIPPING	VERTICAL	DIPPING	VERTICAL	FLAT	DIPPING	VERTICAL
< .5 (CLOSELY JOINTED)	14	17	20	16	18	14	15	12
.5-1.0 (MODERATELY JOINTED)	24	26	30	20	24	24	24	20
1.0-2.0 (MODERATE TO BLOCKY)	32	34	38	27	30	32	30	25
2.0-4.0 (BLOCKY TO MASSIVE)	40	42	44	36	39	40	37	30
> 4.0 (MASSIVE)	45	48	50	42	45	45	42	36

Flat 0 - 20°
Dipping 20° - 50°
Vertical 50° - 90°

Figure 2.3 (continued)

ROCK STRUCTURE RATING
PARAMETER "C"
GROUND WATER
JOINT CONDITION

ANTICIPATED WATER INFLOW (gpm./1000')	SUM OF PARAMETERS A + B					
	20-45			46-80		
	JOINT CONDITION					
	1	2	3	1	2	3
NONE	18	15	10	20	18	14
SLIGHT (<200 gpm)	17	12	7	19	15	10
MODERATE (200-1000 gpm)	12	9	6	18	12	8
HEAVY (>1000 gpm)	8	6	5	14	10	6

Joint Condition:
1 - Tight or Cemented
2 - Slightly Weathered
3 - Severely Weathered or Open

Figure 2.3 (continued)

geologic factors and where applicable with respect to each other.

Parameter A is a general appraisal of the rock structure or formation through which the tunnel is to be driven. Geological information needed to define the limits of measure and describe the structure is available in the pre-construction period. It is usually presented in terms compatible to all disciplines, such as a "massive granite" or "intensely folded serpentine" formation. The assigned weighted value for Parameter A in the first instance would be 30; in the second, 9.

Parameter B relates the joint pattern (strike and dip and joint spacing) and the direction of drive. Most surface geology surveys or maps give an indication of the strike and degree of dip of the various formations. Consequently, approximations as to limits of measure for these two factors can be made. Corresponding direction of drive is determined from project planning. There are usually several sources of information that can be used in determining the anticipated average joint spacing or pattern of the rock structure. Geological terms such as "closely jointed" or "blocky", drillers logs, core analyses or RQD indices are examples. Geology reports usually give some description of anticipated joint spacing. Defining this factor is difficult but it is felt that a reasonable approximation can be made by considering all available information. For purposes of the RSR method of evaluation, five numerical limits of measure are given for joint spacing. The respective bracketed words (Parameter B, Figure 2.3) are used to show intended correlation or equivalency between the given numerical limits and common geological terminology. The value to be assigned to Parameter B can be obtained from the table by considering appropriate limits of measure determined for joint spacing with respect to the strike and dip of the formation and direction of drive. See discussion paragraph 1.2.3.

Parameter C is a general evaluation as to the effect of ground water inflow on support requirements. It takes into consideration the following: 1) the overall quality of the rock structure as indicated by the numerical sum of values assigned to Parameters A and B; 2) the condition of the joint surfaces, and 3) the anticipated amount of inflow. Establishing limits of measure or estimating possible occurrence of the last two factors is normally left to the discretion of the contractor. Data pertaining to pump tests, local wells, ground water levels, surface hydrology, topography and rainfall should be considered in conjunction with the anticipated geological formation in estimating ground water inflows. Condition of joint surfaces would have to be appraised from surface or historical geology, drillers' logs or inspection of core samples. The RSR method allows for three types or conditions of joint surfaces and four quantitative measures of water inflow. The value to be assigned to Parameter C is obtained from the table by using the limits of measure determined for the different factors.

The RSR value of the particular geological section under consideration is the numerical sum of Parameters A, B and C. Values, which will range from 25 to 100, reflect the quality of the rock structure regardless of size of tunnel opening or method of excavation. Some tunnels will be driven through several distinct geological formations, each of which would be separately analyzed with respect to RSR values.

2.3 CONCLUSIONS

Any proposed method of classifying a rock structure for purposes of predicting ground support would be subject to question and/or criticism from various sources. Comments could range from decisions as to what factors are most important, to the general contention that it can't be done. Although this paradox is recognized, the fact remains that some form or method of evaluation, usually within the same general concept as described herein, has been made for all tunnels.

The RSR method of qualifying and ranking geologic factors is not intended to be a "geology by the numbers" approach to the problem. Rather, it is an attempt to formulate a standard procedure by which geologic factors can be evaluated with respect to a common goal. The effective use of the formats and assignment of values requires a comprehensive understanding of both geological and engineering requirements.

Every qualified person would have a somewhat different approach, either as to factors themselves, relative ranking of each, or in overall concept. Questions will also be raised as to whether or not sufficient data can be provided to make realistic appraisals and assignment of numerical ratings. These and other areas of concern are apparent. They can only be resolved by initial acceptance of a method and future evaluation based on experience. The format can be adjusted or modified to accommodate more specific data or information as may be ascertained. To a certain extent, this was accomplished by means of the case history studies and the correlation of RSR values with actual support installations discussed in Sections 3 and 4 respectively.

Most of the information needed to evaluate a rock structure could be provided by a comprehensive surface geology report. By having a common objective, or by establishing a standard requirement as to type of geological data needed, it is likely that more efficient and meaningful results could be obtained from future geologic investigations. The RSR method is one possibility. It could be used to evaluate cores or rock samples and, hopefully, to identify and describe rock structures to be penetrated by the tunnel. Accepted standard procedures would permit the correlation of geology and support installations between different tunnel projects and eventually lead to more reliable methods of predicting support requirements. The ever-present question as to responsibility between the owner and contractor will also have to be resolved.

SECTION 3

CASE HISTORY STUDIES

3.1 INTRODUCTION

Correlation of geologic information with respect to actual support installations was accomplished by case history study method. The format shown on Figure 3.1 was used to record different factors and features pertinent to the study and which, hopefully, could be obtained or evaluated from project records. It allows for the determination of an RSR value (generally in conformance with method #1) for each tunnel or portion thereof which could be analyzed as a separate geological section. Information pertaining to actual ground support was recorded for each respective section. As the study progressed, it became apparent that the type and quantity of historical information was such that it would be difficult to summarize on any standardized form. Consequently, various revisions were made during the course of the study.

Records of projects completed since 1960 were more complete and uniform in content than prior projects. Data for most of these recent tunnels was presented in the form of as-built drawings which provided detailed information pertaining to geology, support installations and construction procedures. This apparent trend toward use of a uniform as-built format should be encouraged. It will provide a valuable source of information for future correlation of tunnel support, geology and construction requirements.

3.2 SOURCES OF INFORMATION

Preliminary discussions were held with various agencies involved in tunnel construction. The purpose was to explain the research effort and anticipated goals and to solicit their help in providing data. They were very receptive and expressed willingness to cooperate in whatever way possible.

CASE HISTORY NO: ____________ NAME OF TNL: ____________

LOCATION: ____________ APPROX. ELEV: ____________ DATE OF CONST: ____________

EXCAV. SIZE: ____________ TOTAL LENGTH: ____________ EXCAV. METHOD: ____________

PRE-CONSTRUCTION GEOLOGY ____________

SURFACE GEOLOGY: ____________

PREDOMINATE ROCK TYPE: ____________

BORINGS: ____________

SEISMIC: ____________

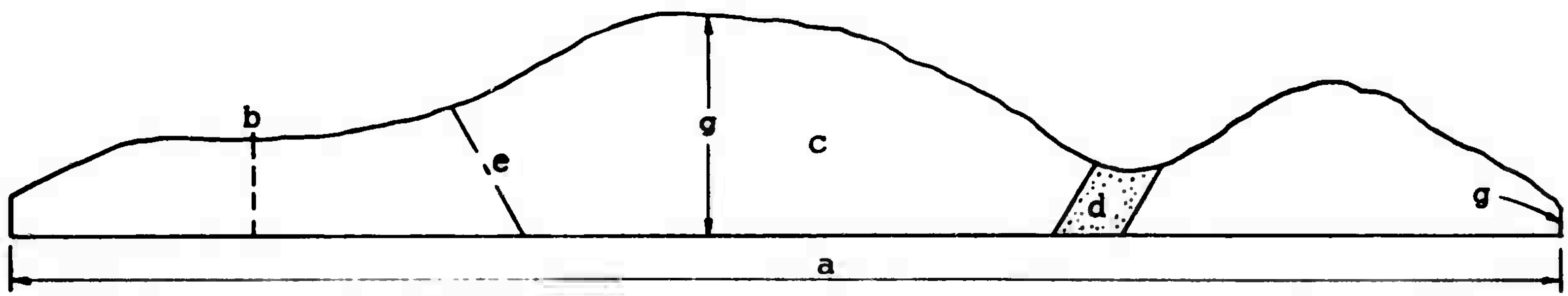
OTHER: ____________

HYDROLOGY: ____________

LAB. TESTS: ____________

GENERAL: ____________

STUDY PROFILE - SECTIONS AS APPLICABLE



DATA FOR STUDY SECTION	# 1	# 2	# 3	# 4
a) LENGTH				
b) BORINGS				
c) ROCK TYPE				
d) MAJOR FAULTS				
e) SHEARS - DISCONTINUITIES				
f) ORIENTATION OF JTS.				
g) MAX/MIN. COVER				
h) WATER				

Figure 3.1

CASE HISTORY NO: ____________ SECTION NO: ____________ ROCK TYPE: ____________

STRUCTURE EVALUATION

1) RQD ____________ 2) SEISMIC VEL. RATIO: ________ 3) ORIENTATION OF JTS: ______

4) DISCONTINUITIES: ________ 5) MAJOR FAULTS: ________ 6) JOINT SEAL: ________

7) AVER. COVER: ________ 8) GRD. WATER: ________ 9) MODULUS RATIO: ________

10) COMP. STRENGTH: ________

11) GENERAL: ____

____

PREDICTED GROUND STRUCTURE:

PREDICTED GROUND SUPPORT

TYPE: ____

SIZE: ____

SPACING: ____

COMMENTS: ____

____

ACTUAL GROUND SUPPORT

TYPE: ____

SIZE: ____

SPACING: ____

COMMENTS: ____

____

Figure 3.1 (continued)

Predicting ground supports for tunnel construction was a common problem and any solution or potential solution would be welcomed. Doubts were expressed as to whether or not case history data would provide a reliable measure between geology and actual support installations, especially for projects where substantially more supports were installed than originally estimated. These doubts relate primarily to the philosophy of contracting which has been discussed in Section 1.

The following agencies provided information for case studies. In some instances a member of the study team researched records at the agency office; in others the agency provided prints or copies of as-built records for in-house use.

1. U.S. Bureau of Reclamation - Denver.
2. Department of Water Resources - Sacramento.
3. Pacific Gas and Electric Company - San Francisco.
4. Hetch Hetchy Water Supply - San Francisco.
5. San Francisco Water Department - San Francisco.
6. Metropolitan Water District of Southern California - Los Angeles.
7. Sacramento Municipal Utility District - Sacramento.

Additional information for many projects was available from Jacobs Associates' files. It included pre-bid reports prepared by consulting geologists, data obtained from site inspection trips and preliminary appraisals of tunnel support requirements.

Thirty-three tunnel projects were investigated. The individual tunnels were divided into one or more study sections, each reflecting different geological formations which may have either been predicted or actually encountered during construction. Approximately 134 sample tunnel sections were developed by this procedure. The table of Figure 3.2 lists the different projects and

CASE HISTORY STUDY PROJECTS

CASE HISTORY NO.	NAME OF TUNNEL	LOCATION	SIZE OF EXCAV. SECTS.		TOTAL LENGTH L.F.	NO. OF STUDY SECTIONS	METHOD OF EXCAV.
			DIMENS.	SQ. FT.			
1	White Rock	Calif.	24x24 HS	480	24,000	2	D&B
2	Divide	Colo.	12x12 HS	130	28,000	1	D&B
3	Spring Creek No. 1	Calif	22 Dia.	380	8,300	4	D&B
4	Spring Creek No. 2	Calif.	22 Dia.	380	4,500	3	D&B
5	Tecolote	Calif.	9x9 HS	70	33,500	12	D&B
6	Glendora	Calif.	20x20 HS	350	32,500	8	D&B
7	Canyon	Calif.	14x14 HS	180	54,000	8	D&B
8	Crystal Springs Bypass	Calif.	13x13 HS/ 13 Dia.	140	17,100	2	D&B/TBM
9	Azotea	N. Mex.	12 Dia.	110	66,000	2	TBM
10	Navajo No. 1	N. Mex.	20 Dia.	310	10,100	2	TBM
11	Navajo No. 2	N. Mex.	19x19 HS	330	25,820	2	D&B
12	Blanco	N. Mex.	11x11 HS/ 11 Dia.	90	45,600	2	D&B/TBM
13	Oso	Colo.	11x11 HS/ 11 Dia.	90	26,700	3	D&B/TBM
14	Starvation	Utah	9 Dia.	60	5,300	2	TBM
15	Water Hollow	Utah	13 Dia.	130	21,600	2	TBM
16	River Mountains	Nevada	12 Dia.	110	20,000	3	TBM
17	Clear Creek	Calif.	20x20 HS	350	56,600	3	D&B
18	Cascade Divide	Ore.	8 Dia.	50	2,100	1	D&B
19	Green Springs	Ore.	8 Dia.	50	4,800	1	D&B
20	Angeles	Calif.	34 Dia.	910	38,800	2	D&B

D&B - Drill and Blast
TBM - Tunnel Boring Machine

Figure 3.2

CASE HISTORY STUDY PROJECTS

CASE HISTORY NO.	NAME OF TUNNEL	LOCATION	SIZE OF EXCAV. SECTS.		TOTAL LENGTH L. F.	NO. OF STUDY SECTIONS	METHOD OF EXCAV.
			DIMENS.	SQ. FT.			
21	Western Pacific Nos. 1 thru 5	Calif.	22x30 HS	600	21,000	5	D&B
22	Castaic Dam Diversion	Calif.	24 H. Dia./ 33 H. Dia.	400/900	3,600	2	D&B
23	Belden No. 1	Calif.	18.5 HS	310	23,600	8	D&B
24	Belden No. 2	Calif.	18.5 HS	310	9,600	5	D&B
25	Pit River No. 4	Calif.	23x22 HS	450	21,300	7	D&B
26	Poe Tunnel (*Partial)	Calif.	23x23 HS	470	*15,100	8	D&B
27	Camino	Calif.	14x15 HS	190	26,500	7	D&B
28	Loon Lake Tailrace	Calif.	18x18 HS	290	20,200	7	D&B
29	Jay Bird	Calif.	14x14 HS	180	21,000	3	D&B
30	Union Valley	Calif.	19x19 HS	320	4,500	2	D&B
31	Butt Valley	Calif.	17x16 HS	240	10,900	4	D&B
32	Caribou No. 2	Calif.	17x16 HS	240	8,700	4	D&B
33	Flathead	Mont.	22x30 HS	600	35,300	7	D&B

Figure 3.2 (continued)

physical features of each by case history number.

3.3 PRE-CONSTRUCTION GEOLOGY

Pre-construction geology was analyzed with respect to both the type of investigation used and the amount and detail of information pertinent to evaluation of the rock structures. Available data for some projects was sufficient to make realistic appraisals of most factors required for each RSR determination. For others, it was necessary to approximate or extrapolate on the basis of best judgement. Although approximately half of the projects had been investigated by a member of the study team during the actual pre-bid period, an attempt was made to record and use only that information provided by the owner which would have been available to all concerned in predicting support requirements.

Figure 3.3 is a tabulation of geologic data provided to prospective bidders in the pre-construction period. It is based on findings of the research and identifies the type of investigation used for each project. It also indicates a general appraisal as to the sufficiency of the given data. Each agency seemed to have its own standard policy with respect to the amount and degree of geologic data to be provided to prospective bidders. These policies; if such was the case, were probably base` or derived from past experiences and limitations imposed by the following conditions:

1. The cost of geological investigations.
2. Lack of new methods or techniques for making investigations.
3. The point at which additional information would cease to be meaningful.
4. The reliability of extrapolating surface geology to tunnel grade.
5. The overall responsibility for constructing the tunnel.

SUMMARY OF
INFORMATION AVAILABLE TO BIDDERS FOR CASE STUDIES

CASE HISTORY NO.	TYPE OF GEOLOGIC DATA					
	SURFACE GEOLOGY	HISTORICAL GEOLOGY	TOPO. MAPS	GEOLOGIC PROFILE	BORINGS	OTHER
1	3	0	3	3	2	0
2	2	0	3	0	2	2
3	3	3	3	0	3	0
4	3	3	3	0	3	0
5	0	0	3	0	0	0
6	3	3	3	3	2	0
7	3	3	3	3	3	0
8	3	0	3	3	3	0
9	3	0	3	0	3	2
10	3	0	3	0	2	0
11	3	0	3	0	2	0
12	3	0	3	0	3	2
13	3	0	3	0	3	2
14	3	0	3	0	3	0
15	3	0	3	0	2	0
16	3	0	3	0	3	0
17	3	0	3	0	3	0
18	3	0	3	0	3	0
19	3	0	3	0	3	0
20	3	3	3	3	3	2
21	3	3	3	3	3	2
22	3	3	3	3	3	0
23	0	0	3	0	1	0
24	0	0	3	0	1	0
25	0	0	3	0	1	0
26	0	0	3	0	1	0
27	3	0	3	3	0	0
28	3	0	3	3	2	0
29	3	0	3	3	2	0
30	3	0	3	3	0	0
31	0	0	3	0	1	0
32	0	0	3	0	1	0
33	3	0	3	3	3	2

LEGEND:
3 Data given - quantitative or descriptive
2 Data available for portion of project
1 May have been available to bidders (no longer available to study team)
0 Data not given

Figure 3.3

Different economic and legal interpretations as to the effects of these conditions presents a major problem to be resolved in the "art" of predicting ground support. Solutions; which will require the combined efforts of those involved in tunnel construction and research, will probably depend to a large extent on economic considerations between the owner and contractor. Although the owner is restricted or limited by a given budget, he should not expect a contractor to finance the construction of a project significantly more difficult than reasonably anticipated from pre-bid geologic data. On the other hand, the owner should not be required to pay premium prices for work less difficult to complete nor pay for contingencies which may have been allowed for but not actually encountered. In all cases, neither the owner nor the contractor can compromise on the safety of the tunnel workers.

In general, the case history pre-construction geologic data consisted of 1) topographic maps 2) surface geology in various amounts of detail 3) a relief profile of the tunnel and 4) core samples and driller's logs. This is noted as typical information provided for tunnel construction and the prediction of ground support during the last 30 or 40 years. It is usually very general in nature and leaves many decisions to the personal judgement and experience of those charged with the responsibility of driving the tunnel. Other types or methods of investigation used in developing project geology are indicated on the table (Figure 3.3) Seismic methods were used occasionally to establish top of bedrock. A few projects gave geological profiles at tunnel grade. Data from resistivity surveys was given in some instances. Most borings were made in the vicinity of the portals or at points of shallow cover. Separate geology reports (not included but referred to in contract documents) were available for some of the projects. The case history pre-construction geology, although limited in content and detail provided basic data used in developing the RSR method of evaluation.

3.4 AS-BUILT GEOLOGY

The only geological information available for some of the study projects was that presented on as-built drawings. Although this type of data can not be considered as a "prediction" it was used to correlate and verify various geologic factors and RSR determinations considered in this study. In some instances both pre-construction and as-built geology were available. This permitted comparisons of predictions made from pre-bid geology with the actual rock structures. The ultimate success and reliability of any prediction method will depend to a large extent on the making of similar correlations and subsequent evaluations of results for both future and previously constructed tunnels.

3.5 GEOLOGIC FACTORS

The occurrence and physical definition of different geologic factors required for the RSR evaluations were determined from available case history data. Surface geology usually indicated the general strike and dip and type of rock formations anticipated at grade. Values of rock material properties; hard, soft, broken, and data pertaining to joint patterns were obtained from drillers' logs. Major faults or other discontinuities were predicted from surface geology or topographic maps. Potential water inflows were estimated from ground water levels, pumping tests and other hydrological data. In some instances, geology reports, as-built drawings, site inspection data and previous appraisals of actual cores were used to compliment and help define the factors. Figure 3.4 lists, by case history number, the geologic factors considered in this research and which were used in making RSR evaluations. The applicable symbol noted for each factor indicates the degree of reliability

RELIABILITY PROFILE OF ROCK STRUCTURE RATING PARAMETERS BASED ON INFORMATION AVAILABLE TO BIDDERS FOR CASE STUDIES

CASE HISTORY NO.	ROCK STRUCTURE RATING PARAMETERS					
	"A"		"B"		"C"	
	ROCK TYPE	GEOL. STRUCT.	JOINT SPACING	DIP & STRIKE	ANTIC. WATER	JOINT CONDITION
1	3	2	3	3	2	3
2	3	2	2	2	2	2
3	3	2	3	3	2	3
4	3	2	3	3	2	3
5	2	0	0	0	0	0
6	3	3	0	3	3	2
7	3	3	3	3	2	3
8	3	2	2	3	0	3
9	3	2	2	3	2	2
10	3	2	2	3	2	3
11	3	2	2	3	2	3
12	3	2	3	3	2	3
13	3	2	2	3	2	3
14	3	2	2	3	2	3
15	3	2	2	3	2	3
16	3	2	3	3	2	3
17	3	2	3	3	2	3
18	3	2	2	3	2	3
19	3	2	2	3	2	3
20	3	3	2	3	2	3
21	3	3	2	3	2	3
22	3	3	2	3	0	3
23	1	0	1	1	0	0
24	1	0	1	1	0	0
25	1	0	1	1	0	0
26	1	0	1	1	0	0
27	3	2	0	3	0	2
28	3	2	3	3	0	2
29	3	2	0	3	0	0
30	3	2	0	3	0	0
31	1	0	1	1	0	0
32	1	0	1	1	0	0
33	3	3	3	3	2	3

LEGEND:
- 3 Data given - quantitative or descriptive
- 2 Data inferred - allowing for reasonable estimate
- 1 May have been available thru core analysis by bidders, but not available now (except in "as-built" records)
- 0 Data not available

NOTE: Supplementary data available from "as built" geology drawings used to compute RSR Values for Nos. 5, 6, 8 and 22 thru 32.

Figure 3.4

assigned to the determined values. Measure of reliability ranges from high (Code 3) in cases where data was sufficient to permit a fairly definite evaluation to low (Code 0) for values of factors which had to be determined by best judgement.

As seen from the table, less than 50% of the factors (and subsequently the determination of RSR values) could be properly evaluated from information provided in the pre-construction period. It indicates the general disparity of typical pre-construction information and emphasizes the personal judgement factor required in making predictions of ground support. An overall evaluation of the reliability of predicting support requirements based on pre-construction information might be made by comparing quantity of support given in bid documents to actual support used. For the case history tunnels in which support quantities were given, this comparison showed a range of plus or minus 100% with an average of plus or minus 30%. Although such a comparison is indicative, it must be kept in mind that total quantity of support used reflects factors other than geology. It does, however, show the large area of potential improvement in the "art" of predicting support requirements.

Within the limits of present-day technology, this improvement can best be made by an accepted empirical approach, whereby pre-construction and as-built geology can be correlated by means of standard procedures or factors and subsequently related to support requirements. It will require a more uniform type of geological investigation directed toward the evaluation of specific conditions and factors affecting the rock structures.

Using the several methods discussed in Section 2, RSR ratings were determined for each study sample on the basis of values assigned to the various geologic factors. These separate ratings or appraisals, as well as individual ratings given to specific sample sections by different members of the study team, were compared and subsequently correlated with actual support installations. Modifications and adjustments to the proposed RSR method and respective weighted values assigned to different geologic factors were made to reflect findings of the research effort. Where applicable as-built and other available data was considered in making final determinations. This tended to give results a higher degree of reliability than previously mentioned.

3.6 ACTUAL SUPPORT INSTALLATIONS

Most case history records provided fairly good information with respect to support installations. As-built drawings usually gave the type, size, location and/or spacing of support used throughout the tunnel. Support systems for most of the examples studied consisted primarily of steel ribs of various sizes placed at from 2 to 8 foot centers along the tunnel. Some project records indicated only the percent of tunnel length that was supported without reference to size, spacing or location. Others gave only total quantities or weight of support used. Some tunnel sections were supported with half ribs, others required invert struts. Use of timber sets was noted in a few tunnels completed in the fifties. Rock bolts and shotcrete were used in some of the more recent projects. Details of actual support installations were recorded on the format shown on Figure 3.1.

Although it is likely that tunnels now under construction; or just recently completed and not included in case studies, might indicate a greater tendency toward rock bolt or shotcrete type of support, the steel rib is considered as the primary support member for purposes of this study. The use of steel ribs introduces an area of doubt as to whether the support is actually required due to ground conditions or used as an expedient to tunnel driving. For example, it would oftentimes be more economical to place support continuously through intermediate sections of supported tunnel than it is to change cycles (support vs unsupported) to accommodate actual ground conditions. This is more prevalent for a drill and blast operation than for a boring machine but is one of the conditions which should be considered.

In order to correlate RSR ratings with actual support used in the respective tunnels it was necessary to establish some standard by which such comparisons could be made. This was accomplished by relating the actual size and spacing of the steel rib used in a case history section to a theoretical rib support that would have been required if the tunnel had been driven through "soft" ground conditions. This standard, referred to as the "Rib Ratio" (RR) is discussed in Section 4. RR's were determined for each study sample in accordance with procedure outlined in that section.

3.7 CONSTRUCTION PARAMETERS

Construction parameters which affect support requirements or installations are discussed in Section 1. The size and method of excavation for each study tunnel are shown on Figure 3.2. It was assumed, unless specified otherwise in the records, that all headings were driven upstream (direction of drive). No special effort was made in studying "contractual obligations" except for general comments made herein. All construction data pertinent to support determinations was noted for each study sample.

3.8 CONCLUSIONS

Historical data obtained from case studies provided the basic information on which this research project was based. Due to lack of uniformity and completeness of recorded information it was necessary to research considerably more projects than initially projected. Although findings and results were not as conclusive as originally anticipated, it is felt that available data is sufficient to establish a realistic method or procedure of predicting ground support requirements. As mentioned, pre-bid geology was augmented with as-built and other data where possible. The proposed RSR method requires that some standard be established with respect to type of geological information needed and its evaluation. This research indicated that standardization could probably be accomplished within the general concept of present-day techniques. It would require the concurrence of various agencies and disciplines involved in tunnel construction.

The general contention that bored tunnels require less support than conventionally excavated tunnels (paragraph 1.4.3) was found not to apply in all cases. Case studies 10 and 11 are examples. (See Figure 3.2) Both tunnels were approximately the same size and driven through similar rock structures; one with a boring machine, the other by drill and blast methods. The tunnel excavated by the drill and blast method used less support than the bored tunnel. This is an exceptional situation due to specific geological and construction conditions but indicates the many different possibilities and exceptions that complicate the problem of predicting ground supports.

SECTION 4

CORRELATION OF ROCK STRUCTURE RATING AND GROUND SUPPORT

4.1 INTRODUCTION

Ground support needed or used in the construction of tunnels depends primarily on the condition of the rock structure through which the tunnel is driven. Section 2 describes a method by which the quality or condition of the structure can be defined by evaluating certain geologic factors which affect the overall stability or behavior of the rock during tunneling operations. This section relates support requirements to rock structure ratings. It considers actual installations determined from case studies as well as other empirical and mathematical relationships developed herein. A method of predicting support requirements on the basis of an RSR evaluation is proposed.

4.2 RIB RATIO

In order to analyze and correlate RSR values with actual support installations it was necessary to develop a datum or measure by which different supports could be compared on a common basis. Since the majority of tunnels studied were supported with steel ribs it was decided to use a measure that would relate actual support installations to some theoretical rib spacing which could be similarly determined for each tunnel or study sample. The concept, designated as the Rib Ratio (RR) was developed from Terzaghi's formula of determining roof loads for loose sand below the water table (datum condition). Using tables provided in "Rock Tunneling with Steel Supports" (Reference 6) the theoretical spacing required for the same size rib as used in a given case study tunnel section was determined for the datum condition. The rib ratio is obtained by dividing this theoretical spacing by the actual spacing and multiplying the answer by 100. For instance, if the theoretical spacing of a 6 WF 25 rib was determined to be 2 feet for the datum condition and the actual spacing of the same rib used in the study sample was 5 feet, the RR would be 40, (2/5 x 100). Or expressed otherwise, the sample tunnel used only 40% of the support which would have been required for the datum condition. Ratios for tunnels with widely spaced support would be low and zero where no support was used. Figure 4.1 shows empirical formulae used in calculating rib ratios. The table of Figure 4.2 lists theoretical (datum) spacings determined for common sizes of steel ribs for various tunnel diameters using formulae (3) and (4) developed in Figure 4.1. It is apparent that different size tunnels, although having the same theoretical rib spacing or calculated RR, would require different weight or size of ribs for equivalent support. The concept is probably a conservative measure of support requirements but can be used as a common basis for correlating RSR determinations with actual support installations.

Rib ratios were computed for each study section where details of actual support installations were available. In the few sections where timber sets were used, equivalent steel ribs were determined to compare these sections on the same basis.

4.3 <u>CORRELATION OF RSR AND RR</u>

Charts were prepared which showed the relation between RSR values determined by use of the several RSR methods discussed in Section 2 and corresponding rib ratios. RSR values were plotted on the vertical axis, respective rib ratios on the horizontal. Each chart was evaluated by determining the number of sample points falling within or near an envelope of curves developed

DETERMINATION OF RIB RATIO

Terzaghi Empirical Formula for Maximum Roof Load for Loose, Cohesionless Sand Below Water Table (From Ref. No. 5) Page 70, Table 2:

$$P1 = [1.38 \ (B + H \ )] \times B \times \gamma_t \quad (1)$$

Where: P1 = Vertical load on rib (lb. per linear foot of tunnel)

B = Tunnel width (ft.)

H_t = Tunnel height (ft.)

γt = Unit weight of sand (assumed 120 lb./cu.ft.)

Formula (1) applies to tunnels with a semi-circular arch.

$$P_1 = 1.38 \ (B + H_t \ ) \ \times \ B \times 120$$

$$P_1 = 165.6 \ B \ (B + H_t) \quad (2)$$

For tunnels that are circular or where height (Ht) = width (B) = Dia. (D)

$$P_1 = 165.6 \ D \ (D + D)$$

$$P_1 = 165.6 \times 2D^2$$

$$P_1 = 331 \ D^2 \quad (3)$$

Using load table from "Rock Tunneling With Steel Supports" by Proctor and White, Page 238: (Reference No. 6)

Pt = Pr x D Where Pt = Total allowable load on rib (lb.)

Pr = Chart value of allowable load per foot of tunnel width (lb.)

To find theoretical rib spacing (Sd) for "Datum" Condition:

$$Sd = \frac{Pt}{P1}$$

$$Sd = \frac{Pr \times D}{331 \ D^2}$$

$$Sd = \frac{Pr}{331 \ D} \quad (4)$$

The rib ratio is a measure of the actual tunnel support provided compared to the datum and is expressed as:

$$RR = \frac{Sd}{Sa} \times 100 \quad (5)$$

Where Sa is actual spacing (ft.) of ribs used in sample tunnel.

Figure 4.1

THEORETICAL SPACING (Sd) OF TYPICAL RIB SIZES FOR DATUM CONDITION SPACING GIVEN IN FEET

Rib Size	TUNNEL DIAMETER										
	10'	12'	14'	16'	18'	20'	22'	24'	26'	28'	30'
4I7.7	1.14										
4H13.0	2.01	1.51	1.16	0.92							
6H15.5	3.31	2.39	1.81	1.42	1.14						
6H20		3.03	2.32	1.82	1.46	1.20					
6H25			2.86	2.25	1.81	1.48	1.23	1.04			
8WF31				3.24	2.61	2.14	1.78	1.51	1.29	1.11	
8WF40					3.37	2.76	2.30	1.95	1.67	1.44	1.25
8WF48						3.34	2.78	2.35	2.01	1.74	1.51
10WF49								2.59	2.22	1.91	1.67
12WF53										2.35	1.91
12WF65											2.35

Figure 4.2

for the average graph of all plotted points. Since rib ratios remained constant, it was possible to see what effect variations in weighted values assigned to different geologic factors or parameters used in RSR evaluations would have on the developed curve. Figure 4.3, which is similar to charts developed for initial stages of the RSR concept, shows the graph of points plotted with respect to RSR values determined by method #2 (Figure 2.3) and the corresponding rib ratios. The table given in Figure 4.4 gives the data used to plot this graph. The narrow width of the band of sample points comprising the 90% envelope indicates a reasonable degree of correlation. As previously mentioned, some of the plotted RSR values reflect as-built or other data which can be considered as a direct correlation between rock conditions and supports.

Some of the more scattered points can be explained by detailed examination of case histories involved, others might be attributed to the empirical approach to the problem. Assuming that the RSR evaluations did in fact reflect actual rock structure conditions, it can be concluded that points falling above the average curve represented tunnels which were "over supported", those below; tunnels in which marginal support was used. Most exceptions to the plotted envelope were in the "over supported" category.

Using the equation of the average curve shown on Figure 4.3, it is possible to determine numerical rib ratios corresponding to different RSR values. These relations are given below:

RSR Values and Rib Ratios
(Based on average curve equation-Figure 4.3)
(RR + 70) (RSR + 8) = 6000

RSR	27	30	35	40	45	50	55	60	65	70	77
RR	100	68	70	55	43	33	25	18	12	7	0

CORRELATION OF RSR AND RR

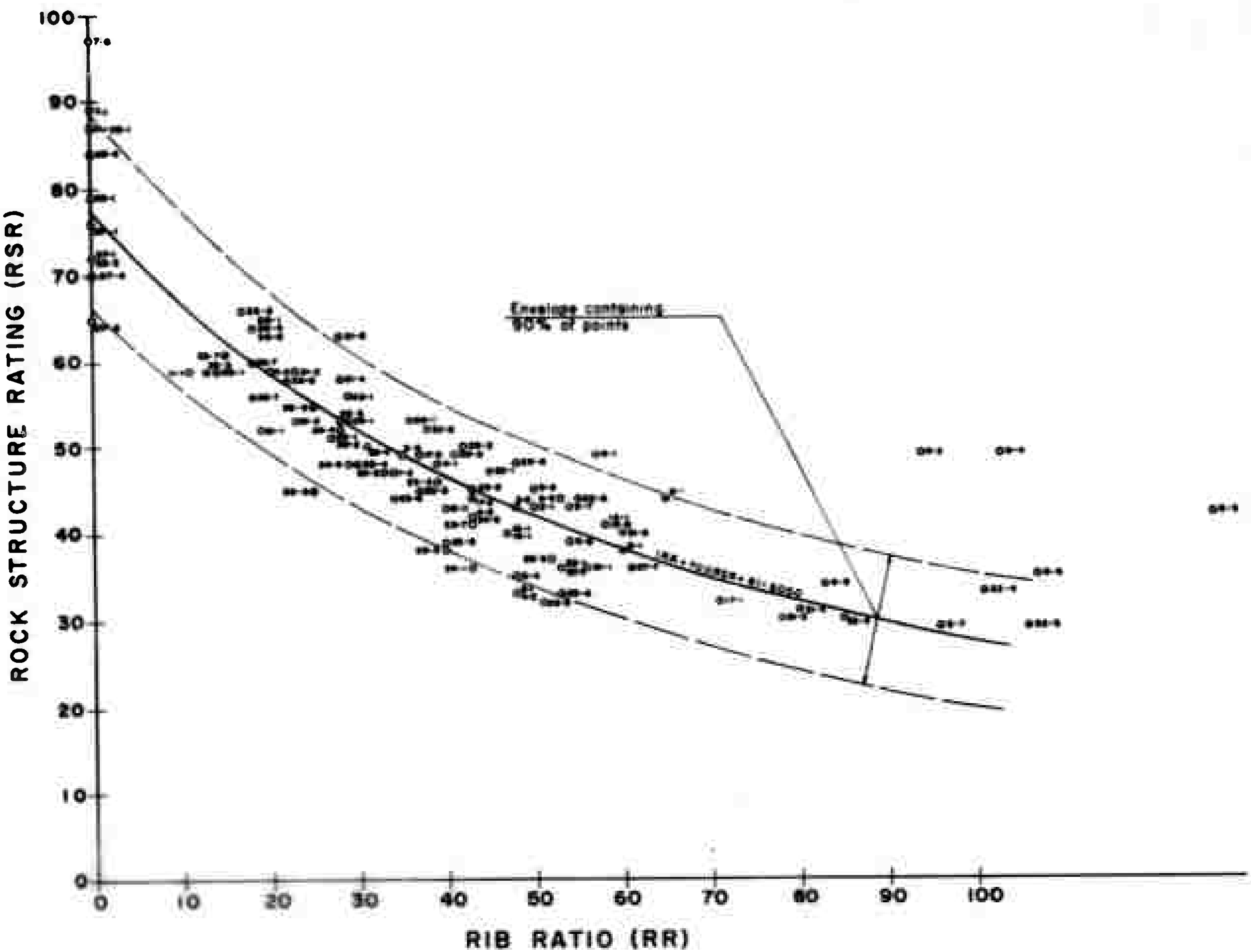


Figure 4.3

ROCK STRUCTURE RATINGS AND RIB RATIOS
DETERMINED FOR DRILL AND BLAST CASE STUDY TUNNELS

CASE NO.	TUNNEL SIZE (ft.)	ROCK TYPE	RSR DETERMINATION				SUPPORT		
			A	B	C	TOTAL	SIZE	SPACE	RIB RATIO
1-1	24X24HS	1	28	42	17	87	0	-	0
-2		3	16	24	7	47	8WF28	4' ctrs.	34
2-1	12X12HS	1	12	16	15	43	5WF18.9	5' ctrs.	50
3-1	22 DIA	1	12	12	9	33	8H34	4' ctrs.	48
-2		1	15	16	12	43	8H34	4' ctrs.	48
-3		1	17	23	9	49	8H34	5.5'ctrs.	35
-4		1	12	16	7	35	8H34	4' ctrs.	48
4-1	22 DIA	1	18	20	10	48	8H34	5' ctrs.	39
-2		1	10	16	7	33	8H34	4' ctrs.	48
-3		1	16	16	10	42	8H34	5' ctrs.	43
5-1	9X9HS	2	12	16	10	38	4H13	4' ctrs.	60
-3		2	12	15	18	45	4H13	4.8'ctrs.	50
-5		2	8	18	18	44	4H13	4.5'ctrs.	53
-7		2	8	14	7	29	4H13+	2.5'ctrs.	96
-11		2	12	25	6	43	4H13+	6' ctrs.	40
6-1	20X20HS	1	10	27	12	49	8M32.6	4' ctrs.	57
-2		1	10	27	12	49	8H40+	2.7'ctrs.	94
-3		3	9	27	6	42	8H40+	2.0'ctrs.	127
-4		1	10	27	12	49	8M32.6+	2.4'ctrs.	103
-5		3	9	19	6	34	8M32.6	2.8'ctrs.	83
-6		1	10	19	6	35	8M32.6+	2.3'ctrs.	107
-7		1	10	27	6	43	8M32.6	4.1'ctrs.	54
-8		2	8	19	12	39	8M32.6	4.1'ctrs.	54
7-1	14X14HS	1	28	47	14	89	0	-	0
-6		1	30	47	20	97	0	-	0
8-1	13X13HS	2	12	14	18	44	6H20	4' ctrs.	65
11-1	19X19HS	2	20	24	15	59	Rk Bolts	6X6 ±	11
-2		2	20	24	15	59	6WF18	5.6'ctrs.	20
12-1	11X11HS	2	12	14	15	41	4WF13	3' ctrs.	58
13-2	11X11HS	3	12	14	15	41	4WF13	3' ctrs.	58
17-1	20X20HS	3	14	12	6	32	8WF31	3' ctrs.	71
-2		1	15	20	9	44	6WF25	3.4'ctrs.	43
-3		3	14	20	15	49	6WF25	4' ctrs.	37

Figure 4.4

ROCK STRUCTURE RATINGS AND RIB RATIOS DETERMINED FOR DRILL AND BLAST CASE STUDY TUNNELS

CASE NO.	TUNNEL SIZE (ft.)	ROCK TYPE	RSR DETERMINATION				SUPPORT		
			A	B	C	TOTAL	SIZE	SPACE	RIB RATIO
18-1	8 DIA	1	10	15	15	40	4WF13	6' ctrs.	47
19-1	8 DIA	1	10	15	15	40	4WF13	6' ctrs.	47
20-1	34 DIA	2	12	24	15	51	10WF49+	4.5'ctrs.	27
-2		2	12	24	15	51	10WF49+	4.5'ctrs.	27
21-1	22X30HS	3	14	20	18	52	8WF28	6.7'ctrs.	19
-2		3	14	27	18	59	8WF28+	5.7'ctrs.	23
-3		3	14	27	12	53	8WF28+	5.6'ctrs.	23
-4		3	14	27	17	58	8WF35	6.0'ctrs.	28
-5		3	14	32	17	63	8WF35	6.0'ctrs.	28
22-1	24H.DIA	2	12	14	10	36	10WF33	3.2'ctrs.	53
-2	33H.DIA	2	12	14	10	36	10WF45	2.6'ctrs.	53
23-1	18.5HS	3	14	30	12	56	6M25	5.9'ctrs.	29
-2		3	-	-	-	-	-	-	-
-3		3	14	20	12	46	6M25	4.4'ctrs.	39
-4		3	14	30	6	50	6M25	5.5'ctrs.	31
-5		3	14	17	6	38	6M25+	4.2'ctrs.	40
-6		3	14	24	6	44	6M25	5.0'ctrs.	34
-7		3	14	18	9	41	6M25	4.0'ctrs.	43
-8		1-3	9	16	7	32	8M32.6+	4.3'ctrs.	51
24-1	18.5HS	3	9	17	10	36	6M25	4.0'ctrs.	43
-2		3	14	18	15	47	6M25	5.2'ctrs.	33
-3		2	12	24	12	48	6M25	5.9'ctrs.	29
-4		3	22	24	6	52	6M25	6.1'ctrs.	28
-5		3	14	18	10	42	6M25	4.0'ctrs.	43
25-1	23X22HS	2	23	15	15	53	10X10	2.5'ctrs.	29
-2		1	26	15	18	59	10X10+	5.9'ctrs.	13
-3		1	15	15	15	45	12X12+	2.9'ctrs.	43
-4		2	8	15	7	30	16X16	2.5'ctrs.	85
-5		1	15	15	9	39	12X12+	2.7'ctrs.	40
-6		2	12	15	6	33	12X12+	2.5'ctrs.	53
-7		1	26	15	15	56	10X10+	4.3'ctrs.	18
26-1	23X23HS	3	22	24	18	64	8WF24+	6.1'ctrs.	18
-2		3	22	24	20	66	8WF24+	6.5'ctrs.	17

Figure 4.4 (continued)

ROCK STRUCTURE RATINGS AND RIB RATIOS DETERMINED FOR DRILL AND BLAST CASE STUDY TUNNELS

CASE NO.	TUNNEL SIZE (ft.)	ROCK TYPE	RSR DETERMINATION				SUPPORT		
			A	B	C	TOTAL	SIZE	SPACE	RIB RATIO
26-3	23X23HS	3	14	24	15	53	8WF24+	4.0'ctrs.	28
-4		3	22	24	18	64	8WF24+	6.1'ctrs.	18
-5		3	22	24	18	64	8WF24+	6.3'ctrs.	18
-6		3	14	24	10	48	8WF24+	3.1'ctrs.	48
-7		3	22	24	14	60	8WF24+	6.2'ctrs.	18
-8		3	14	15	15	44	8WF24	2.3'ctrs.	55
27-1	14X15HS	3	22	30	20	72	NONE	-	0
-4		2	20	30	20	70	NONE	-	0
-6		3	22	25	18	65	NONE	-	0
-7		3	14	12	10	36	6M20	3.8'ctrs.	61
28-1	18X18HS	1	26	41	20	87	NONE	-	0
-4		1	26	38	20	84	NONE	-	0
-5		3	22	30	20	72	NONE	-	0
-7		1	15	24	14	53	6H25	5.0'ctrs.	36
29-1	14X14HS	3	22	37	20	79	NONE	-	0
-2		3	14	24	12	50	6H20	5.5'ctrs.	42
-3		2	12	15	10	37	6H20	4.5'ctrs.	52
30-1	19X19HS	3	22	36	18	76	NONE	-	0
-2		3	14	25	10	49	6H25	4.0'ctrs.	41
31-1	17X16HS	2	12	15	9	36	10X10+	2.5'ctrs.	56
-2		2	8	15	7	30	12X12+	2.1'ctrs.	78
-3		1	15	15	10	40	10X10+	2.3'ctrs.	60
-4		2	9	15	7	31	12X12+	2.3'ctrs.	80
32-1	17X16HS	2	13	24	10	47	10X10+	2.9'ctrs.	45
-2		3	13	24	15	52	10X10	3.4'ctrs.	38
-3		2	8	15	6	29	12X12+	2.1'ctrs.	106
-4		2	8	15	10	33	12X12	2.0'ctrs.	101
33-1	22X30HS	3	22	25	12	59	RK.Blts.+	4'X4'±	14
-2		3	22	25	8	55	6H20+	4.4'ctrs.	25
-3		3	14	25	6	45	8H34+	3.9'ctrs.	37
-4		3	14	24	10	48	6H20+	4.3'ctrs.	30
-5		3	22	24	12	58	6H20+	4.7'ctrs.	22
-6		3	14	19	12	45	6H20+	4.6'ctrs.	25
-7		3	22	24	15	61	6H20+	4.9'ctrs.	15

NOTES: ROCK TYPE: 1)Igneous 2)Sedimentary 3)Metamorphic

8WF28+ indicates size most prevalent in this area of tunnel (more than one size used)

Figure 4.4 (continued)

The upper and lower limits of RSR values defined by rib ratios of 0 and 100 respectively, indicate the general range or type of rock structure with which this study is concerned. Structures with an RSR rating of less than 27 would require heavy support, those with ratings above 77 would probably be unsupported. Rock structures with a rating of between 27 and 77 would require various types and quantities of ground support which is discussed in the following paragraphs.

4.4 SUPPORT REQUIREMENTS

This section of the report considers three primary support systems; steel ribs, rock bolts and shotcrete. The rib ratio concept, developed as a tool to be used in correlating actual support installations with determined RSR evaluations, relates only to steel ribs. Records of tunnel projects in which rock bolts were used generally indicated only the total number or weight of bolts without reference to location, spacing or length. Records or information pertaining to shotcrete were of the same general nature. In both instances, data was of little value in either analyzing or correlating support requirements with respect to rock structures.

Although there is a definite increase in the use of rock bolt and/or shotcrete support, there appears to be little factorial data by which these systems can be directly correlated with geological predictions. General appraisals which show equivalent conventional support systems for various rock types have been presented as guidelines to be used in the design of tunnel structures. Deere (Reference 3), Sutcliffe and McClure (Reference 7), Linder (Reference 8) and Lauffer (Reference 9) have made studies or presented papers which relate load carrying capacities of the three ground support systems. Those studies, which combine theoretical analysis and empirical evaluations along with various rules-of-thumb developed in the tunnel industry, reflect the general approach presently used in determining the requirements or use of shotcrete and rock bolts. These types of support are often installed primarily as a safety precaution rather than a designed structural system or member; the same as with use of steel ribs.

By using the data and relationships derived from rib ratio determinations, rules-of-thumb and various theoretical analyses, it is possible to show a correlation between conventional ground support systems and geological predictions (RSR).

The rib ratio basically defines an anticipated rock load by considering the load carrying capacity of different sizes of steel ribs. By using case history data, a general relationship between rib ratios (or equivalent rock loads) and RSR evaluations has been developed. It follows that RSR values can also be expressed in terms of unit rock loads for various sized tunnels. Derivation of this empirical relationship is shown on Figure 4.5. Formula (14) was used to determine RSR values corresponding to various combinations of tunnel diameters and rock loads. Results are tabulated on Figure 4.6.

Requirements of conventional support systems are usually determined on basis of anticipated rock loads. Figure 4.6 shows a relation between geological predictions (RSR) and anticipated rock loads which can be used to determine appropriate support for different sized tunnels.

4.4.1 Steel Rib Support

Requirements for a particular steel rib are usually expressed by the rib spacing determined for different rock loads and size of tunnels. This determination was made for the datum condition, and reflects a rib ratio of 100 and corresponding Rock Structure Rating value of 27. Spacings for other RSR

EMPIRICAL FORMULAE FOR RSR, RR AND ROCKLOAD

Using values of rock structure rating (RSR) and rib ratios (RR) computed from case study geologic sections, a graph (Figure 4.3) was plotted using RSR from 0 to 100 as ordinate and RR from 0 to 100 as abscissa, Formula (6) shows the average curve for these points.

$$(RR + 70)\ (RSR + 8) = 6000 \tag{6}$$

Or

$$RSR = \left[\frac{6000}{RR + 70}\right] - 8 \tag{7}$$

It was observed that a direct relationship exists for the rock structure rating and unit rock load (Wr = K/Sq. Ft.) for a specified size of tunnel. This empirical relationship can be derived as follows:

$$Wr = \frac{Pr}{Sa} \div 1000 \tag{8}$$

$$Sa = \frac{Pr}{1000 \times Wr} \tag{9}$$

Combining Formulae (5) from Figure 4.1 and (7)

$$RSR = \left[\frac{6000}{\left(\frac{Sd \times 100}{Sa}\right) + 70}\right] - 8 \tag{10}$$

Substituting for Sa (Formula (9))

$$RSR = \left[\frac{6000}{\left(\frac{Sd \times 100 \times Wr \times 1000}{Pr}\right) + 70}\right] - 8 \tag{11}$$

Restating Formulae (4) from Figure 4.1

$$\frac{Sd}{Pr} = \frac{1}{331D} \tag{12}$$

Figure 4.5

Substituting for $\frac{Sd}{Pr}$ in Formula (11)

$$RSR = \left[\frac{6000}{\left(\frac{100,000\ Wr}{331D}\right) + 70} \right] - 8 \qquad (13)$$

Or

$$RSR = \left[\frac{6000}{\left(\frac{302\ Wr}{D}\right) + 70} \right] - 8 \qquad (14)$$

Restated to find Wr, given RSR & D:

$$Wr = \frac{D}{302} \left[\frac{6000}{RSR + 8} \right] - 70 \qquad (15)$$

OR

$$Wr = \frac{D \times RR}{302} \qquad (16)$$

General empirical formulae for (6), (14) & (15) can be written as follows:

$$(RR + A) \quad (RSR + B) = C \qquad (6)$$

$$RSR = \left[\frac{C}{\left(\frac{302\ Wr}{D}\right) + A} \right] - B \qquad (14)$$

$$Wr = \frac{D}{302} \left[\frac{C}{RSR + B} \right] - A \qquad (15)$$

For this report:

A = 70

B = 8

C = 6000

Figure 4.5 (Continued)

CORRELATION OF ROCK STRUCTURE RATING TO ROCK LOAD AND TUNNEL DIAMETER

(Based on Formula (14) in Figure 4.5)

TUNNEL DIAMETER (D)	(Wr) ROCK LOAD ON TUNNEL ARCH (K/sq. ft.)											
	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
	CORRESPONDING VALUES OF ROCK STRUCTURE RATINGS (RSR)											
10'	62.5	51.9	44.0	38.0	29.4	23.4						
12'	64.7	55.0	47.7	41.9	33.2	27.2						
14'	66.3	57.5	50.6	45.0	36.5	30.4	25.7					
16'	67.5	59.5	53.0	47.7	39.4	33.2	28.5	24.7				
18'	68.5	61.1	55.0	49.9	41.9	35.8	31.0	27.2				
20'	69.4	62.5	56.8	51.9	44.0	38.0	33.2	29.4	26.1			
22'	70.1	63.7	58.2	53.6	46.0	40.0	35.3	31.4	28.1	25.4		
24'	70.6	64.7	59.5	55.0	47.7	41.9	37.1	33.2	30.0	27.2		
26'	71.1	65.5	60.6	64.4	49.2	43.5	38.8	35.0	31.7	28.8	26.4	
28	71.6	66.3	61.6	57.0	50.6	45.0	40.4	36.5	33.2	30.4	27.9	25.7
30'	72.0	66.9	62.5	58.6	51.9	46.4	41.9	38.0	34.7	31.9	29.4	27.2

Figure 4.6

values (or equivalent rock loads shown in Figure 4.6) vary proportionately from the datum as the inverse ratio of the respective rib ratios. Figure 4.7 shows typical rib sizes and required spacing with respect to tunnel size and RSR evaluations.

4.4.2 Rock Bolts and Shotcrete

An appraisal of rock bolt requirements (spacing or pattern) can be made by considering rock loads with respect to the tensile strength of the bolt. This is a very general approach; it assumes adequate anchorage and that all bolts act in tension only. It does not allow for interaction between adjacent blocks nor assumption of compression arch formed by the bolts. These and other conditions would probably be evaluated in detailed design, but for purposes of this study the following criteria, based on these assumptions, is used:

Size of bolt	1" Ø
Length	Adequate
Working Load	24,000 lb.
Rock load in kips/sq.ft.	= Wr
Spacing or pattern of bolts (in feet)	$= \sqrt{\frac{24}{Wr}}$ (17)

Although shotcrete support has been successfully used under many varied conditions, there is still no accepted theory as to its ultimate effect as a structural member. Most applications have been made on basis of rules-of-thumb. As previously mentioned, various studies have indicated a general relationship between thickness of shotcrete lining and other equivalent support systems. An attempt was made to correlate available theoretical and empirical data with some standard measure of the shotcrete requirement which could be

RIB SPACING (IN FEET) BASED ON RSR AND TUNNEL DIAMETER

RR	RSR	10' DIA.			12' DIA.			14' DIA.		
		4I7.7	4H13	6H15.5	4H13	6H15.5	6H20	4H13	6H15.5	6H25
100	27	1.14	2.01	3.31	1.51	2.39	3.03	1.16	1.81	2.86
88	30	1.30	2.28	3.76	1.72	2.72	3.44	1.32	2.06	3.25
70	35	1.86	2.87	4.73	2.16	3.41	4.33	1.66	2.59	4.09
55	40	2.07	3.65	6.02	2.75	4.35	5.51	2.11	3.29	5.20
43	45	2.65	4.67	7.70	3.51	5.56	7.05	2.70	4.21	6.65
33	50	3.45	6.09	10.03	4.58	7.24	9.18	3.52	5.48	8.67
25	55	4.56	8.40		6.04	9.56		4.64	7.24	
18	60	6.33			8.39			6.44	10.06	
12	65	9.50						9.67		

RR	RSR	16' DIA.			18' DIA.			20' DIA.		
		6H15.5	6H25	8WF31	6H15.5	6H25	8WF40	6H20	8WF31	8WF48
100	27	1.42	2.25	3.24	1.14	1.81	3.37	1.20	2.14	3.34
88	30	1.61	2.56	3.68	1.30	2.06	3.83	1.36	2.43	3.80
70	35	2.03	3.21	4.63	1.86	2.59	4.81	1.71	3.06	4.77
55	40	2.58	4.09	5.89	2.07	3.29	6.13	2.18	3.89	6.07
43	45	3.30	5.23	7.53	2.65	4.21	7.84	2.79	4.98	7.77
33	50	4.30	6.82	9.82	3.45	5.48	10.21	3.64	6.48	10.12
25	55	5.68	9.00		4.56	7.24		4.80	8.56	
18	60	7.89			6.33	10.06		6.67		
12	65				9.50			10.00		

Figure 4.7

RIB SPACING (IN FEET) BASED ON RSR AND TUNNEL DIAMETER

RR	RSR	22' DIA.			24' DIA.			26' DIA.		
		6H25	8WF31	8WF48	6H25	8WF40	10WF49	8WF31	8WF40	10WF49
100	27	1.23	1.78	2.78	1.04	1.95	2.59	1.29	1.67	2.22
88	30	1.40	2.02	3.16	1.18	2.22	2.94	1.47	1.90	2.52
70	35	1.76	2.54	3.97	1.49	2.79	3.70	1.84	2.39	3.17
55	40	2.24	3.24	5.05	1.89	3.55	4.71	2.35	3.04	4.04
43	45	2.86	4.14	6.47	2.42	4.53	6.02	3.00	3.88	5.16
33	50	3.73	5.39	8.42	3.15	5.91	7.85	3.91	5.06	6.73
25	55	4.92	7.12		4.16	7.80	10.36	5.16	6.68	8.88
18	60	6.83	9.89		5.78	10.83		7.17	9.28	
12	65	10.25			8.67			10.75		

RR	RSR	28' DIA.			30' DIA.		
		8WF31	8WF48	12WF53	8WF40	10WF49	12WF65
100	27	1.11	1.74	2.35	1.25	1.67	2.35
88	30	1.26	1.98	2.67	1.42	1.90	2.67
70	35	1.59	2.49	3.36	1.79	2.39	3.36
55	40	2.02	3.16	4.27	2.27	3.04	4.27
43	45	2.58	4.05	5.47	2.91	3.88	5.47
33	50	3.36	5.27	7.12	3.79	5.06	7.12
25	55	4.44	6.95	9.40	5.00	6.68	9.40
18	60	6.17	9.67		6.94	9.28	
12	65	9.25			10.42		

Figure 4.7 (continued)

related to geologic predictions. Results were negative. Consequently the following empirical relationship is suggested. It is used in subsequent evaluations of shotcrete requirements:

$$t = 1 + \frac{Wr}{1.25} \quad \text{or} \quad t = \frac{D}{150}(65 - RSR) \tag{18}$$

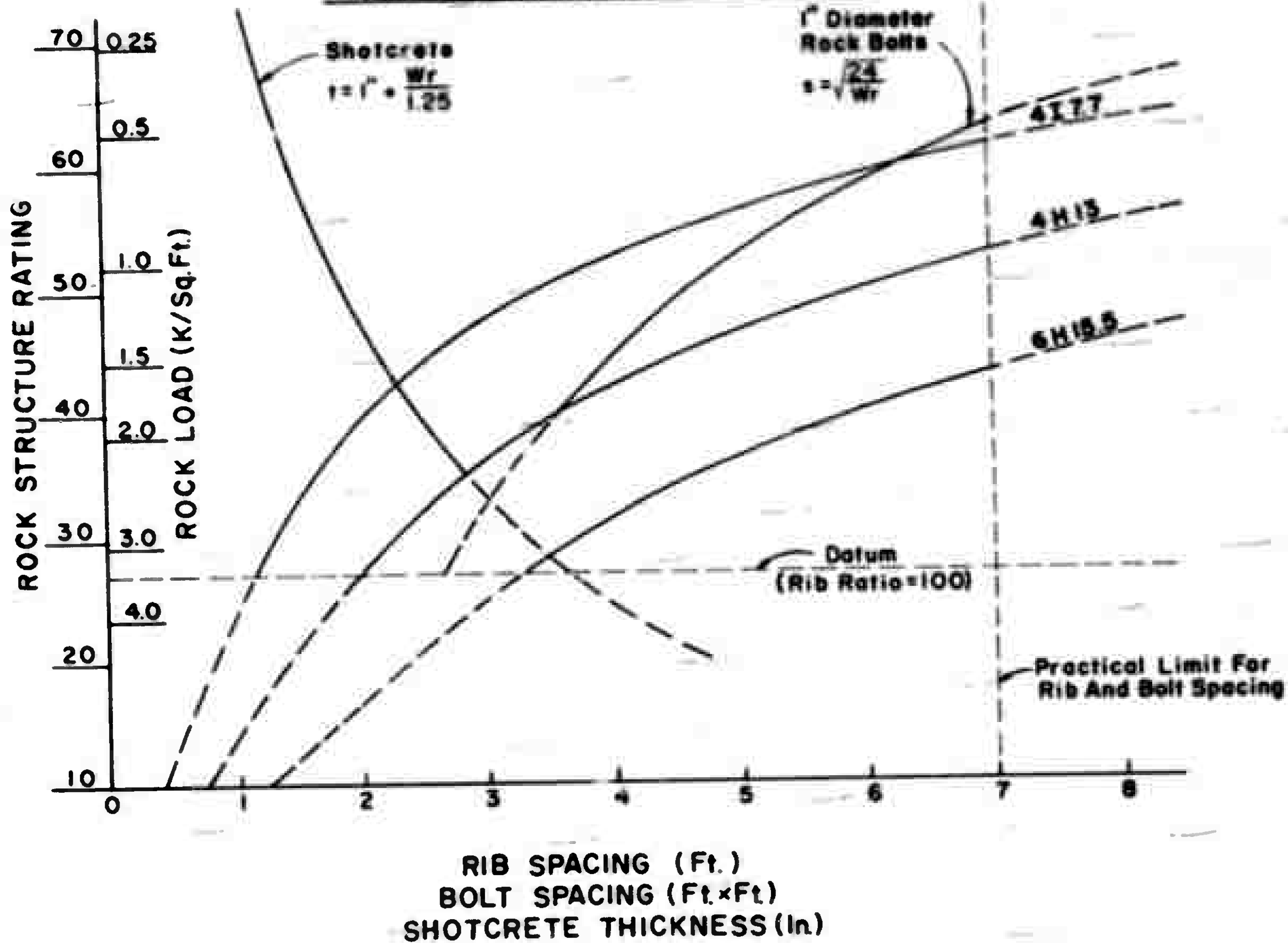
Where (t) equals nominal thickness of shotcrete lining in inches and Wr = anticipated rock load in kips per sq. ft.

4.5 SUPPORT REQUIREMENT CHARTS

The preceding paragraphs have discussed various support requirements and have indicated common measures by which these requirements can be correlated with respect to geologic predictions and tunnel size. Using the derived data shown on Figures 4.6 and 4.7 and relationships given in paragraph 4.4.2 it is possible to develop "Support Requirement Charts" for tunnels driven through different rock structures. Typical charts are shown in Figures 4.8 through 4.12. Others could be similarly developed for different sized tunnels. The three steel rib support curves shown on each chart reflect the typical sizes of ribs used for the particular tunnel diameter. Dashed portion of the respective curves indicate conditions for which the indicated rib size would probably not be used due to practical considerations. Curves for shotcrete and rockbolt requirements are similarly shown.

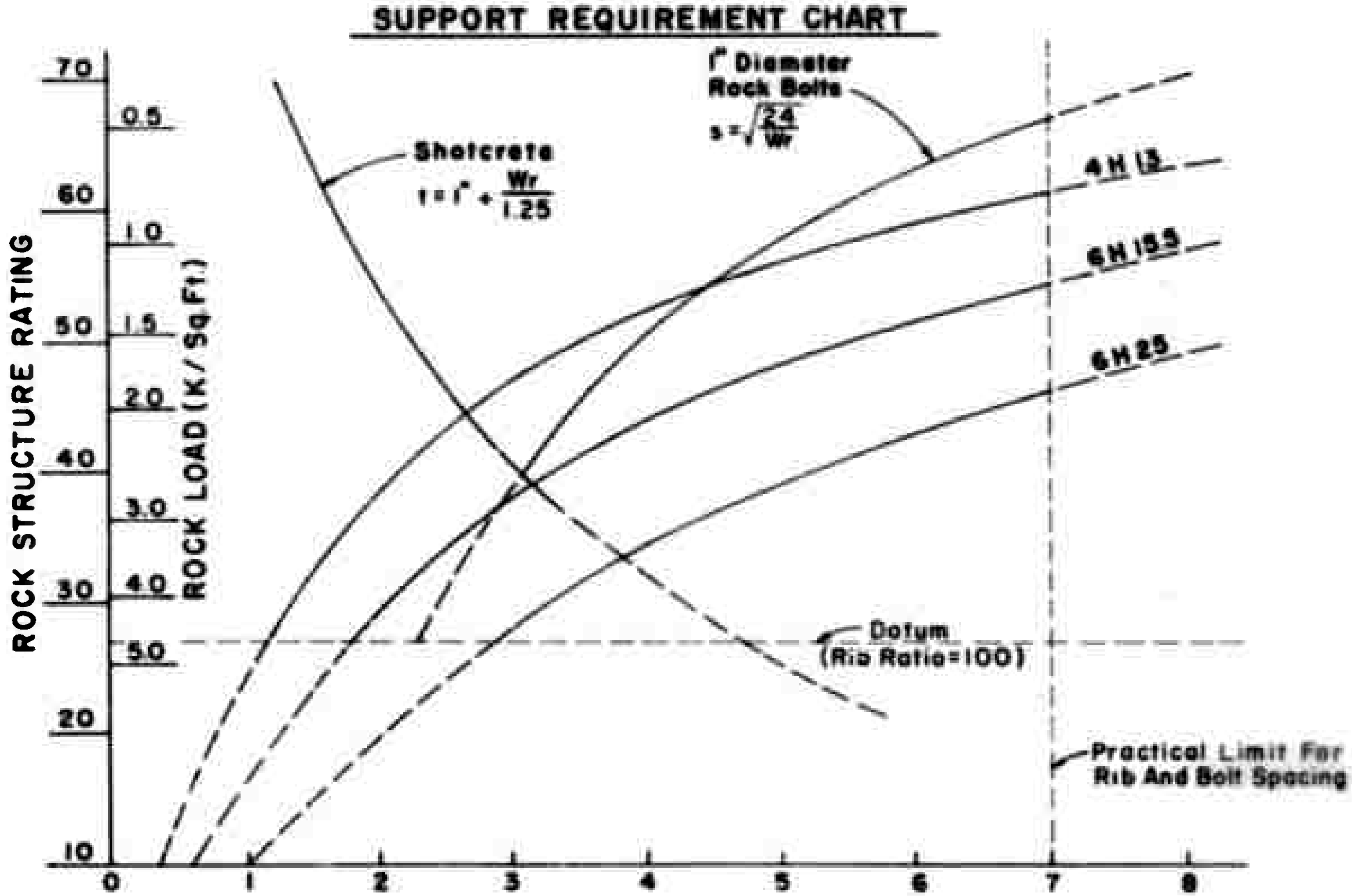
The charts would be used as follows: Assume a 30' tunnel to be driven through a rock structure with an RSR value of 60. From Figure 4.12 three support systems could be used -- 1) a 2-1/2" nominal thickness of shotcrete, 2) 1" dia. rock bolts on a 3.5' pattern or 3) 8" WF 40# ribs on 6' centers. The most appropriate system would be determined by a cost analysis of each, which is discussed in Section 8.

SUPPORT REQUIREMENT CHART



10' DIAMETER TUNNEL

Figure 4.8

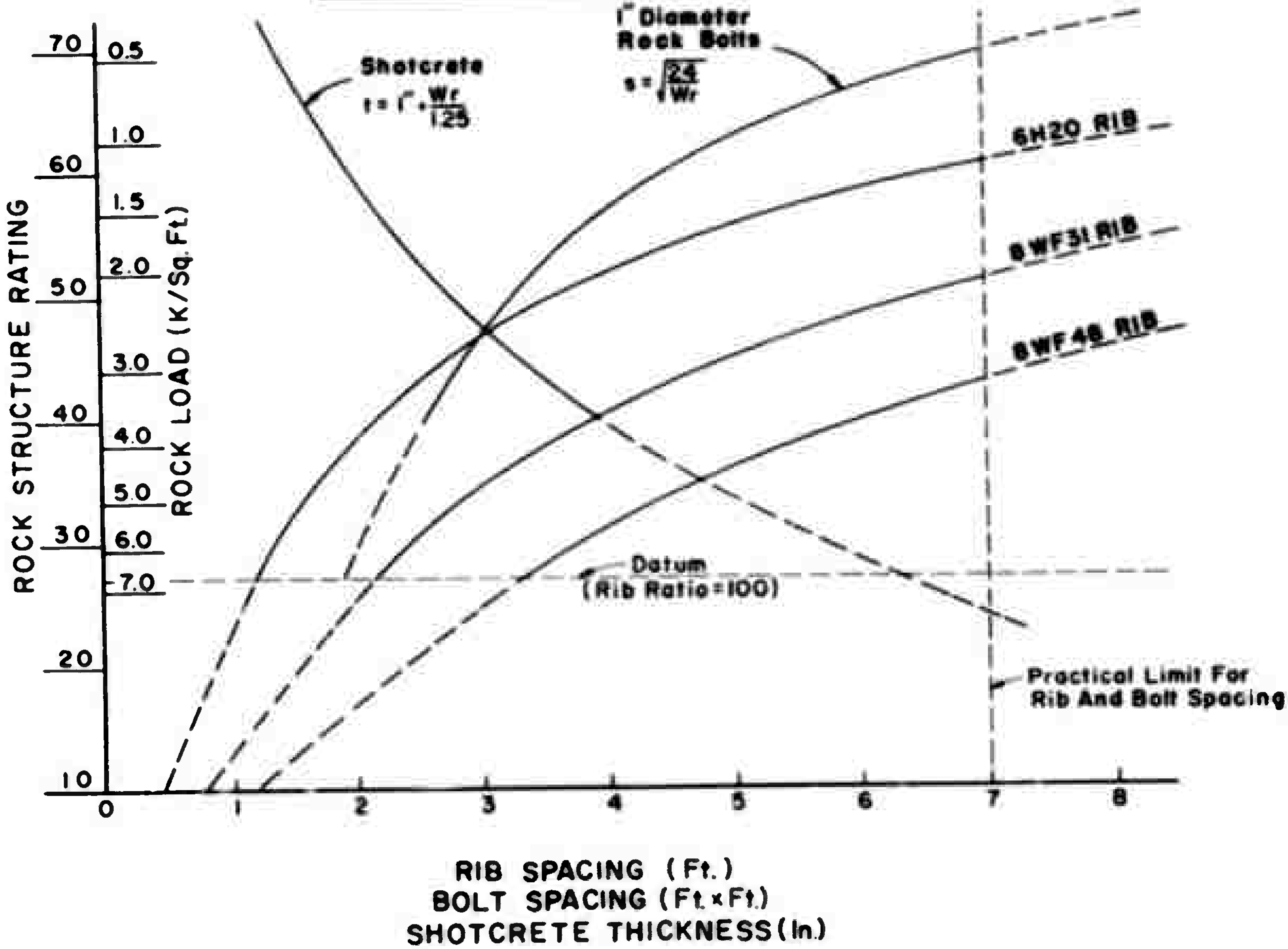


RIB SPACING (Ft.)
BOLT SPACING (Ft. × Ft.)
SHOTCRETE THICKNESS (In.)

14' DIAMETER TUNNEL

Figure 4.9

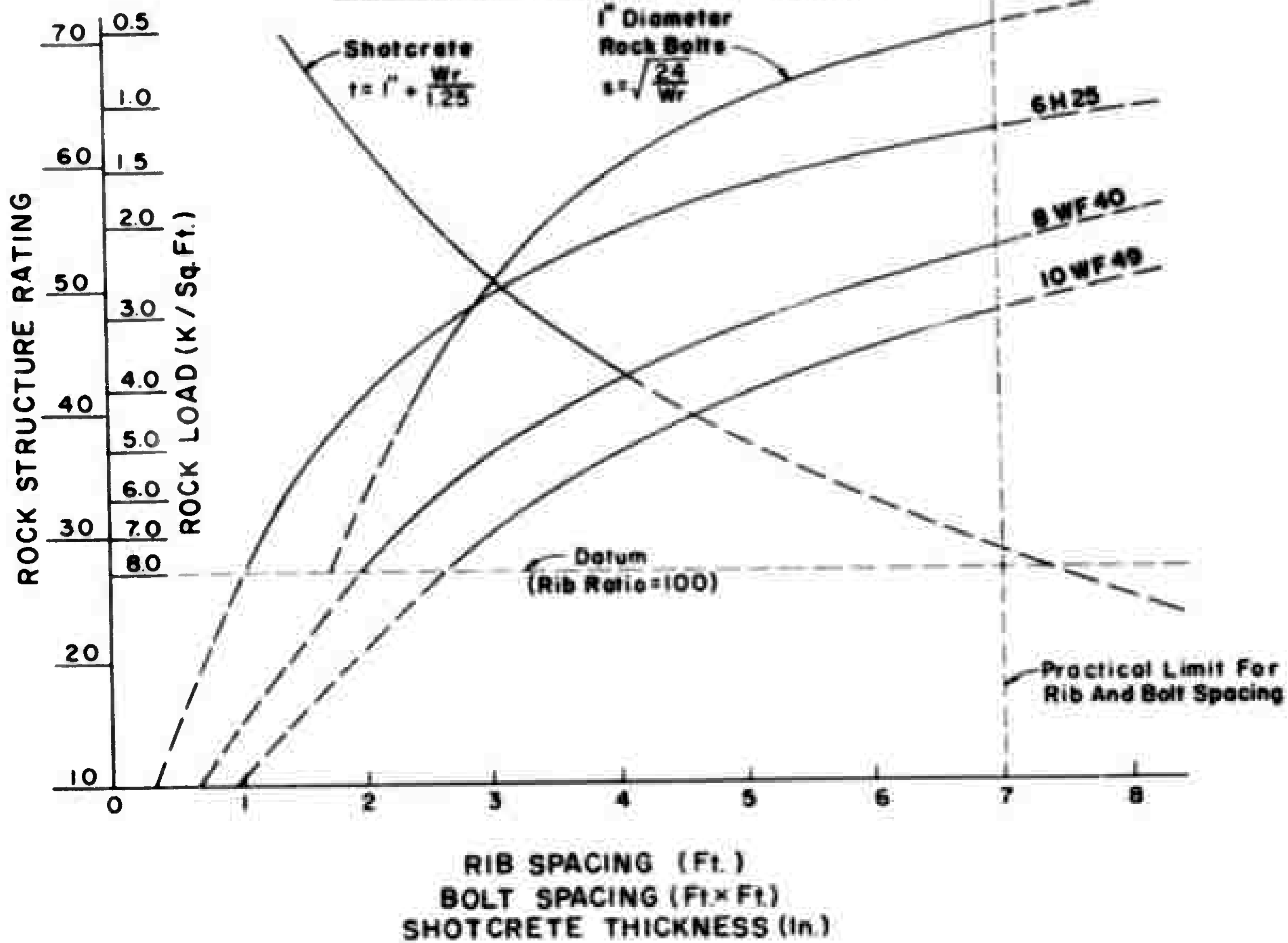
SUPPORT REQUIREMENT CHART



20' DIAMETER TUNNEL

Figure 4.10

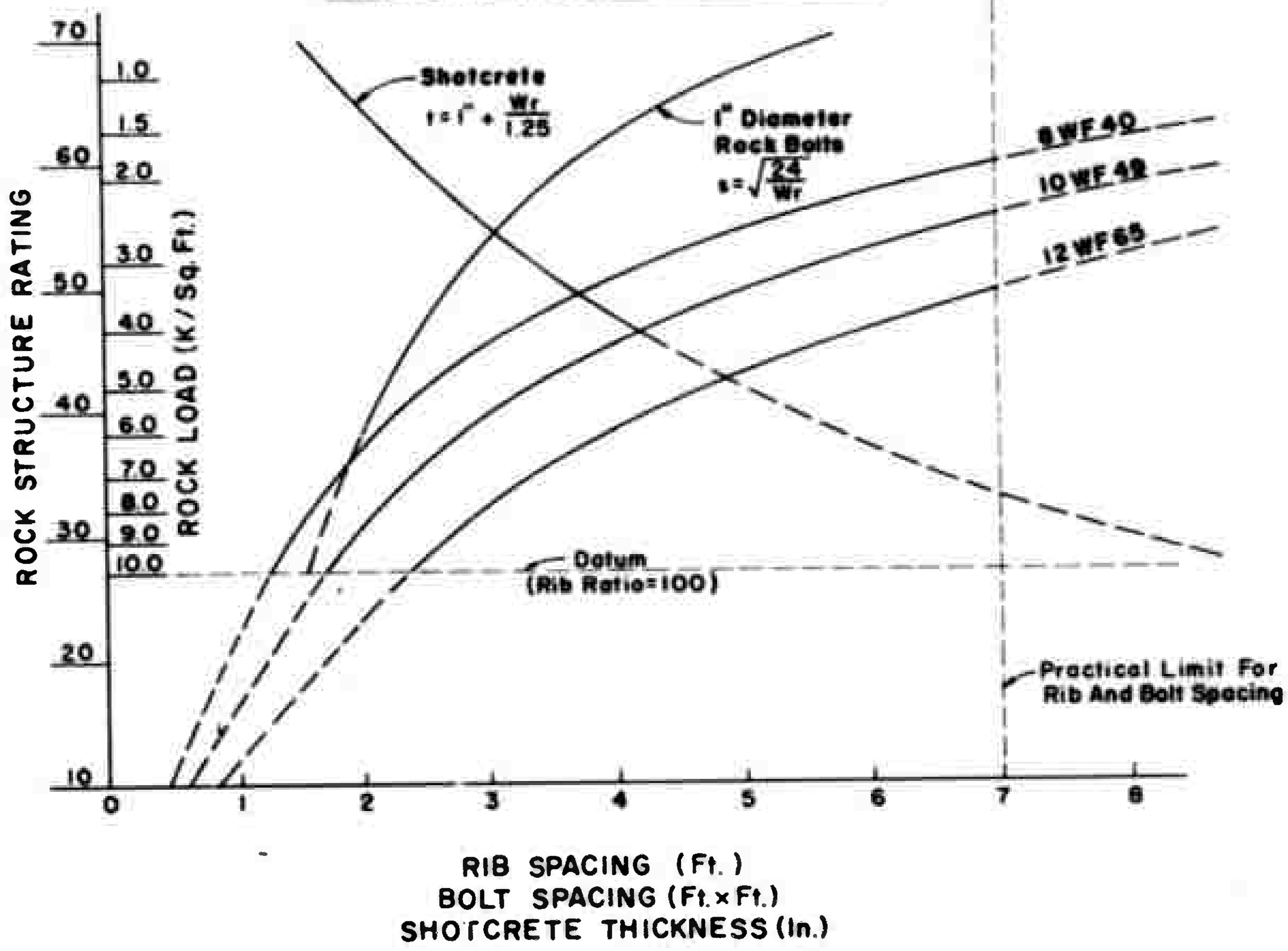
SUPPORT REQUIREMENT CHART



24' DIAMETER TUNNEL

Figure 4.11

SUPPORT REQUIREMENT CHART



30' DIAMETER TUNNEL

Figure 4.12

4.6 CONCLUSIONS

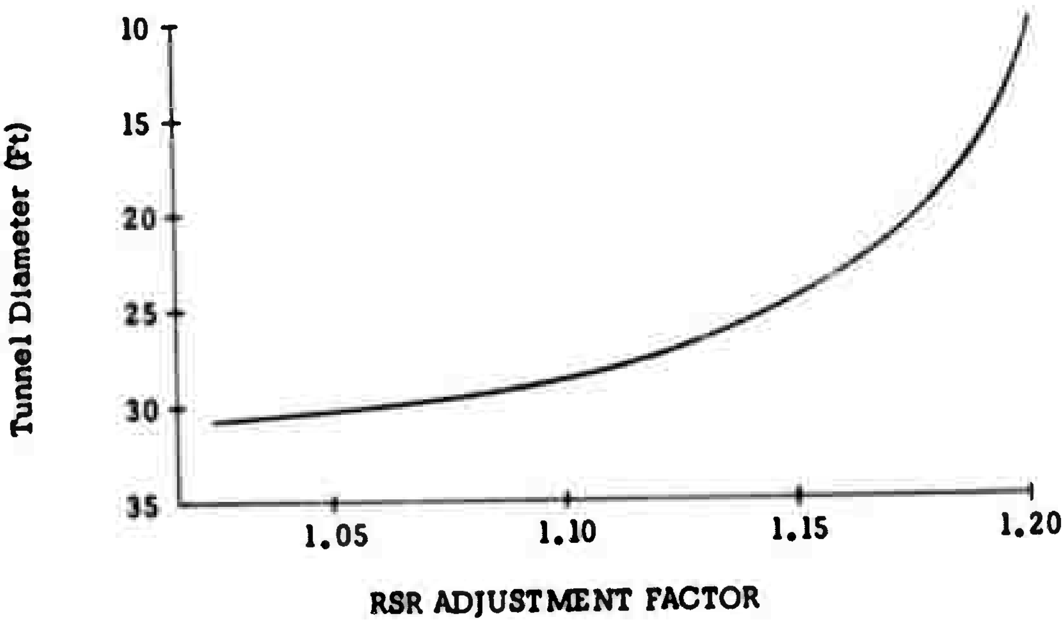
The overall determination of ground support requirement is based on case history data obtained from various sources, the RSR method of evaluating rock structures, and the rib ratio concept discussed in paragraph 4.2. The chart shown on Figure 4.3 gives an indication of possible deviation or degree of reliability that might be expected for any specific determination. The proposed methods and evaluations could be modified to reflect more definitive data that might be available from continued research. The datum condition used in developing the rib ratio concept is not critical, and could be changed without affecting the results.

Although existing methods or concepts of determining support requirements were also considered, no comparative analysis was made between these and the proposed method. However, this could be accomplished by using the intrinsic relationship between rib ratios and rock loads. Most support calculations consider loads in terms of feet of rock to be supported. Height (in feet) of the unit rock column is defined as $\left[n\ (B + H)\right]$ where n is a variable factor and B and H represent physical dimensions of the tunnel opening. Assuming the unit weight of rock as 165#/cu.ft. and that B = H = D (for a circular tunnel) the factor "n" can be approximated by dividing rib ratios used in this study by 100, i.e.,

$$n \cong \frac{RR}{100} \qquad \left(n = \frac{RR}{99.6}\right) \qquad (19)$$

The support requirement charts reflect drill and blast tunneling operations. Although boring machines were used on several case study projects, information was not sufficient to make any conclusive correlation of support requirements between the two methods. Considering data that was available, it is suggested that the following procedure be used in determining support requirements for machine driven tunnels. The RSR value would be adjusted upward to reflect a better condition of the penetrated rock structure normally associated with the use of a boring machine. Such a factor might be defined by the following curve:

RSR ADJUSTMENT FOR TBM OPERATION



For example - An RSR value of 50 has been determined for a 25 ft. tunnel. In considering appropriate support systems for a boring machine operation an RSR value of 58 (50 x 1.15) would be used when entering the Support Requirement Chart.

SECTION 5

GEOLOGICAL INVESTIGATIONS - AREA OF IMPROVEMENT

5.1 INTRODUCTION

This section deals with areas of potential improvement and indicates desirable goals and/or new concepts for making geological investigations which could lead to more reliable predictions of ground support. It relates primarily to data pertinent to rock structure ratings and discusses briefly, various techniques such as 1) drilling, 2) surface geology, 3) historical geology and records and 4) geo-physical methods.

The present state-of-the-art of making geological investigations for tunnels consists of methods or modifications thereof which have been used for many years. In general, they are limited to surface geology and vertical borings. These and other techniques have been discussed in previous sections and comments made as to the amount of detail provided and the degree of reliability in using given data for the prediction of ground support.

Some of the improvements or new concepts which have contributed to the art of making geological investigations during the last half century include: more rapid coring by wire line coring techniques; electronic well surveys; seismic and sonic geo-physical methods; sidewall coring; thermic, magnetic and gravimetric surveys; aerial photography and other airborne sensors. Most of the effort directed toward the development of these methods or procedures has been put forth by the mining and petroleum industries. Their primary goal has been to locate or define the limits of mineral deposits. Rock structure characteristics pertinent to ground support may have been considered but usually any such data would be secondary to the primary goal. Consequently, most of the results obtained from these improved techniques are not sufficient in themselves to provide the type or amount of geological information needed to predict ground support. They do, however, provide the major source of technological advances to be considered in the development of new or improved concepts for making geological investigations for tunnel construction.

5.2 STANDARDIZATION

Although continued research will undoubtedly provide better or new techniques for making geological investigations, the most immediate and probably most significant area for improvement would be in the standardization of requirements or criteria used to obtain, record and interpret geological information. This seemingly simple goal which has been advocated by many individuals is unduly complicated by the fact that several disciplines are involved. It will require certain compromises in presently accepted standards and necessitate the general concurrence of all involved disciplines with respect to the following:

1. Designation of most pertinent geologic factors affecting rock structure and support requirements.
2. Defining those factors in common terms and delineating limits of measure which can be ascertained in the pre-construction period.
3. Establish limits of responsibility between owners and contractors which could afford most feasible solution to the problem of support requirements.
4. Recommend feasible methods for making geological investigations which would provide necessary data.

The rock structure rating concept is related to the initial two requirements and provides at least the basis for a solution by which geologic data could be assimilated and correlated with respect to support requirements. The third item deals with legal and economic problems which are beyond the scope of the present study. The fourth factor deals with improvement of the present state-of-the-art for making site investigations and is discussed in the following paragraphs.

5.3 DRILLING

Most tunnel site investigations include various amounts of exploatory drilling; usually consisting of vertical borings near the portals or at locations of relative shallow cover along the tunnel alignment. Although general information pertaining to ground conditions, water tables, etc. is obtained; the primary purpose of the drilling is to provide core samples of the geological formations at or near tunnel grade.

Diamond core-drilling, which is the most broadly used present tool for investigating subsurface conditions, is nearly always done in conjunction with vertical holes. Occasionally short horizontal holes, usually less than 100 feet, have been drilled out ahead of an active tunnel job. Rarely, if ever, have long horizontal holes been used in planning or by contractors prior to bidding a tunnel to determine geological conditions.

The mining and petroleum industries have supported a large amount of diamond core drilling research. Some of this may be applicable to tunneling, particularly that which has been done for mining. There are about five major manufacturers of small to medium sized diamond exploratory drilling machines in the United States. At least three of these companies are large enough to support a reasonable amount of research and development. There has also been much work abroad to develop the exploratory drilling art, including work on diamond bit design and very deep drilling with small diameter holes in

South Africa. Even with the high pressures of inflation during the past few decades these progressive companies have been able to maintain a fairly uniform cost of drilling.

The petroleum industry has supported the development of tools for very deep coring. These holes; usually 6 to 12 inches in diameter, are frequently as deep as 10,000 to 20,000 ft. with a record depth of 30,000 ft. established in March, 1972. Most of this industry's drilling is in sedimentary rock. At the great depths in which they drill, the weaker shales can become as tough to drill as the hardest igneous or strongest metamorphic rock. The depth capacity of these rigs is far more than will be required for tunnel exploration as envisioned. They are generally too large and expensive to be used for tunnel investigations but their drilling techniques must be examined.

Each of the major diamond drill manufacturers offer at least four portable rigs ranging in size from 12 to 60 horsepower with depth capacities from approximately 700 to 4,000 feet. The cost range is between $6,000 and $20,000. All except the smallest rig will handle the four sizes of standard drill rod assemblies approved by the Diamond Core Drill Manufacturers Association (DCDMA). These sizes; A,B,N and H, are adaptable to wire line coring techniques. The drill rigs weigh from 1,000 to 6,000 pounds and are usually skid mounted; some are trailer mounted and the larger ones are sometimes truck mounted. They can be driven by conventional prime movers; gasoline, diesel, electric or air.

Wire line core barrels have become very popular in recent years since they permit pulling the core through the drill rod thus saving time in rod handling. A crew of two or three men can obtain about 40 feet of core under ordinary drilling conditions in an 8 hour shift. Quality, or integrity, of the core will vary with rock formations, equipment and skill of the crew. Accessory equipment required besides core barrels and overshots includes a hoist, swivel, fishing tools, pump (about 30 gpm at 500 psi), miscellaneous subs and a mud pit which is sometimes made at the site. In most areas of the United States, contract diamond drilling crews are locally available for this type of exploratory drilling.

Diamond drilling is time consuming and rather high in cost. The cost per foot of vertical holes could vary from $3.00 to $20.00, depending on location, access and work conditions and type of rock encountered. In vertical drilling it is obviously necessary to pay for many more feet than actually needed to sample the rock structure at tunnel grade. In remote areas difficult access often raises cost and time requirements to such a level that drilling is not economically feasible. The contractors, who wish to submit bids for a tunnel job, cannot undertake an extensive drilling program at their own expense. In many cases the owners' design budget is not sufficient to cover an adequate amount of exploratory drilling.

There would undoubtedly be an increase in the number of vertical probe holes used in exploratory investigations for tunnels if there could be a substantial reduction in cost and time requirements. At the present time, however, it is unlikely that there will be any significant improvement in vertical core drilling technology beyond that which can be expected from the diamond drilling manufacturing industry. Some increase in drilling speed occasioned by longer bit life may be achieved. Time saved also may result from: continuous bit feed; a faster means of drilling open hole above the formation to be cored; or decrease in mobilization efforts.

Present cost of vertical drilling could be reduced by increasing the drilling speed and reducing time required for mobilization. Unfortunately, increasing mobility often works against reduction of time because such mobility requires lighter rigs, usually with a reduction in drilling speed capability. To reach the level where cores may be required there is the possibility that the speed of making vertical probes may be increased by using down-hole drills. However, the only successful drills of this type now on the market are air operated. They can be used only in reasonably dry holes as they operate poorly under any significant head of water.

Horizontal drill holes with existing techniques are limited to about 2,000 feet and those beyond 500 feet have been very slow and expensive. The Japanese have been the most successful in developing equipment for drilling horizontal holes of several thousand feet length. Their equipment to date appears to be too massive and expensive for the type of drilling envisioned for tunnel exploration. Directional control of long horizontal drill holes is a major problem to be solved.

It would be highly desirable to be able to drill rapidly to at least 5,000 feet horizontally with some confidence of direction control. Such a capability from each end of a proposed tunnel would provide geological samples for 10,000 feet which would probably represent a substantial portion of the individual lengths of many rock tunnels.

The greatest potential improvement in the art of exploratory drilling lies in the area of horizontal drilling techniques. Separate work by the Bureau of Mines being conducted under the ARPA program is directed toward this goal. (Reference 16) The primary purpose of this work is to probe approximately 1,000 feet ahead of a tunnel boring machine to determine ground conditions and possible hazards. The techniques being developed for that research contract might be expanded to drill horizontal holes several thousand feet in depth prior to start of tunnel construction. This would permit more reliable evaluation of geological conditions and determination of ground support requirements.

Briefly, the proposed system provides a method of storing a minimum of 1,000 feet of coupled drill rod in a ground storage pipe in back of a hollow spindle drill. The drill rod is run in and out of the hole by means of a rapid rod extractor, which is also being developed. This reduces greatly the normal time of handling individual lengths of rod. The system will permit changing from a core drilling mode (required for sampling at 50 foot intervals) to a more rapid in-hole percussion drilling for the major length of the hole. It would be fairly simple to run an electronic survey in these holes to determine if observed differences in intermittent cores could be correlated with differences in electronic resistivity or response to exposure to a radioactive source. The advantage here would be that less expensive and more rapid non-coring method of drilling might be used for future horizontal exploration for tunnels.

5.4 SURFACE GEOLOGY

The most reliable geological prediction tool for a tunneling contractor is probably the analysis of surface geology. Other techniques, such as borings, can be and should be used to expand and verify geologic information developed from surface investigations. The geology of some areas might be classified as predominantly sedimentary, metamorphic or igneous which facilitates the extrapolation of surface data to tunnel grade. In other areas the surface survey may only indicate the possibility of encountering various types of geological formations along the tunnel line. In either instance, the skill and knowledge of an engineering geologist is required to develop and interpret pertinent surface geology data.

A potential area of improvement with respect to surface geology lies in a better understanding and definition of the relationship between geological data and the practical aspects pertaining to ground support requirements.

This is part of the standardization procedure previously mentioned. The ever increasing need and importance of underground excavation projects should provide the incentive necessary to accomplish this goal. Better utilization of case history records, correlation of surface and as-built geology and the comparison of results and findings between different projects will be helpful.

It is obvious that any extensive surface investigation requires adequate access along or near the surface alignment of the tunnel. At times it is very difficult and costly to provide this needed access. Under such circumstances it is likely that little or no surface geology would be prepared for the particular project. The solution of this problem is mainly one of economics. However, surface access should be given a high priority in the allocation of funds which may be available for site investigations.

5.5 HISTORICAL GEOLOGY

There will usually be some record of local geology available for nearly all potential tunnel projects. Most of the United States has fairly detailed state geologic surveys, particularly those with large mineral resources. The U. S. Geological Survey and other government agencies have good records covering most of the country. In areas where there has been oil well drilling, the rock bit manufacturing companies keep drill logs of all wells which would probably be available for informational purposes. Water well drillers have been active in many areas and may provide logs of wells drilled. In many instances these logs have been made a part of public records. Other potential sources would be mining companies who have conducted exploratory drilling operations in a particular area, records of previous underground construction, or deep excavations such as quarries.

Some of the information available from historical records may not be pertinent to the determination of ground support and in some cases may even be misleading. However, all such data should be considered. Improvements could be made by 1) providing a common source where all information would be available for review and 2) grouping, or cataloging the information by areas of interest such as tunnel construction, mining, etc.

5.6 PHOTOGRAPHY AND AIRBORNE SENSORS

Airborne techniques other than photography include radar, infrared, passive microwave mapping systems, passive microwave radiometers, radio frequency devices, spectrometers, laser profiles and specialized equipment for measuring induction effects. To date, only aerial photography, infrared mapping and radio imagery have been used to any significant extent. These techniques show promise in delineating rock boundaries and locations of faults.

Aerial photography is a very useful aid in locating observable surface features for geological mapping. Photographic analysis of ground covered by trees and plants frequently show distinctive boundaries between types of soil and/or rock outcrops based on type and extent of vegetation observed. Borehole cameras which can be inserted into small diameter holes to photograph the hole wall or rock in place have been developed and successfully used. For best results the hole must be dry. The Bureau of Mines has recently shown that rock movement or weaknesses can be detected with infrared, but the device must be within a few inches of the sample and does not provide a quantitative measure of the weakness.

In summary, aerial photographs show only very broad geological features. They give little information as to rock structure characteristics. Remote sensing techniques will require considerable research before they can give reliable results for predicting ground support. Until and unless there are significant and unforeseen new developments in aerial photography, remote sensors or other such devices there appears to be little prospect of using these techniques for obtaining the type of geological information needed for tunnel construction.

5.7 SEISMIC

Seismology is one of the primary tools of the petroleum geologist and is used to a lesser extent by geologists and engineers in mining and construction. The seismic technique creates shock waves in or near the earth's surface and times the reflection of these waves from geological variations to reach shock recorders spaced at various intervals along the surface. Profiles of subsurface irregularities such as boundaries between sedimentary formations, dikes or faults can thus be plotted. Optimum interpretation of results from a seismic study requires some prior knowledge of local geology. Where there is a mixture of surface soils, rock types, ground water conditions, etc., only very general data can be achieved.

Surface excavators have used seismology to classify surface or near surface materials. Depending on recorded seismic velocities they can identify the material with respect to type of construction effort required for excavation, such as drill and blast, ripping, or the use of shovels and scrapers. The range of velocities and subsequent correlation with types of materials has been developed through actual experience and use of the method. The present state-of-the-art is very limited with respect to tunnel construction and support determination. It is adaptable only to areas of shallow cover, provides a very broad and general definition of subsurface conditions and requires the use of highly specialized equipment and trained personnel.

It is felt, however, that this technique offers great potential in the improvement of geological investigations either singularly or in conjunction with other methods. Current research, such as being conducted by Honeywell Research, Inc. under the ARPA program may provide useful answers. One possible goal has been discussed in paragraph 1.3.5. Another might be the use of seismic methods to determine rock structure properties between two fairly close spaced parallel horizontal holes drilled along the tunnel alignment.

5.8 DATA COLLECTION & RETRIEVAL SYSTEMS

Within the foreseeable future the art of predicting ground supports will depend essentially on empirical evaluations of subsurface conditions. The electronic computer could be used to a great advantage in improving the reliability of such evaluations. As more pertinent data relating to underground construction becomes available it would be possible to establish data banks which would provide geological and construction information for any particular geographic area of concern.

As found by the case history studies, there is a considerable amount of usable data available but most of this data is so scattered and varied that it is very difficult to arrive at meaningful conclusions. The first prerequisite is to establish a standard format for requirements, criteria and procedures by which needed data could be obtained and recorded. Data from past projects could be used to formulate the initial program which could be revised or modified to reflect findings, determinations and projections for future projects.

The use of data bank retrieval systems is common to many industries and should easily be adapted to tunnel construction. It could include all aspects of tunneling but the intent of this discussion is directed toward basic tunnel site geological considerations and ground support requirements.

SECTION 6

DETERMINATION OF SUPPORT REQUIREMENTS HYPOTHETICAL TUNNEL

6.1 INTRODUCTION

An important decision in the design and construction of any tunnel is the initial determination as to whether or not ground support will be required and, if so, what support system should be used. This decision is relevant to all phases of planning, design and construction and has a marked influence on ultimate costs. In the pre-construction period, it provides the basis of making comparative evaluations of competitive bids. Tunneling methods or systems used during construction are dependent on predictions of support requirements. This is especially true with respect to use of boring machines which are usually designed for specific conditions. Most claims or litigation pertaining to tunnel work arise from differences between "anticipated" and "actual" support requirements.

Although in-situ testing and as-built geology provide useful, after-the-fact information, the initial decision requires a realistic appraisal or prediction of subsurface conditions and the subsequent correlation of those conditions with appropriate support systems. The RSR method of prediction and Support Requirement Charts as proposed in this report would assist in making that decision. The procedure is illustrated by considering a hypothetical project, the Donjay Tunnel. Various steps, type of information required, necessary evaluations and other aspects of the problem are discussed in the following paragraphs. An economic analysis of both conventional and innovative support systems as determined for the Donjay Tunnel is presented in Section 8.

6.2 DONJAY TUNNEL

This example tunnel is a composite simulation of various tunnel sections considered in case history studies. It is to be constructed in one of the Western States; is approximately 16,000 feet long and can be driven either as a modified horeshoe or circular tunnel section at the option of the contractor. See Figure 6.1. Other tunnels have been driven through similar formations within the same general area. The general and special conditions, technical specifications and other contract stipulations are typical of most tunnel projects. Construction time is not critical and no liquidated damages are specified. It is assumed that the hypothetical tunnel site was inspected during the pre-bid period. Available cores and other physical features of the work were examined at that time. Although permanent concrete lining is required throughout, this discussion treats only those operations and determinations relating to excavation and initial ground support.

6.3 PRE-CONSTRUCTION GEOLOGY

Geological data provided with the documents consist of the following:

1. Surface geology.
2. Geological profile along tunnel center line.
3. Drillers' Logs of Bore Holes.
4. Geologist's report.

The specifications include typical disclaimer clauses within the following general context:

"Geological data is made available only for informational purposes...."

"Owner disclaims any responsibility for conclusions, interpretations...."

"It is the contractor's sole responsibility...."

"Owner does not represent that geologic data is indicative of conditions to be encountered...."

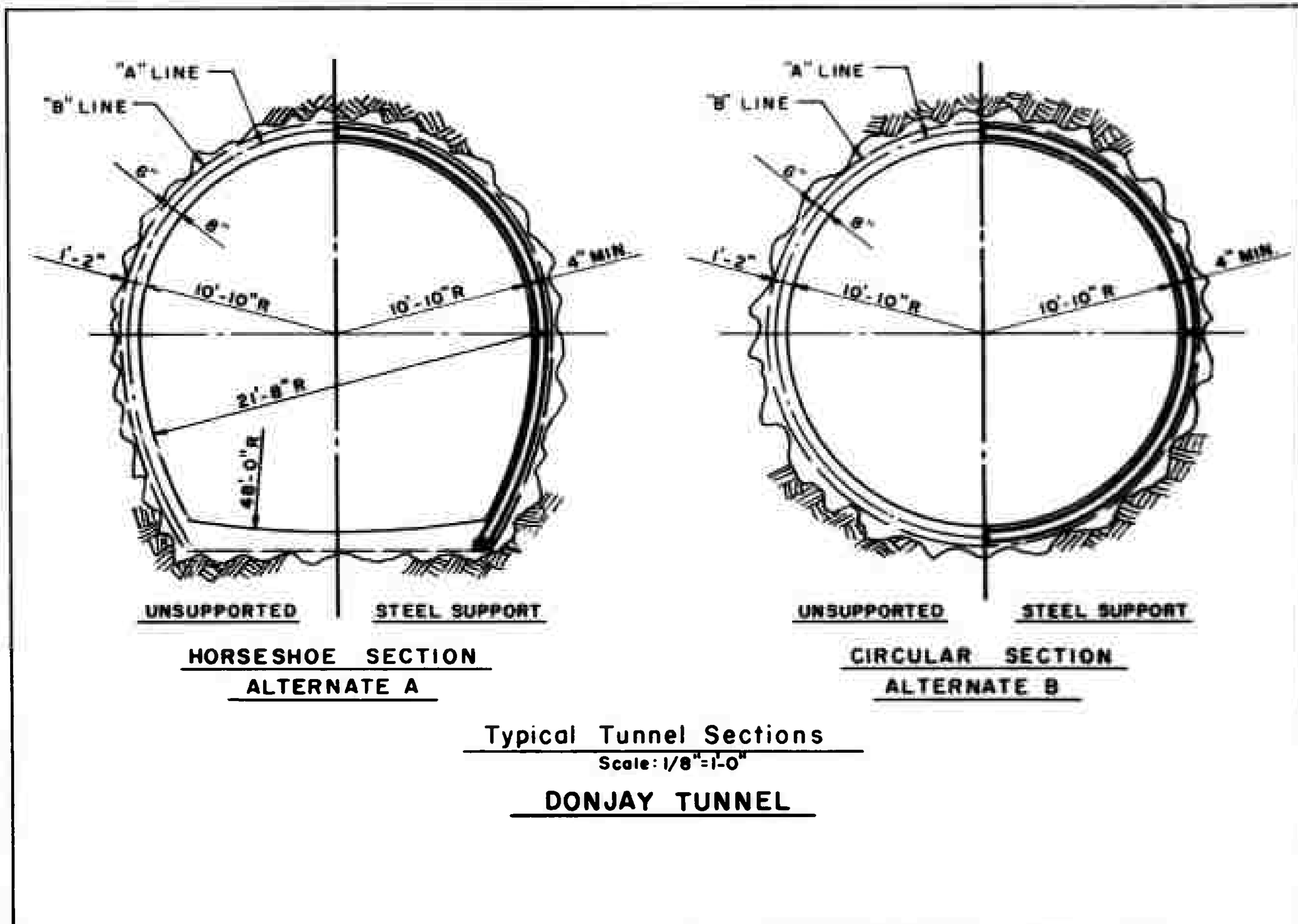

"A" LINE
"B" LINE
6"
8"
1'-2"
10'-10"R
10'-10"R
4" MIN.
21'-8"R
48'-0"R
UNSUPPORTED
STEEL SUPPORT
HORSESHOE SECTION
ALTERNATE A
"A" LINE
"B" LINE
6"
8"
1'-2"
10'-10"R
10'-10"R
4" MIN.
UNSUPPORTED
STEEL SUPPORT
CIRCULAR SECTION
ALTERNATE B
Typical Tunnel Sections
Scale: 1/8"=1'-0"
DONJAY TUNNEL

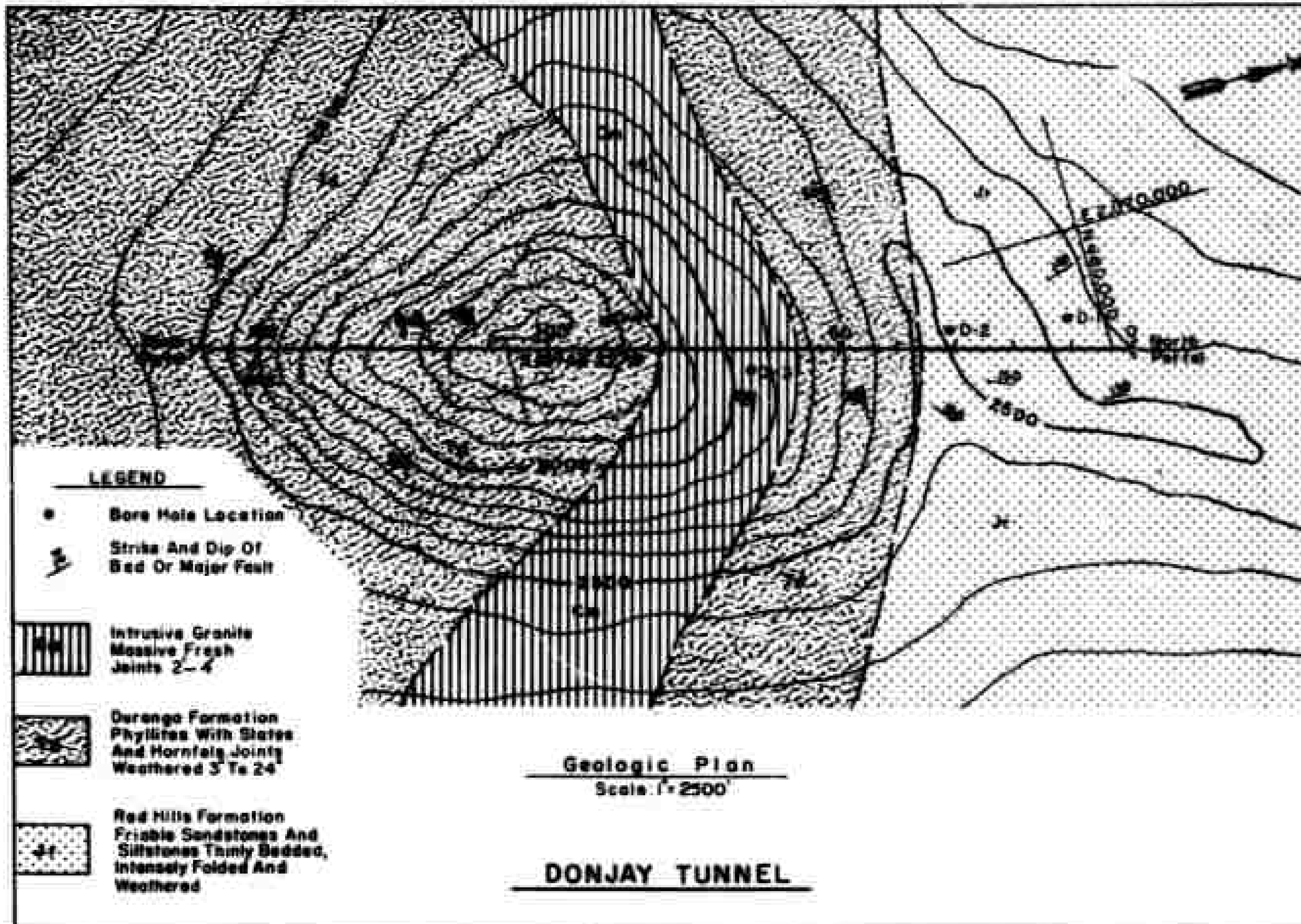
Figure 6.1

These statements tend to nullify the validity or usefulness of considerable effort and expense which was probably required to prepare project geology. The owner is in a far better position to conduct geological investigations and reach conclusions pertaining to subsurface conditions than any potential bidder. This applies to both time and cost considerations. The tunnel will penetrate all rock structures along the alignment regardless of whether or not they require support and irrespective of who (the owner or contractor) made the initial decision as to support requirements. It is also likely that approximately the same quantity of support will be used in constructing the tunnel regardless of the contractor assigned or the quantity of support indicated in the bid documents. The common goal should be to make the best possible determination of support requirements prior to start of construction rather than to see which party could or might be held responsible in the event subsurface conditions are not exactly as predicted.

Regardless of the above, the pre-construction geology provided for the Donjay Tunnel is more complete and detailed than typical information given in the 33 case studies. It is sufficient to make reasonable evaluations of geologic factors which affect support requirements and illustrates the types of information required to determine RSR values.

Surface geology is shown on Figure 6.2. It gives the area topography and shows the approximate extent and general description of geological formations anticipated along the tunnel line. Surface observations of strike and dip, location of bore holes and other general information are also noted.

Figure 6.3 is the developed geological profile of the Donjay Tunnel. It shows the owner's; or his geologist's, interpretation and extrapolation of all geologic information developed during the pre-construction investigation. The profile should reflect also, any pertinent data which may have been



Geologic Plan
Scale: 1" = 2500'

DONJAY TUNNEL

Figure 6.2

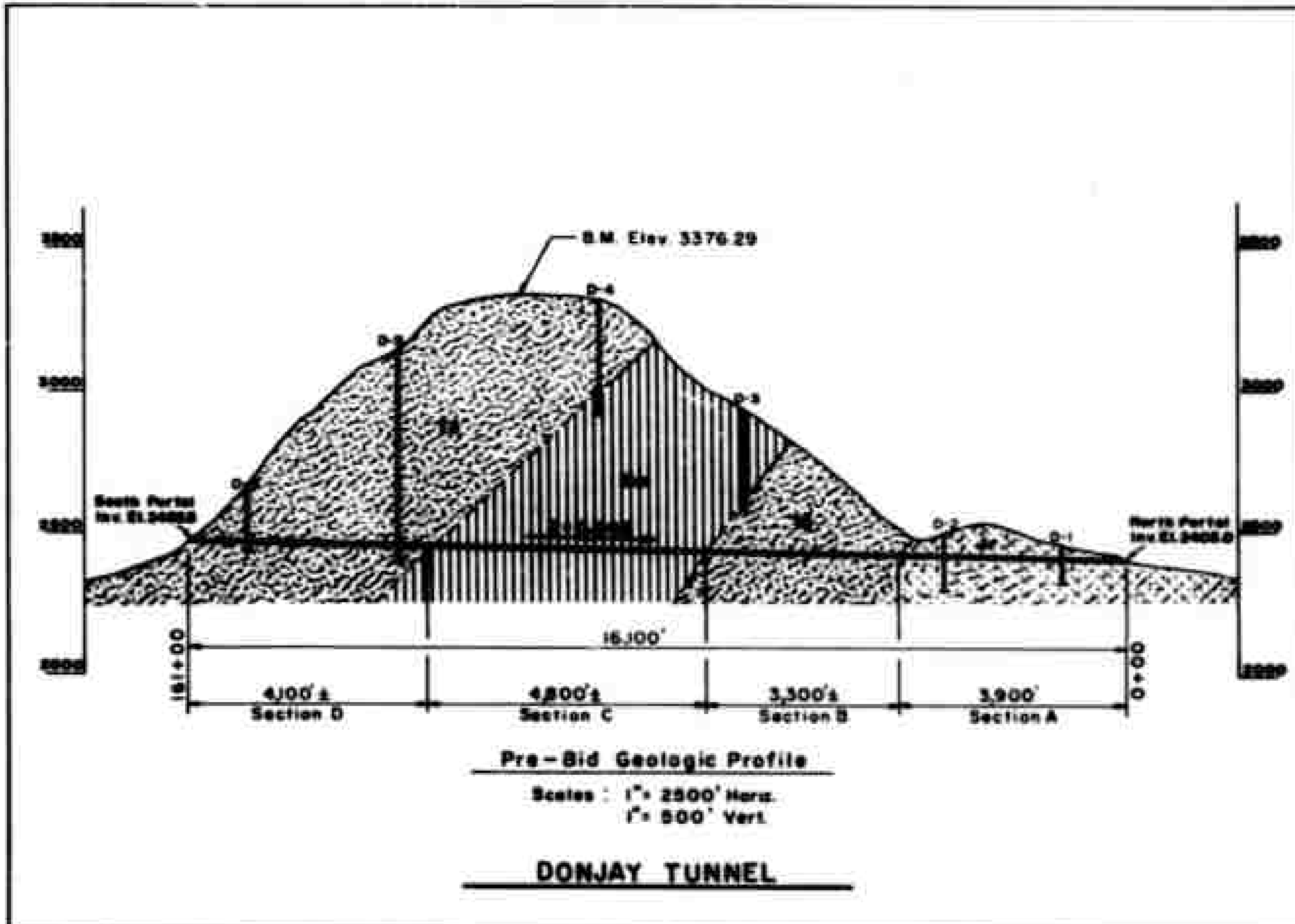

B.M. Elev. 3376.29
D-4
D-3
D-2
D-1
South Portal
North Portal
16,100'
161+00
0+00
4,100'±
Section D
4,800'±
Section C
3,300'±
Section B
3,900'
Section A
Pre-Bid Geologic Profile
Scales : 1" = 2500' Horz.
1" = 500' Vert.
DONJAY TUNNEL

Figure 6.3

obtained from a study of historical geology and/or records of previous underground construction. Location and depth of various bore holes are shown. Boundaries between different rock types or formations are projected from the surface to tunnel grade as either a solid or dashed line. A solid line indicating a rather definite definition, the dashed line an extrapolation made by the owner's geologist. Support requirements are usually determined with respect to a geological profile, whether it is provided by the owner or developed by the contractor. Using bore hole information and surface geology given for the Donjay Tunnel, it is likely that all parties would have developed approximately the same profile as given in the documents. This may not have been the case if the geology had been more complicated; i.e., consisted of numerous folds, faults, etc. The profile indicates that the tunnel will penetrate four distinct formations or rock structures. They are identified as Sections A, B, C and D on Figure 6.3. Subsequent determinations of RSR values and support requirements are related to those sections of the tunnel.

The logs of various bore holes made during the investigation are shown on Figure 6.4. These logs are typical of bore hole information provided for tunnel projects. In some cases Deere's RQD Index might be included. A possible addition would be to describe the cores with respect to an RSR evaluation in accordance with methods developed in this study. An important consideration is the location of the bore holes. The geology and types of rock in the area of the Donjay Tunnel are comparatively well defined which helps in specifying the location of borings. Very often this is not the case. Extensive faulting, erosion and altering of rock may leave transition zones which would be difficult to define even though numerous borings were made at various locations. There is always an elusive point of diminishing returns where the value of information that may be gained from additional borings would not

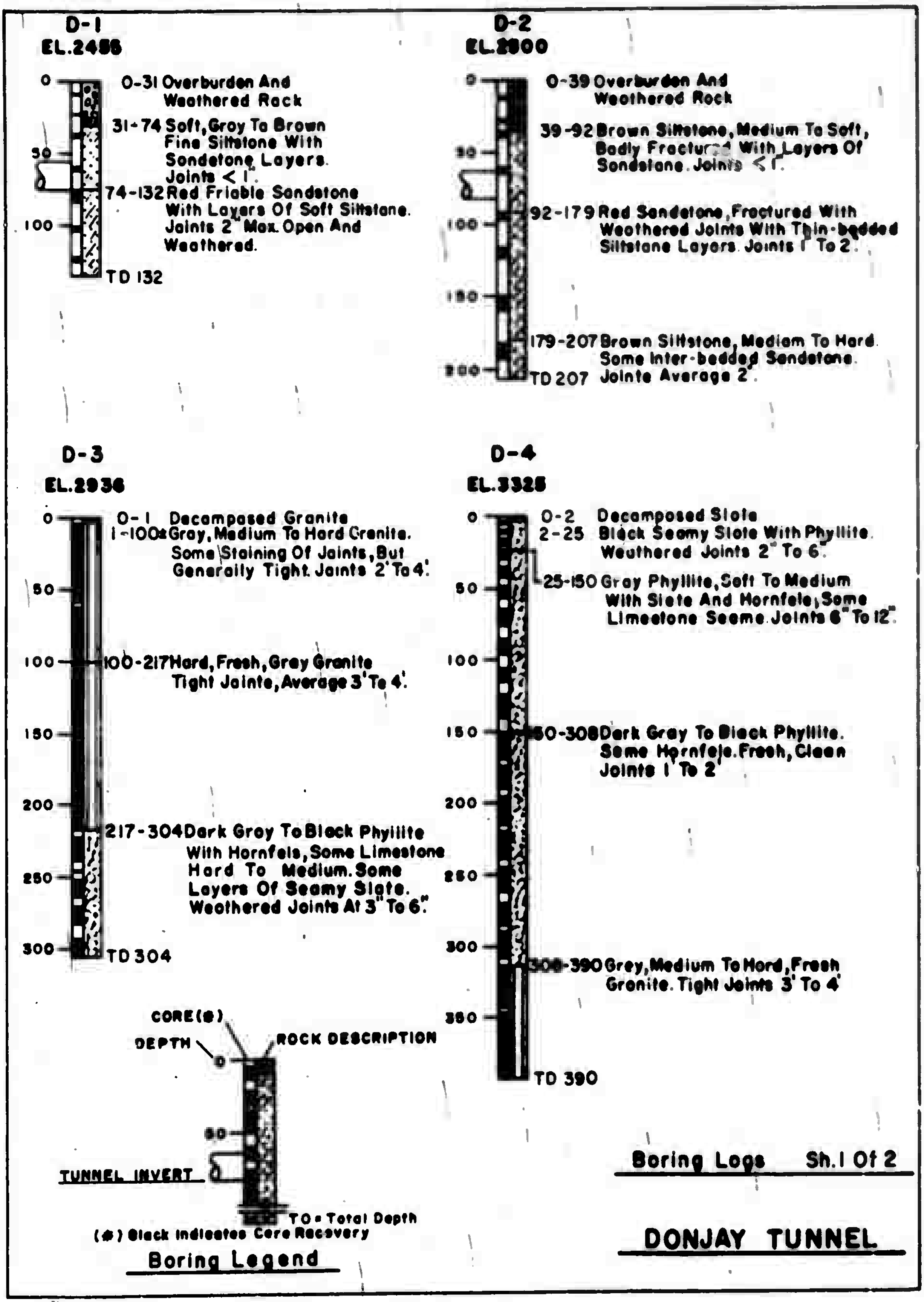

D-1
EL.2456
0-31 Overburden And Weathered Rock
31-74 Soft, Gray To Brown Fine Siltstone With Sandstone Layers. Joints < 1".
74-132 Red Friable Sandstone With Layers Of Soft Siltstone. Joints 2" Max. Open And Weathered.
TD 132
D-2
0-39 Overburden And Weathered Rock
39-92 Brown Siltstone, Medium To Soft, Badly Fractured With Layers Of Sandstone. Joints < 1".
92-179 Red Sandstone, Fractured With Weathered Joints With Thin-bedded Siltstone Layers. Joints 1" To 2".
179-207 Brown Siltstone, Medium To Hard. Some Inter-bedded Sandstone. Joints Average 2".
TD 207
D-3
EL.2936
0-1 Decomposed Granite
1-100± Gray, Medium To Hard Granite. Some Staining Of Joints, But Generally Tight. Joints 2' To 4'.
100-217 Hard, Fresh, Gray Granite Tight Joints, Average 3' To 4'.
217-304 Dark Gray To Black Phyllite With Hornfels, Some Limestone Hard To Medium. Some Layers Of Seamy Slate. Weathered Joints At 3" To 6".
TD 304
D-4
EL.3325
0-2 Decomposed Slate
2-25 Black Seamy Slate With Phyllite. Weathered Joints 2" To 6".
25-150 Gray Phyllite, Soft To Medium With Slate And Hornfels, Some Limestone Seams. Joints 6" To 12".
150-308 Dark Gray To Black Phyllite. Some Hornfels. Fresh, Clean Joints 1' To 2'.
308-390 Grey, Medium To Hard, Fresh Granite. Tight Joints 3' To 4'.
TD 390
CORE(*)
DEPTH
ROCK DESCRIPTION
TUNNEL INVERT
TD = Total Depth
(*) Black Indicates Core Recovery
Boring Legend
Boring Logs Sh. 1 Of 2
DONJAY TUNNEL

Figure 6.4

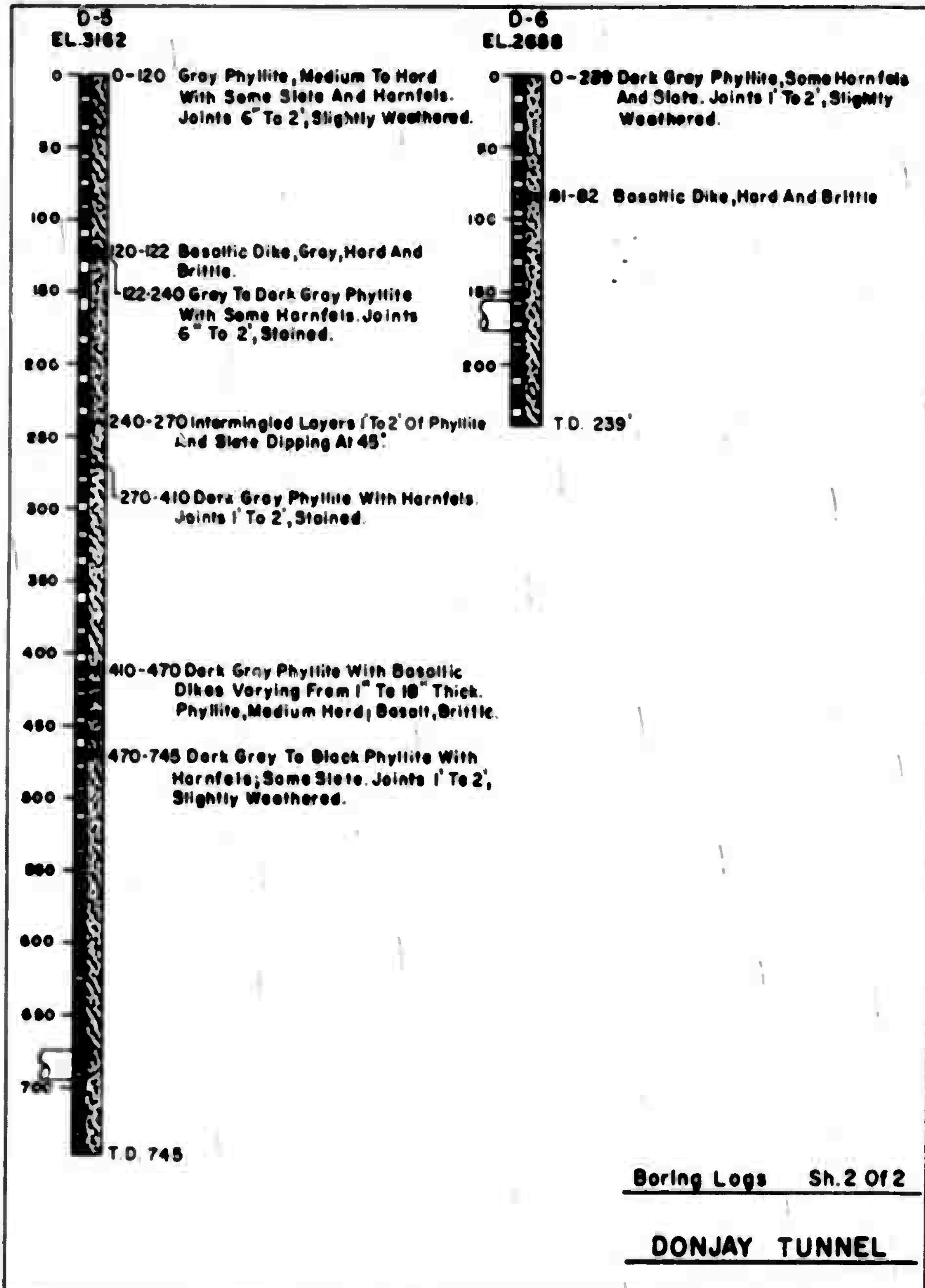


Figure 6.4 (continued)

materially add to the accuracy of determining support requirements. Where possible, the boundaries between different rock structures should be defined. This is illustrated by borings D-3, D-4 and D-5 (see Figure 6.3) which were made in an attempt to establish the boundaries of two zones of metamorphic rocks and the thick layer of intrusive granite between them. Location of D-5 was approximated by considering the strike and dip of the exposed formations. It was made to verify the projection to grade of the southernmost extent of the intrusion. The fact that it did not enounter the granite even though carried below the tunnel invert, indicates that the boundary lies somewhere to the north of the bore hole. Consequently the projection of this boundary is shown as a dashed line on the profile. The log of D-5 shows the rock at tunnel grade to be more competent than indicated by surface exposures. This information is helpful in determining RSR values for Section D. Boring D-2 was made to define an obvious weakness in the rock structure. Borings D-1 and D-6 depict portal conditions.

Available cores, rock outcrops, road cuts, topographic maps and other data which give indications of subsurface conditions were inspected and considered during the site visit. No apparent discrepancies were found between conclusions drawn from that inspection and the geologic data presented on the surface geology map, the tunnel profile or driller's logs.

To be complete, pre-construction geology should contain a report, either in full or in summary, of the findings and interpretations of the geologist who made the investigation and who is familiar with the needs and understanding of tunnel engineers and contractors. In some instances, the desire of the owner to refrain from assuming an implied responsibility for pre-construction geology results in vague or nonconclusive statements. The owner and his engineer representative might spend several years considering a particular project before taking bids. The contractor rarely has more than a few weeks in which he must determine his methods for excavating, supporting and lining the tunnel; consider acquisition of equipment, plant and material and prepare a detailed cost estimate for completing the work. Although a contractor may use a geologist to interpret available pre-bid geology data, or even to make an independent appraisal of the site; it is unreasonable to expect him to conduct geological investigations comparable to that performed by the owner. It should be understood by all concerned that pre-construction geology is not a guaranty as to the actual conditions that might be encountered during tunnel construction. It should, however, be accepted as the best available appraisal of subsurface conditions on which to base project planning and costing. Decisions pertaining to ground support requirements should be made by disciplines directly involved in tunnel construction, not by the courts or related agencies.

A summary of the geology report provided with the Donjay documents is given in Figure 6.5. Any such report should include comments pertaining to historical geology, laboratory tests, conditions encountered in previous underground construction, ground water studies or any other data which may have been considered in initial planning or investigation of the tunnel. On the assumption that the RSR method of evaluation is pertinent, special emphasis should be made to identify and define in as much detail as possible those geologic factors and parameters (see Figure 2.3) which are required for such a determination.

6.4 EVALUATION OF ROCK STRUCTURE RATINGS

RSR values for each of the four Donjay Tunnel sections were determined in accordance with procedure discussed in paragraph 2.2.2 and illustrated by

GEOLOGIC REPORT SUMMARY
OF THE PROPOSED DONJAY TUNNEL
(simulated Tunnel Model)

It is anticipated that this tunnel will be most conveniently driven from the north portal as a one-heading operation. This portal area affords more room for a contractor's surface plant and by driving from north to south, the tunnel heading will advance uphill minimizing the pumping of ground water. The amount of time available for construction appears to be sufficient to eliminate the necessity of working from both ends. The description of the rock to be encountered will be given on this basis; however, it will be the contractor's option to drive from either heading.

The first tunnel section adjacent to the north portal, Section A, will probably contain the most severe tunneling conditions to be encountered. This section approximately 3900 ft. in length will be through Jurassic sedimentary deposits known as the Red Hills Formation. This formation consists of intensely folded interbedded layers of siltstones and friable sandstones. This thinly bedded material averages well below 2 inches between joints. The stike and dip vary considerably but average about 30 degrees to 50 degrees in dip, with the strike almost parallel to the tunnel centerline. Borings D-1 and D-2 taken in this formation show RQD Ratings varying between 0 and 30%. The pumping tests taken on Boring D-2 in the saddle of a slight valley indicate that a flow of 200 gallons/minute and possibly as much as 500 gallons/minute can be expected in this area. Flows of 100 gallons/minute or more can be anticipated anywhere in this formation, especially at the contact with Section B.

At approximately Sta. 39 + 00 the tunnel will start passing into the Durango Formation. This formation consists of metamorphic rock; principally phyllites with some slates and hornfels and occasional basaltic dikes.

Fig. 6.5

(This metamorphic rock will exist in two sections of tunnel, separated by a massive granite intrusion) Section B, between Sta. 39 + 00 and Sta. 72 + 00, consists of thickly layered strata of phyllites and slates. It is generally more seamy than the section at the south portal with joint spacing averaging 3 inches to 6 inches and moderately folded. Although it did not reach tunnel grade Boring D-3, shows a RQD of 60%. The dip of the rock in this section averages 30 degrees to 55 degrees to the south. The strike runs east and west. It is anticipated that water inflow at the face in this area will not exceed 50 to 100 gallons/minute.

From Sta. 72 + 00 to approximately Sta. 120 + 00, Section C, the heading will advance through a hard massive intrusive granite. This rock is tightly jointed with joint spacing varying from 2 to 4 ft. Boring D-3 and Boring D-4 (which penetrates this rock) show RQD of 90% to 100%. Little or no water is expected in this formation, although fracture zones may temporarily yield water.

From approximately Sta. 120 + 00 to the south portal 161 + 00 the tunnel will again pass through the Durango Formation of metamorphic rock. The rock in this area based both on surface outcrops and borings D-5 and D-6 is generally harder, more uniform in texture than the similar rock in Section B. Core RQD range from 65% to 90%. Joint spacing averages 1 to 2 ft. and joints are slightly weathered. The rock consists primarily of phyllites with occasional layers of slate and hornfels. The dip in this area is also 30 degrees to 50 degrees to the south and the strike is generally east to west. Water flows will be between 50 gpm and 100 gpm and because of steep surface topography, run off is expected to be greater than over Section B.

It is anticipated that Section A will require heavy steel temporary bracing with 50% to 100% timber lagged. Section B will probably require medium support with a minimal amount of lagging. Section C will probably require no support. Section D may require support consisting of light ribs or roof bolts. Use of shotcrete as

Fig. 6.5 (Continued)

an alternate support will be permitted. The contractor will have the option of selecting supports with size and/ or thicknesses to be approved by the engineer.

Results of laboratory tests of uni-axial compressive strengths:

Boring	Depth	Comp. Str. (psi)
D-1	64'	7,900
	79'	9,500
D-2	91'	8,200
D-3	202'	26,900
	298'	11, 000
D-4	252'	13,800
	380'	29,200
D-5	684'	16,700
D-6	161'	14,600

Fig. 6.5 (Continued)

Figure 2.3. Results are shown on Figure 6.6. The description and occurrence of geologic factors used to define parameters A, B and C were based on information provided in the pre-construction geology. The corresponding values assigned to the different parameters were obtained from Figure 2.3. The four tunnel sections encompass a large range of RSR values. Section A, with a rating of 29, is at the lower end of the scale, indicating heavy support requirements. Section C (RSR = 87) is within the range of good component rock requiring little or no support. Sections B and D with respective rock structure ratings of 43 and 63 will require various types and quantities of support.

The above RSR values relate to conventional drill and blast method of excavation. It is possible, however, that a boring machine might be used for Donjay. Geological formations which are anticipated for tunnel sections A, B and D could be readily excavated. Section C (hard granite) is marginal with respect to use of present-day machines. If a contractor chose to use a boring machine, an approximation of corresponding rock structure ratings could be made as outlined in paragraph 4.6. Using the indicated adjustment factor for a 24-foot diameter tunnel, the RSR values to be considered with respect to a machine operation are as follows:

Section	Basic RSR Value	Adjustment Factor	RSR Value For TBM
A	29	1.15	33
B	43	1.15	44
C	87	1.15	100
D	63	1.15	72

6.5 DETERMINATION OF SUPPORT REQUIREMENTS

Conventional support systems (steel ribs, rock bolts or shotcrete) that may be appropriate for various support requirements of the Donjay Tunnel can now be identified from a Support Requirement Chart developed for a 24-foot

DONJAY TUNNEL
COMPUTATION OF ROCK STRUCTURE RATINGS

	PARAMETER	GEOLOGIC INFORMATION	VALUE	TOTAL
SECTION A	A	Rock Type Sedimentary Intensely Folded	8	
	B	Drive ⊥⊥ to Axis Dip 30^{o}-50^{o} Joint Spacing < 2"	15	
	Subtotal		23	
	C	Water Inflow-Moderate Joints Badly Weathered	6	
	RSR Value			29
SECTION B	A	Rock Type - Metamorphic Moderately Folded	14	
	B	Drive ⊥ & with DIP 30^{o}-55^{o} Joint Spacing 3"-6"	17	
	Subtotal		31	
	C	Water Inflow - Slight Joints Slightly Weathered	12	
	RSR Value			43
SECTION C	A	Rock Type - Igneous Slightly Folded	26	
	B	Drive ⊥ & with DIP 35^{o}-50^{o} Joint Spacing 2'-4'	42	
	Subtotal		68	
		Water Inflow - Slight Joints Tight	19	
	RSR Value			87
SECTION D	A	Rock Type - Metamorphic Moderately Folded	14	
	B	Drive ⊥ & with DIP 30^{o}-50^{o} Joint Spacing 1'-2'	34	
	Subtotal		48	
	C	Water Inflow - Slight Joints Slightly Weathered	15	
	RSR Value			63

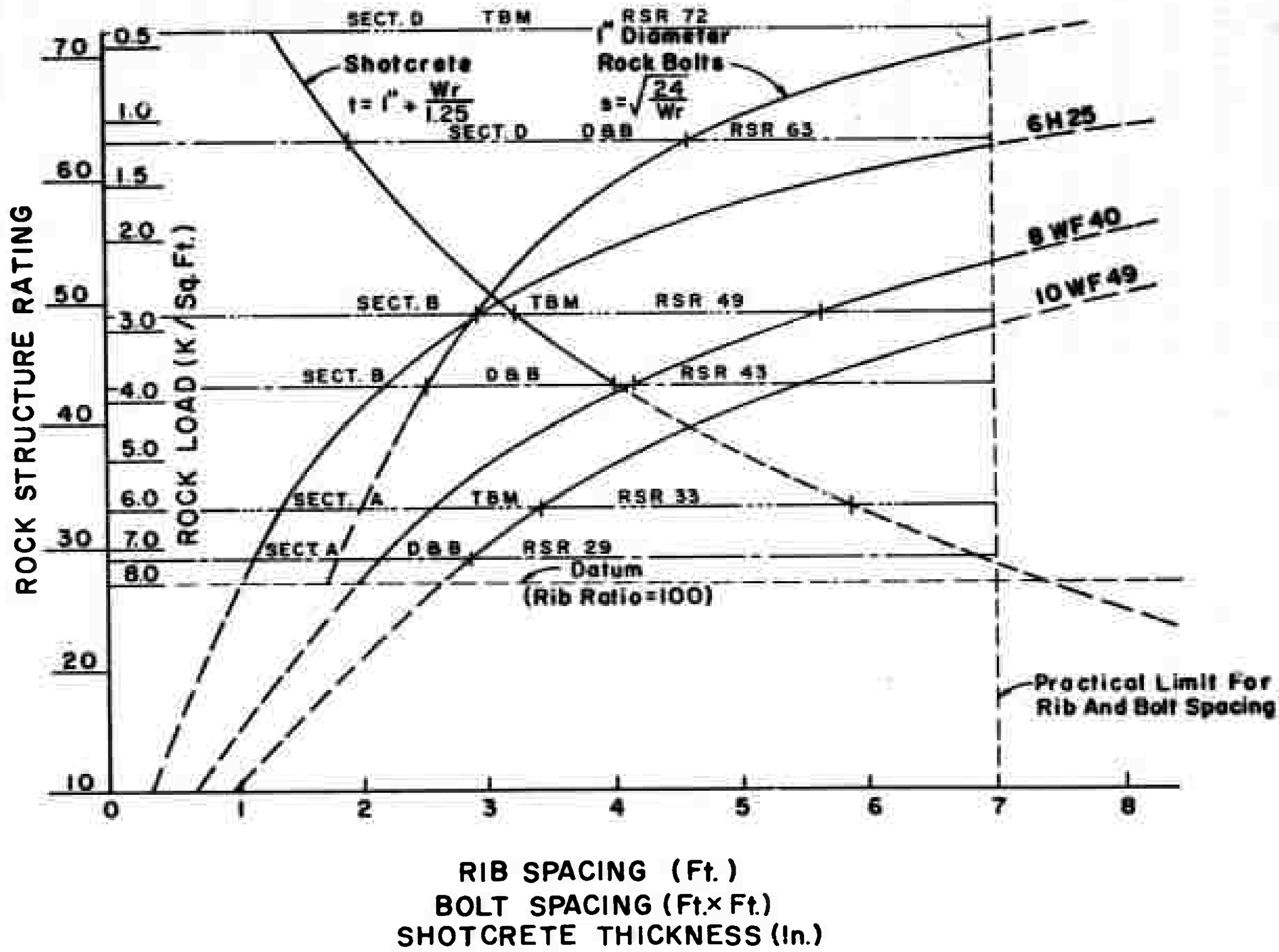
Figure 6.6

tunnel. See Paragraph 4.5. Figure 6.7 shows the different systems (type, size, spacing, etc.) that could be used. Horizontal lines are shown at the respective RSR values determined for tunnel sections A, B and D. One line for each section represents RSR evaluations for a drill and blast operation, the other, an adjusted RSR value based on use of a boring machine (TBM). The intersection of these lines with various support curves identifies a support system which would satisfy the support requirement. The RSR values for tunnel section C are above 77, hence support is not considered necessary (see paragraph 4.3). The indicated support systems are tabulated below:

Donjay Support Requirements

Tunnel Section	Possible Support Systems: Drill & Blast	Possible Support Systems: Machine
A	10WF49@ 3'	10WF49 @ 3-1/2'
B	8WF40 @ 4' Rock Bolts @ 2-1/2' Shotcrete (4")	8WF40 @ 5-1/2' Rock Bolts @ 3' Shotcrete (3")
C	Unsupported	Unsupported
D	6H25 @ 6' RockBolts @ 4-1/2' Shotcrete (2")	6H25 @ 7' Rock Bolts @ 6' Shotcrete (1-1/2")

The user of a Support Requirement Chart must bear in mind how they were developed and what limitations are imposed. The charts give an average determination of various support systems which would be appropriate for a particular section of tunnel or rock structure. They are not meant to replace the judgement of the man at the heading. Few geological formations would present uniform conditions affecting ground support for any appreciable distance. Consequently, variations of the support system might be required as the tunnel advances. The charts can, however, be used for initial planning or



24' DIAMETER TUNNEL

Figure 6.7

prediction of ground support for future tunnels. Correlation of actual conditions with the prediction method and chosen support system will eventually lead to a fairly reliable basis for making determinations of ground support requirements.

An economic evaluation of the different support systems listed in the above table is given in Section 8.

SECTION 7

NEW CONCEPTS OF GROUND SUPPORT

7.1 INTRODUCTION

"The growing national concern for enhancing and maintaining the quality of the environment in the face of growing resource and urban development demands would be substantially lessened if greatly improved underground-excavation technology were available; i.e., if the real cost of underground excavation were reduced 30 to 50 percent, and if sustained rate of advance were increased 200 to 300 percent in both soft, medium and hard rock."

The above statement is taken from the National Academy of Sciences' report on Rapid Excavation, submitted to the Bureau of Mines in 1968 (Reference 17). It defined a goal to be achieved within a period of ten years. The two requirements - reduction in costs and increase in rate of advance - are relative to each other; that is, an increase in rate of advance is tantamount to a reduction in cost. The proportional relationship varies depending on method of excavation (drill and blast or boring machine), type of rock structure and if required, the support system being used. The effect of the support requirement is probably the most crucial element to be considered. To achieve the designated goal, it will be necessary to develop an optimum support system which is defined as "That system which provides safe, efficient and economical ground support with little or no reduction in the potential rate of advance that could be achieved in driving an unsupported tunnel." It must be an integral part of the overall tunneling process with respect to all components of work and cost.

The purpose of this section is to indicate new concepts of ground support which might lead to an optimum system. It involves the investigation of new materials and techniques; variations of existing methods, and/or possible combinations thereof. Due to large variations in requirements depending on rock structure, tunnel size and method of excavation, no one support system is expected to provide optimum results for all tunnels. However, the general appraisal made for specific conditions as discussed in the following paragraphs are indicative of concepts which would be applicable to most tunnels considered within the scope of this study.

7.2 COMPONENTS OF THE TUNNELING PROCESS

The tunneling process in composed of various subsystems, all of which must be effectively integrated to provide an efficient and continuous operation. These subsystems, which are generally defined as 1) excavation, 2) ground control, 3) logistics, and 4) environmental control, can be evaluated with respect to various applicable cost components such as labor, material, equipment operation, etc. Although each subsystem can be analyzed individually, it is necessary to consider the relative effect of each with respect to the others in final determinations. This is due primarily to the cyclic nature of tunnel construction. In most instances the tunneling process can be described or evaluated in terms of cost per lineal foot of tunnel, which would reflect the total of individual cost components pertaining to each subsystem involved. Figure 7.1 shows the estimated costs for an unsupported (without the ground control subsystem), 20-foot bored tunnel being advanced at the rate of approximately 200 feet per day. It lists the dollar cost per lineal foot of tunnel as well as percent of total cost represented by each component.

ESTIMATED COST
20' ϕ TUNNEL - UNSUPPORTED
MEDIUM HARD ROCK - TBM METHOD
COST PER LINEAL FOOT

COST COMPONENT	ESTIMATED DOLLARS	PERCENT OF TOTAL COST
Direct Labor	$ 44.00	19%
Equipment Operation	25.00	11%
Cutter Costs	38.00	16%
Job M & S	5.00	2%
Support Materials	0.00	0%
Overhead Expense	18.00	8%
Plant & Equipment (Including TBM)	65.00	27%
Profit & Contingency	40.00	17%
TOTALS	$235.00	100%

Figure 7.1

7.2.1 EFFECT OF GROUND CONTROL SUBSYSTEM

Assuming the rock structure for the above example was such as to require continuous support, it would be necessary to add the ground control subsystem to the overall evaluation. This addition will affect all work and cost components, but its principal effect is reflected in increased cost of direct labor and support materials which, in turn, are dependent on type of support being installed. Figure 7.2 shows the cost and percentage increase of direct labor and support materials resulting from the necessity of installing conventional support systems at the face. Although the direct labor component reflects additional requirements (logistics, support installations, etc), the major portion of the indicated increase is due to the substantial decrease in daily advance rate occasioned by driving a supported tunnel within the concept of the present state-of-the-art.

The total effect of adding the ground control subsystem to the tunneling process is shown by the cost summary given on Figure 7.3. This comparison shows the increase in total costs per lineal foot due to support installation to be 49% to 74% of the basic cost of an unsupported tunnel. These increases, which include consideration of all applicable components of the respective tunneling operations, are substantially less than shown by the comparisons on Figure 7.2. They do, however, indicate the large area of improvement which could be achieved by use of a more optimum support system. Similar comparisons could be made with respect to use of the drill and blast method of excavation. The cost of individual components for the drill and blast method would be different, but the relative increases would be of the same order-of-magnitude as indicated for the machine-type of excavation.

All comparisons would relate to respective component costs determined for the potential maximum rate of excavation or advance of an unsupported

COMPARISON
DIRECT LABOR & SUPPORT MATERIAL COST COMPONENTS
UNSUPPORTED VS SUPPORTED TUNNEL

TYPE OF SUPPORT	DIRECT LABOR		SUPPORT MATERIALS COST/L.F.	TOTAL COST DIRECT LABOR & SUPPORT MATERIALS	% OF INCREASE OVER UNSUP. SECTION
	COST/L. F. TUNNEL	% OF INCREASE OVER UNSUP. SECTION			
Unsupported	$ 44	-	$ 0	$ 44	-
Rock Bolts 10' Bolts - 6/ring 5' Spacing	$115	161%	$12	$127	189%
Shotcrete 4" Nominal Thickness Above Springline	$160	264%	$16	$176	300%
Steel Ribs 6 WF 21 @ 4' Ctrs.	$120	173%	$43	$163	270%

Figure 7.2

COMPARISON OF COST COMPONENTS
20 FT - BORED TUNNEL

COST COMPONENT	TYPE OF SUPPORT			
	UNSUPPORTED	ROCK BOLTS	SHOTCRETE	STEEL RIBS
Direct Labor	$ 44	$115	$160	$120
Equipment Operations	25	32	36	36
Cutter Costs	38	36	36	35
Job M&S	5	7	8	9
Support Materials	0	12	16	43
Overhead Expense	18	28	30	32
Plant & Equipment	65	67	70	70
Profit & Contingency	40	51	54	55
Total Cost/L.F.	$235	$350	$410	$400
Increase Over Unsupported	-	49%	74%	70%

Figure 7.3

tunnel. Consequently the optimum support system must be sensitive to possible improvements of underground-excavation technology.

7.3 NEW SUPPORT MATERIALS

The scope of work for this report included the investigation of new materials which might fulfill the requirements of an optimum support system. Although the desired ultimate characteristics and properties of such a material can be defined, the results of the research effort were somewhat less than encouraging. Various new materials such as polymers, fiber glass, epoxies and polyurethane were investigated. Discussions were held with different agencies and organizations involved in the research and development of materials which might fulfill the need. The apparent disadvantages of present prospects outweighs the advantages. With the exception of possible proprietory information, which was not made available to the study team, it is concluded that within the limits of present-day technology there are no new materials which would immediately meet requirements for an optimum support system. However, it is likely that continued research will provide the ultimate product and that additional improvements in conventional materials such as high-early cement or fiber-impregnated concretes can be expected. Current and recent studies being conducted by the Bureau of Mines and the Department of Transportation, deal specifically with this problem. Examples are "Innovations in Tunnel Support Systems" (Reference 10) and "Preliminary Survey of Polymer-Impregnated Rock" (Reference 18). The reader is referred to these and similar studies for detailed information pertaining to the present stage of development of new ground support materials.

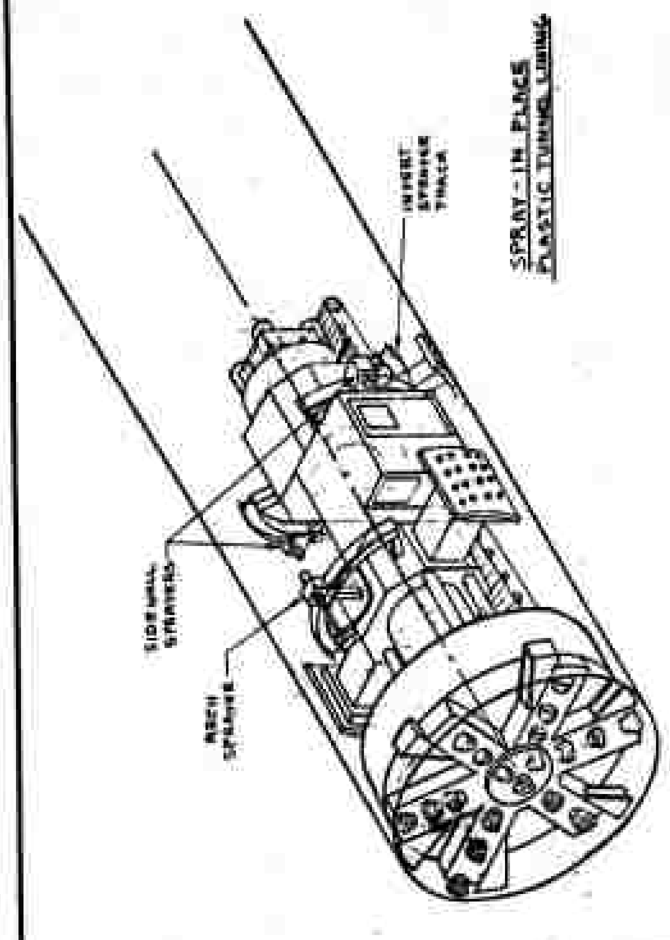
7.4 NEW CONCEPTS OF GROUND SUPPORT

As used herein a "new concept" is taken as any combination of support materials and method of installation which has not been used extensively in previous tunnel construction. Most involve new techniques or methods as opposed to use of new materials. They relate primarily to tunnels driven with a boring machine which is considered the primary tool for achieving the goal of rapid excavation.

The individual concepts are illustrated on Figures 7.4 through 7.19. A brief critique is given which points out potential advantages and disadvantages as well as general descriptive comments pertinent to each. These and other noted considerations are used in the overall evaluation given in paragraph 7.5. The intent was to show a variety of concepts even though some are beyond the limits of present-day technology.

A 14-foot diameter tunnel is used to depict the various concepts. It is felt that this is the smallest practical sized tunnel to be considered due to the critical space limitations between the tunnel wall and configuration of present-day boring machines. The feasibility of some of the concepts would be improved if mechanically compact boring machines could be developed, or if considered with respect to larger sized tunnels which usually provide more working space between the top of the machine and the tunnel arch. The common practice of using sidewall grippers poses restrictions on the use of full circle support placed behind the cutter head. Some of the concepts would not be adaptable to the drill and blast method of excavation due to the cyclic nature of the operation and the effects of blasting. Some would require an elaborate material handling system to accommodate continuous support installation and several would require vastly improved ventilation systems for successful use. These and other problems as well as advantages are considered in the following evaluation of the concepts.

GROUND SUPPORT CONCEPT SUMMARY



No: 1

Title: SPRAYED-IN-PLACE PLASTIC LINING

Purpose: Support behind TBM Cutter.

AREA OF USE

RSR Range: 40-77

D & B: Face - Behind -

T.B.M.: Face X Behind X

Chance of Success: Fair

Patentability: Good

Comments: Requires development of new material.

Originators:

Wickham & Tiedemann

Description: A plastic lining having physical properties similar to Fiberglass (but without the drawbacks listed below), if developed, the arch could be sprayed behind the cutter head and the sides and invert at the tail end of the TBM.

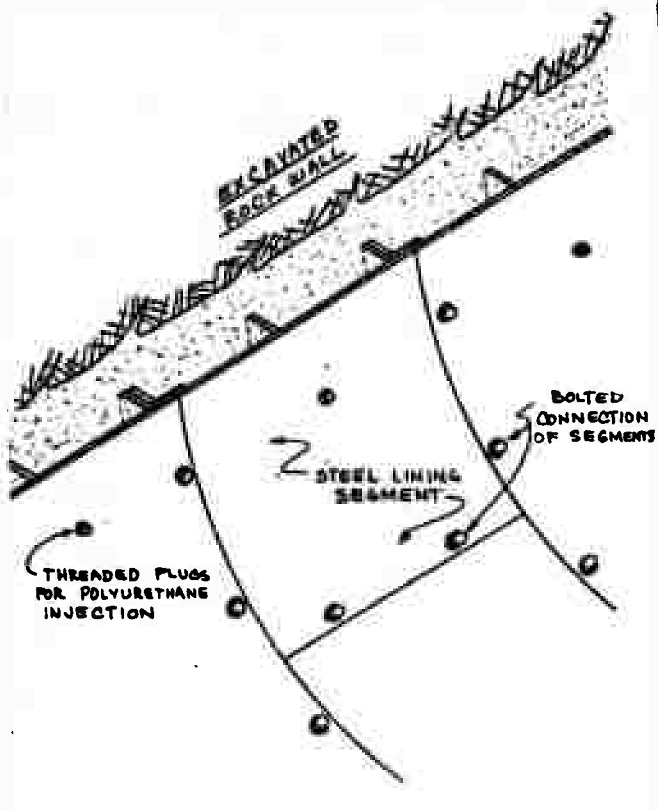
Advantages: Lining would provide temporary and permanent support. Requires minimal material handling and placing labor. Reduced rebound problem (compared to shotcrete).

Disadvantages: 1) General: high cost; low heat resistance.

2) Fiberglass spray: toxic, inflammable. Will not adhere to wet surface, will not hold to arch until "set".

Figure 7.4

GROUND SUPPORT CONCEPT SUMMARY



THIN SHELL, SEGMENTED STEEL LINING WITH POLYURETHANE BACKING

No: 2

Title: STEEL SEGMENTED CYLINDER WITH POLYURETHANE BACKING

Purpose: Support near face.

AREA OF USE

RSR Range: 35-77

D & B: Face X Behind ____

T.B.M.: Face ____ Behind X

Chance of Success: Good

Patentability: Fair

Comments:

Originator: Tiedemann

Description: Thin shell segmented lining would be set near face in D & B tunnel or at tail end of TBM. Polyurethane foam would be injected to fill void between lining and rock, to act as continuous, impervious blocking. Thickness of lining can vary with anticipated rock loads.

Advantages: Provides complete temporary and permanent support within minutes after lining is set. Polyurethane provides more uniform loading, allowing thinner lining. Good resistance to shock from tectonic or other forces. Good resistance to squeezing ground.

Disadvantages: High material cost. Requires mechanical erector for steel lining. Requires protection during blasting of face.

Figure 7.5

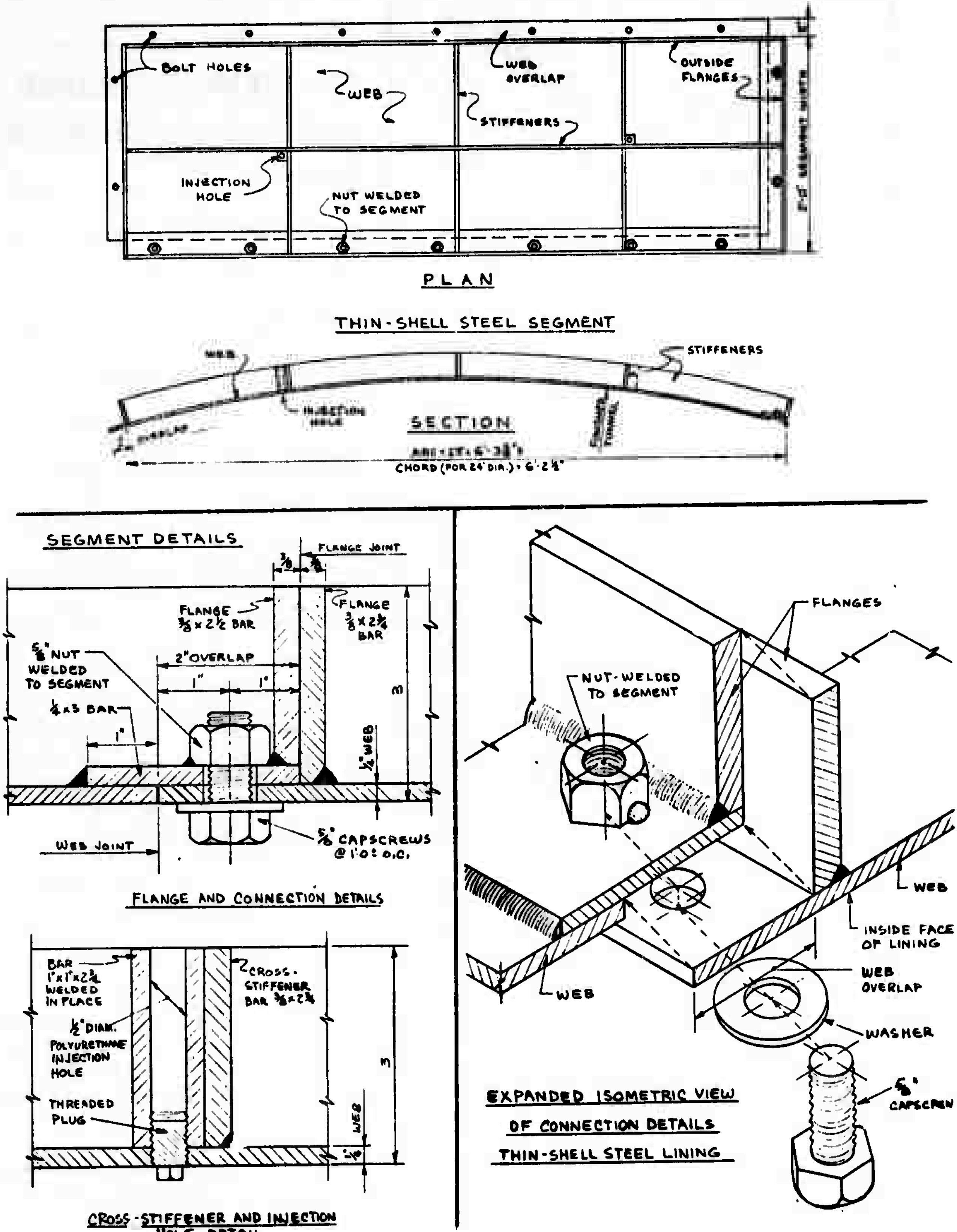
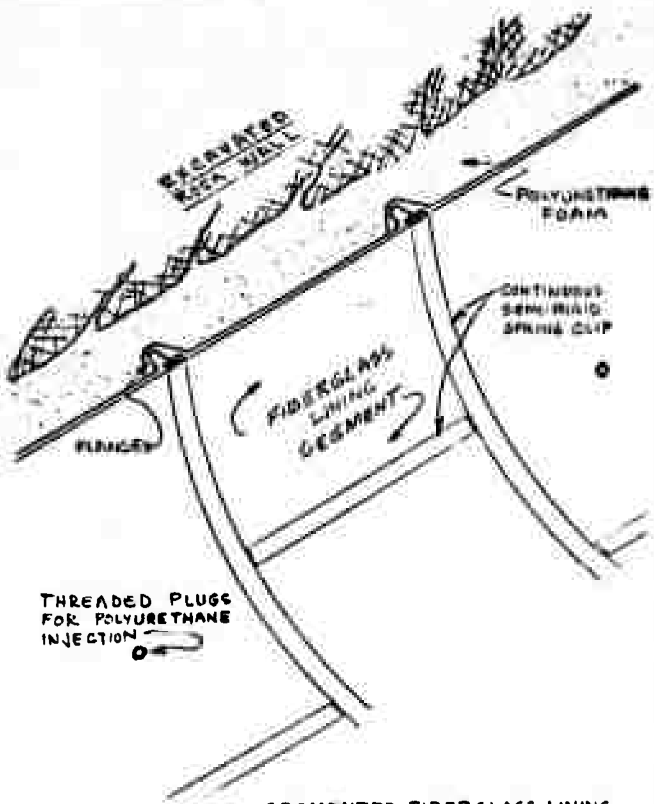


Figure 7.5 (continued)

GROUND SUPPORT CONCEPT SUMMARY



SEGMENTED FIBERGLASS LINING WITH POLYURETHANE BACKING

No: 3

Title: FIBERGLASS SEGMENTED CYLINDER WITH POLYURETHANE BACKING

Purpose:

Support near face.

AREA OF USE

RSR Range: 35-77

D & B: Face X Behind ____

T.B.M.: Face ____ Behind X

Chance of Success: Fair

Patentability: Good

Comments: One of several possible designs presented.

Originator: Tiedemann

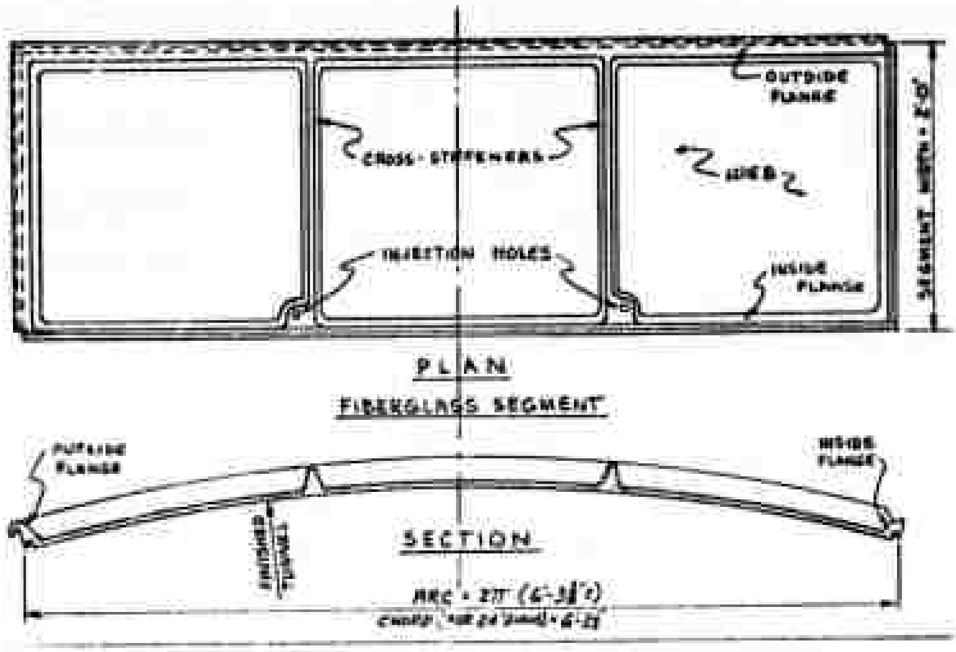
Description: Thin shell segmented lining would be set at face in D & B Tunnel or at tail end of TBM. Polyurethane foam would be injected to fill void between lining and rock, to act as continuous, impervious, blocking. Thickness of web can vary with anticipated rock loads. Design and detail should take advantage of fiberglass properties, light weight, moldability, etc. Concept shown reduces erection time and cost by eliminating bolting. Segments sized as shown can be erected by hand or light weight erector.

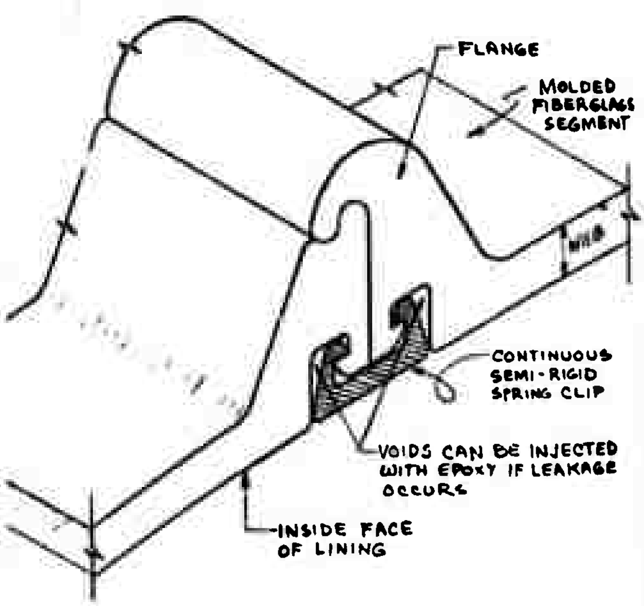
Advantages: Provides complete temporary and permanent support within minutes after lining is set. Segments light, easy to erect, no bolting. Polyurethane provides more uniform loading and good resistance to shock.

Disadvantages: High material cost. Low heat resistance. Requires protection during blasting of face.

Figure 7.6

No. 3a





CONNECTION DETAILS

FIBERGLASS TUNNEL LINING SEGMENT

CONCEPT: H.R.TIEDEMANN

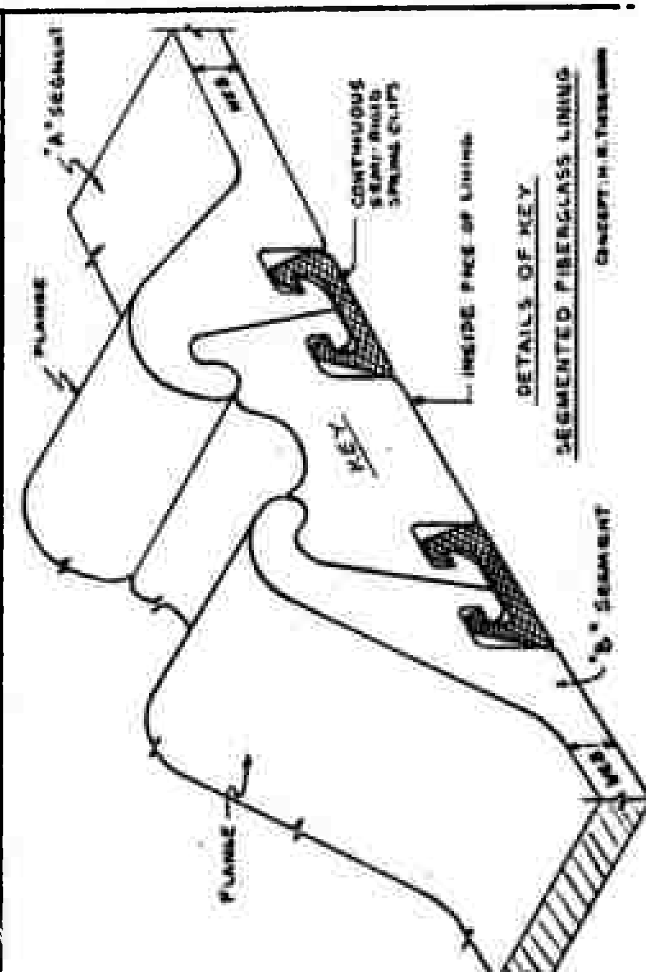
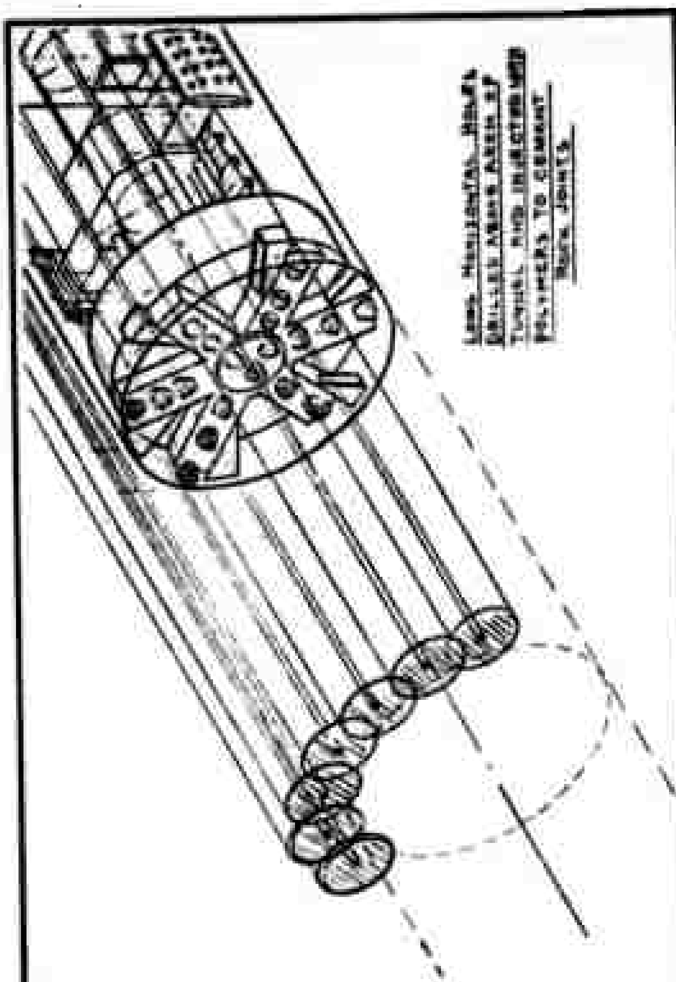


Figure 7.6 (continued)

GROUND SUPPORT CONCEPT SUMMARY



No: 4

Title: POLYMER INJECTION INTO LONG HORIZONTAL HOLES IN ARCH.

Purpose: Cementation of rock joints.

AREA OF USE

RSR Range: 27-77

D & B: Face X Behind ____

T.B.M.: Face X Behind ____

Chance of Success: Fair

Patentability: Poor

Comments: Long drill technique being developed by Jacobs Assoc. under Contract HO 220020.

Originator: Williamson

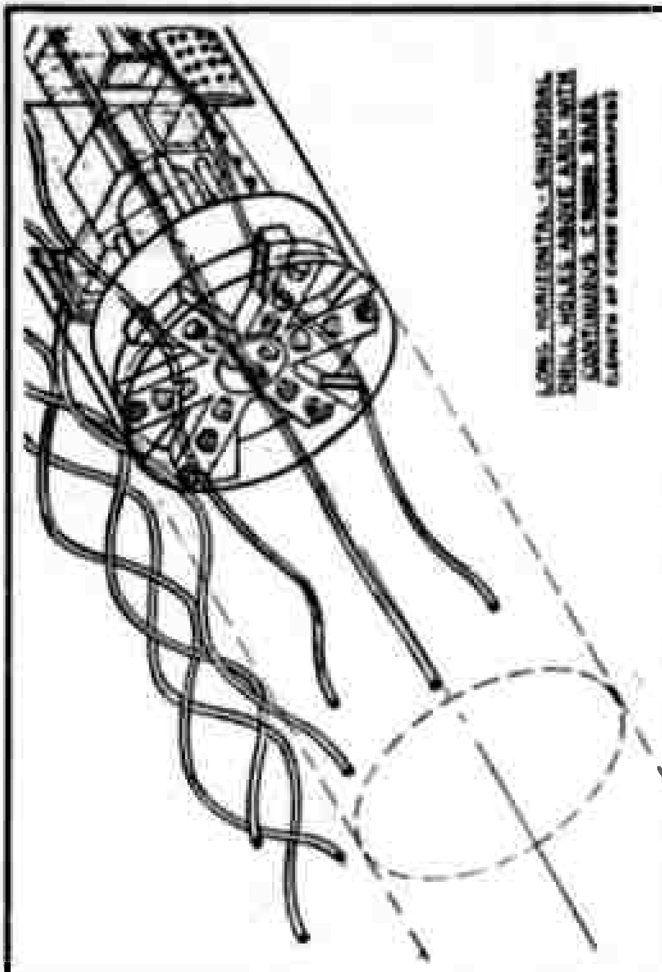
Description: Long (1000 LF ±) holes are driven in advance of the tunnel face above the arch of the tunnel. This can be done from within the tunnel or from a special niche cut in the arch. The holes are then filled with liquid polymers under pressure to disperse thru rock joints and seal them. Equipment for this injection is being developed by others.

Advantages: Rock reinforcement is achieved in advance of the face. Drilling can be done on weekends to reduce interference with excavation. Long holes provide information on condition of rock ahead.

Disadvantages: High cost. Results are difficult to predict. In poor rock, holes may cave. If dispersement is not complete, additional support may be required.

Figure 7.7

GROUND SUPPORT CONCEPT SUMMARY



No: 5

Title: LONG DRILL HOLES WITH CONTINUOUS CROWN BARS

Purpose: Support arch ahead of face.

AREA OF USE

RSR Range: 30-60

D & B: Face X Behind ___

T.B.M.: Face X Behind ___

Chance of Success: [illegible]

Patentability: Doubtful

Comments: Long drill hole technique to be developed.

Originator: Williamson

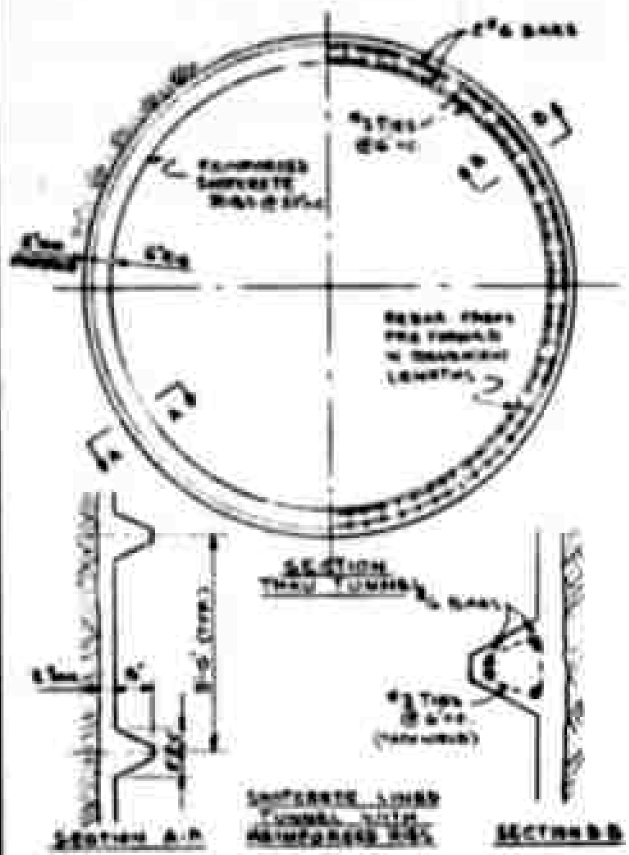
Description: Long drill holes (1000 LF +) are drilled above arch ahead of excavated face. Using techniques developed in oil drilling, it is proposed that these holes be drilled as long sinusoidal curves varying in a plane of the radius with alternate holes rising or falling. This would help to tie more layers of rock than plain horizontal holes. Continuous crown bars would then be placed and grouted in holes.

Advantages: Provides good support ahead of face. Drilling could be done on weekends to reduce interference with excavation.

Disadvantages: High cost. Requires additional support such as steel ribs or shotcrete in transverse direction.

Figure 7.8

GROUND SUPPORT CONCEPT SUMMARY



No: 6

Title: REINFORCED, SPRAYED-IN-PLACE SHOTCRETE RIBS

Purpose: Additional support in shotcrete lined tunnel.

AREA OF USE

RSR Range: 30-60

D & B: Face X Behind ____

T.B.M.: Face ____ Behind X

Chance of Success: Good

Patentability: No - extension of existing art.

Comments:

Originator: Unknown

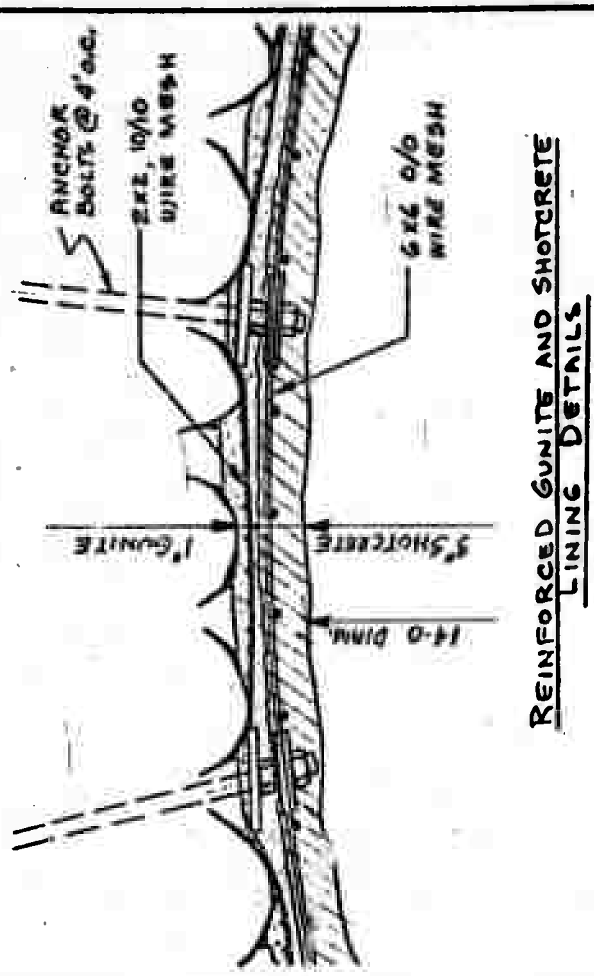
Description: Provide additional support where required in a shotcrete lined tunnel. Preformed reinforcing cages are placed at predetermined spacing and covered with shotcrete at same time as remainder of tunnel.

Advantages: Relatively low cost additional reinforcing in shotcrete lined tunnel. Particularly useful for large tunnels. Easy to install. Reduces required thickness of shotcrete. Adaptable to all sizes of tunnels.

Disadvantages: May delay shotcreting operation. Not desirable in tunnel where smooth finish is required.

Figure 7.9

GROUND SUPPORT CONCEPT SUMMARY



No: 7

Title: REINFORCED GUNITE & SHOTCRETE SUPPORT

Purpose: Temporary support in "heavy" or spalling rock.

AREA OF USE

RSR Range: 40-60

D & B: Face X Behind X

T.B.M.: Face X Behind X

Chance of Success: Good

Patentability: No - extension of existing art.

Comments:

Originator:

Petrofsky & Tiedemann

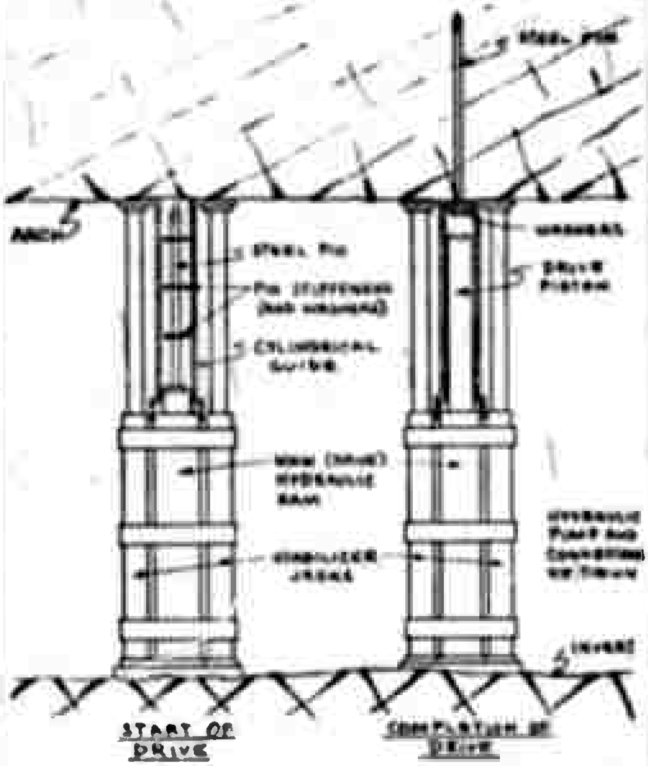
Description: Rock bolts with 2 X 2 wire mesh placed in arch at face. 1" inch covering of gunite is applied. Heavier 6x6 mesh is attached to rock bolts to hold large pieces of rock and reinforce future concrete. 3" layer of shotcrete added when heading is advanced sufficiently so that shotcrete operation does not interfere with excavation. Unreinforced shotcrete is placed on walls and invert.

Advantages: Provides temporary support under heavy load conditions while permitting most of shotcreting to be done away from face.

Disadvantages: Duplication of operations warranted only if sufficient time is saved by shotcreting away from face. Difficult installation.

Figure 7.10

GROUND SUPPORT CONCEPT SUMMARY



USE OF DRIVEN STEEL PINS FOR ROCK REINFORCEMENT

No: 8

Title: USE OF DRIVEN STEEL PINS

Purpose: Rock reinforcement

AREA OF USE

RSR Range: 40-77*

D & B: Face X Behind ___

T.B.M.: Face ___ Behind X

Chance of Success: Good

Patentability: No - used experimentally in coal mines.

Comments:

Originator: Unknown

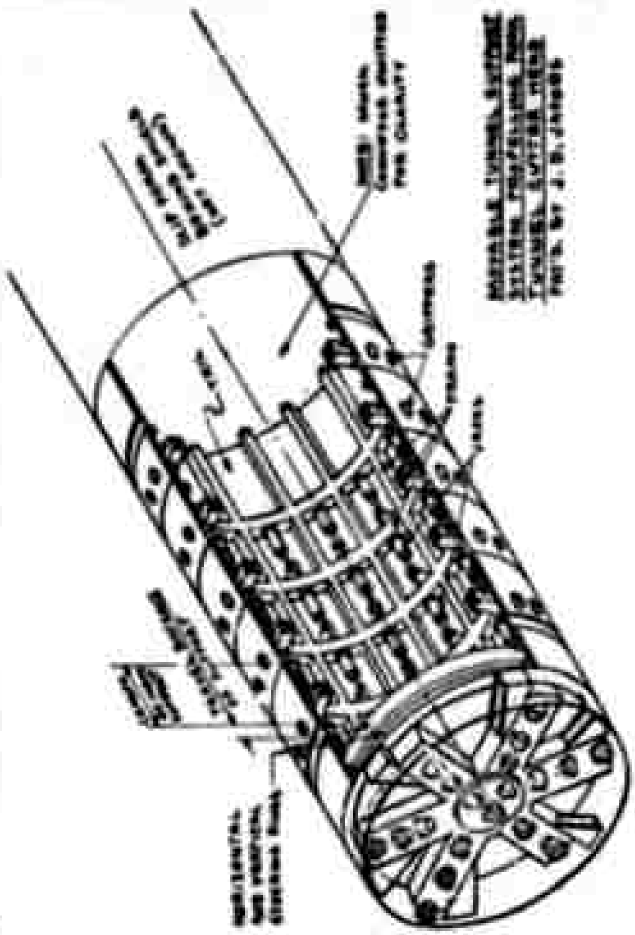
Description: Hydraulic ram pin driver is moved into position by suitable specially designed mobile unit. Side stabilizer jacks raise top support plate and cylindrical guide and exert positive pressure on arch to hold device during driving. Pin is driven all the way by main piston. Circular, tight fit washers are spaced along pin to stiffen against bending during driving. These remain under head as washers on completion of driving.

Advantages: Fast and economical compared to roof bolts as pins do not require pre-drilling. Friction along entire pin gives higher pull-out resistance than comparable rock bolts.

Disadvantages: *Useful only in soft to medium hard, stratified rock in horizontal or near horizontal layers. Also restricted to relatively short pin lengths.

Figure 7.11

GROUND SUPPORT CONCEPT SUMMARY



No: 9

Title: MOVABLE TUNNEL SUPPORT SYSTEM

Purpose: Support ground temporarily at face.

AREA OF USE

RSR Range: 27-77

D & B: Face - Behind -

T.B.M.: Face X Behind

Chance of Success: Good

Patentability: Already patented.

Comments: Patent by J. D. Jacobs (No. 3, 613, 379)

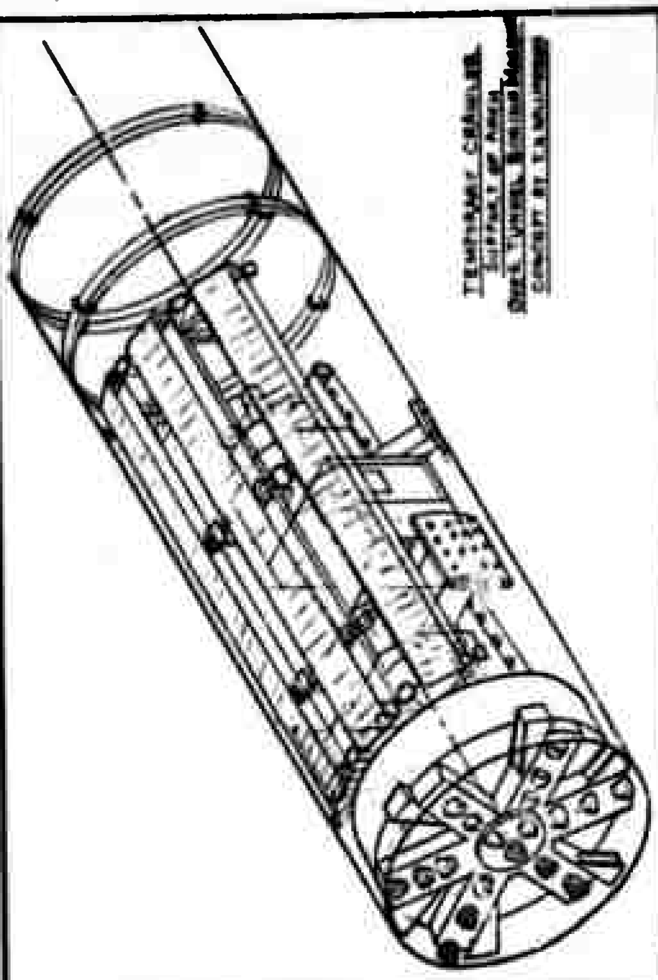
Description: A system of continuous, partly overlapping rings with an appropriate cutter head. Serves the dual function of temporary support at the face, and propulsion of the cutter head. The rings move in small increments, (by use of jacks), one at a time, from front to rear. By use of transverse jacks (not shown) the ring to be moved reduces its diameter slightly and pulls in its grippers. It then moves forward by pushing against the frame system. The other rings maintain a constant pressure against the frame (and in turn the rotating cutter head). These rings are held in position by pressing outward on the rock with multiple small grippers. This machine was designed to be used in conjunction with a slip form behind with continuous reinforcing (concept No. 11), But any suitable support could be erected in the protection of the tail.

Advantages: Provides continuous temporary support. In addition, it provides continuous excavation by eliminating the need to retract and move large sidewall grippers. Thus this type of machine makes possible an optimum system of excavation and support.

Disadvantages:

Figure 7.12

GROUND SUPPORT CONCEPT SUMMARY



No: 10

Title: CRAWLER SUPPORT OVER TBM

Purpose: Support ground temporarily at face.

AREA OF USE

RSR Range: 40-77

D & B: Face - Behind -

T.B.M.: Face X Behind ____

Chance of Success: Good

Patentability: Good

Comments:

Originator: Williamson

Description: Continuous tractor type steel crawlers are mounted, closely spaced, above TBM, running from cutting head to tail end of machine. They will be held in place by hydraulic jacks and be capable of being raised or lowered as required. Crawlers would not be powered.

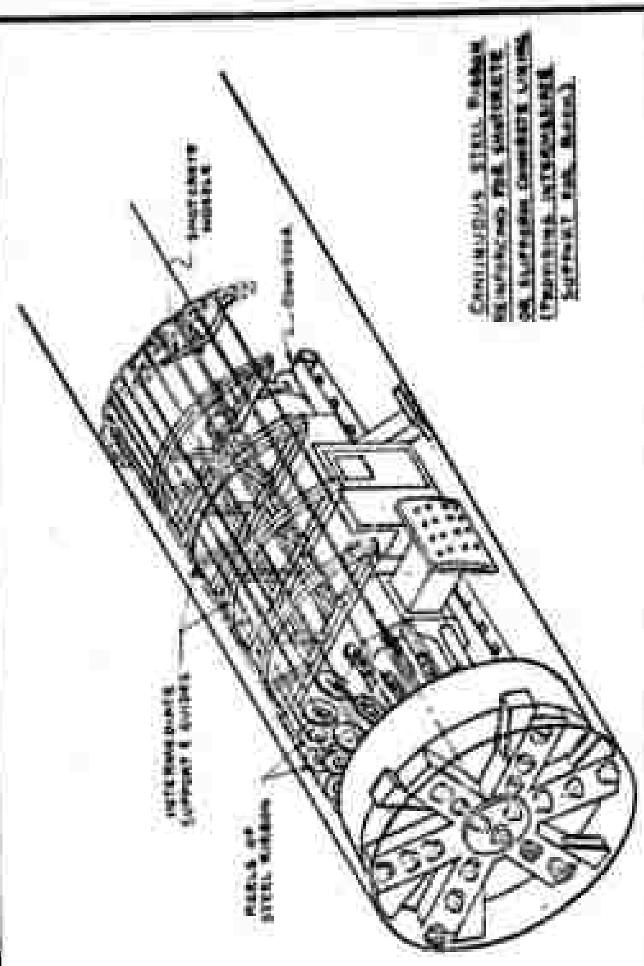
Their function is to hold the rock until other support can be placed behind the TBM.

Advantages: Permits setting of ground support behind machine where there is more room and less interference with excavation. Reduces drag friction of shield over TBM by maintaining point to point contact with rock.

Disadvantages: Small rocks may fall between crawlers. Rock has more time to loosen, which may make load transfer difficult in lower RSR range.

Figure 7.13

GROUND SUPPORT CONCEPT SUMMARY



No: 11

Title: CONTINUOUS STEEL RIBBON REINFORCING

Purpose: For use with shotcrete or slip forms.

AREA OF USE

RSR Range: 30-77

D & B: Face - Behind -

T.B.M.: Face X Behind

Chance of Success: Good

Patentability: Already patented.

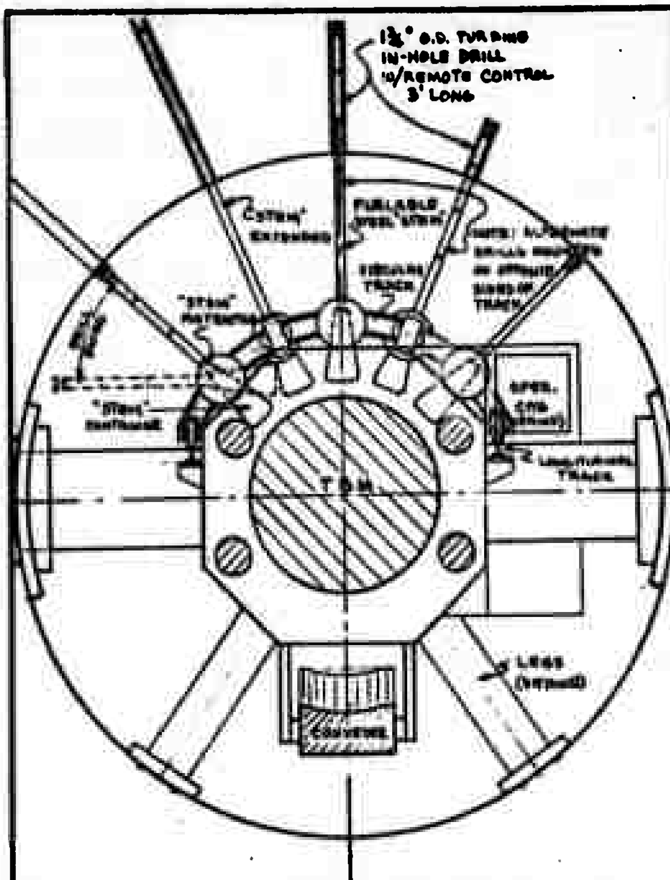
Comments: Patent held by I. D. Jacobs

Description: Reels attached to rear end of TBM cutter head provide continuous steel ribbons for reinforcing of shotcrete and temporary support between shotcrete and face. If shotcrete is applied behind TBM one or more guide supports are provided, as shown, above machine. Ribbons are held tight and restrict loose rocks from falling into tunnel.

Advantages: Provides inexpensive temporary support and reinforcing for shotcrete.

Disadvantages: Value of reinforcing limited unless shotcrete is also reinforced perpendicular to tunnel axis.

Figure 7.14



REMOTE CONTROLLED TURBINE DRILLS MOUNTED ON GANG DRILL CARRIAGE TO DRILL HOLES IN ARCH FOR ROCK BOLTS OR POLYMER INJECTION

No: 12

Title: RADIAL GANG DRILL CARRIAGE

Purpose: Drill for rock bolts or polymer injection.

AREA OF USE

RSR Range: 45-77

D & B: Face X Behind ____

T.B.M.: Face X Behind ____

Chance of Success: Fair

Patentability: Fair

Comments: "STEM" - Storable Tubular Extendible Member (Pat'd.) - short turbine drill being developed by Dyna-Drill.

Originator: Wickham

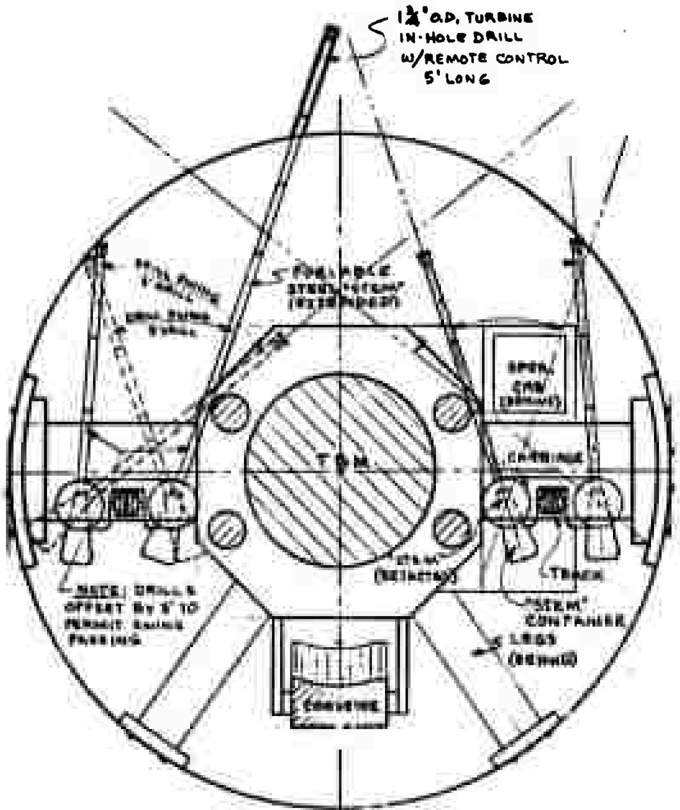
Description: Drills mounted on movable track to drill radial (or near radial) holes for insertion of rock bolts, or polymer injection for rock joint cementation. Short, lightweight, in-hole turbine drills, and strong furlable drill steel are shown, but alternate possible combinations exist.

See 12a for alternate drill set-up utilizing longer drills if shorter drills cannot be developed.

Advantages: Permits rapid gang drilling of holes behind cutter head of TBM not possible with present equipment.

Disadvantages: Much development and testing necessary for drills, furlable drill steel and remote controls.

Figure 7.15

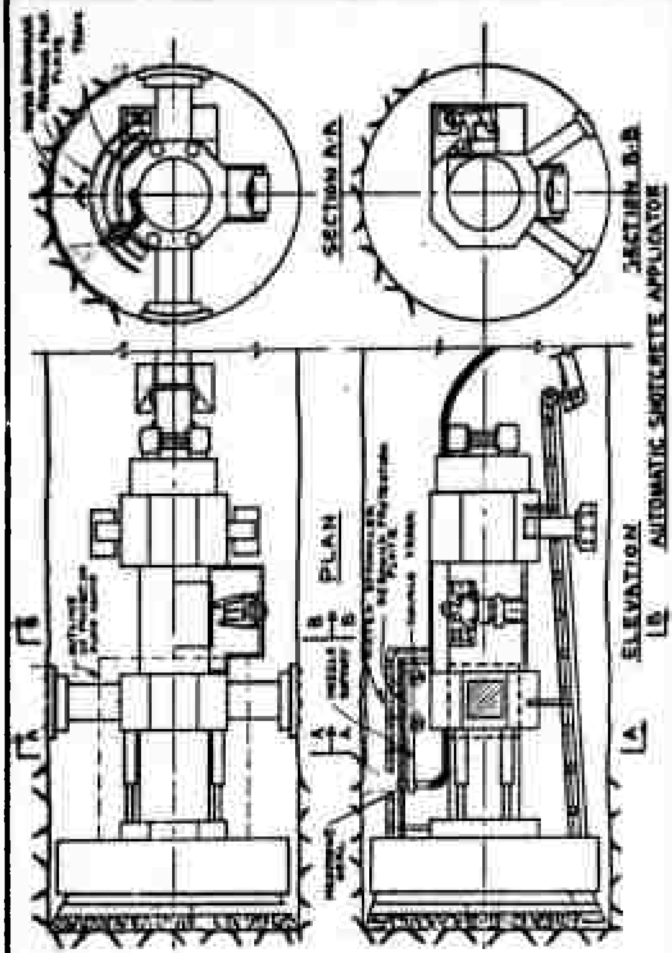


REMOTE CONTROLLED TURBINE DRILLS MOUNTED ON T.B.M. TO DRILL HOLES IN ARCH FOR ROCK BOLTS OR POLYMER INJECTION

Note: Turbine drill lengths shown are maximum for 14' tunnel with T.B.M. as shown. Larger tunnels could accommodate longer drills.

Figure 7.15 (continued)

GROUND SUPPORT CONCEPT SUMMARY



No: 13

Title: AUTOMATIC SHOTCRETE APPLICATOR

Purpose: Apply shotcrete over TBM or drill jumbo.

AREA OF USE

RSR Range: 40-77

D & B: Face X Behind ____

T.B.M.: Face X Behind ____

Chance of Success: Good

Patentability: Others are working on similar concepts.

Comments:

Originator: Wickham

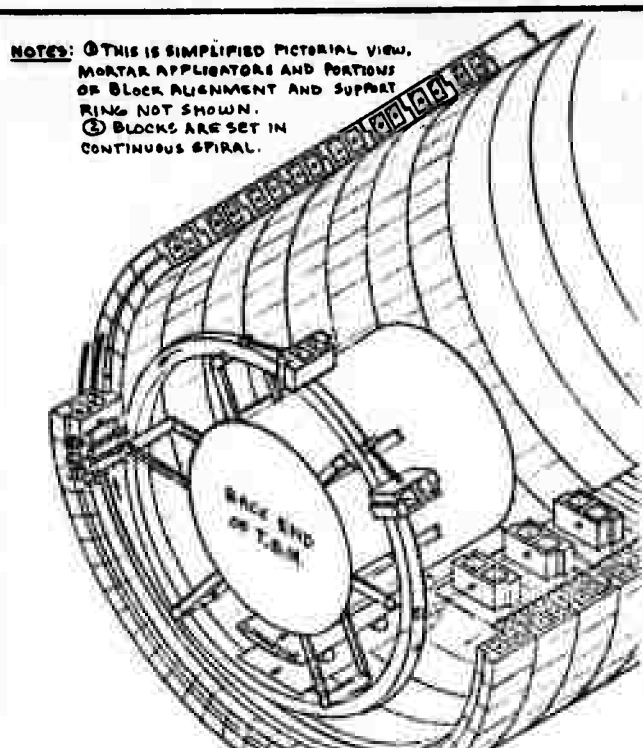
Description: Applicator would be used on a remote controlled carriage on a circular track mounted above a TBM or drill jumbo. Nozzle would project thru a slot in a steel rebound plate. The slot would have a split neoprene seal. A water sprinkler system would keep rebound plate wet and troughs (not shown) would deposit wet rebound material on muck conveyor.

Advantages: Particularly useful for rock support in lower ranges of RSR values that may not stand unsupported for long.

Disadvantages: Takes up a lot of space - probably could not be used in small (under 14' ft. diameter) tunnels. Dust - fog, etc. associated with shotcrete.

Figure 7.16

GROUND SUPPORT CONCEPT SUMMARY



CONTINUOUS BLOCK SETTING MACHINE

No: 14

Title: AUTOMATIC BLOCK SETTING MACHINE

Purpose: Continuous lining at back end of TBM

AREA OF USE

RSR Range: 40-77

D & B: Face - Behind -

T.B.M.: Face ___ Behind X

Chance of Success: Fair

Patentability: Good

Comments: New concept - needs to be developed.

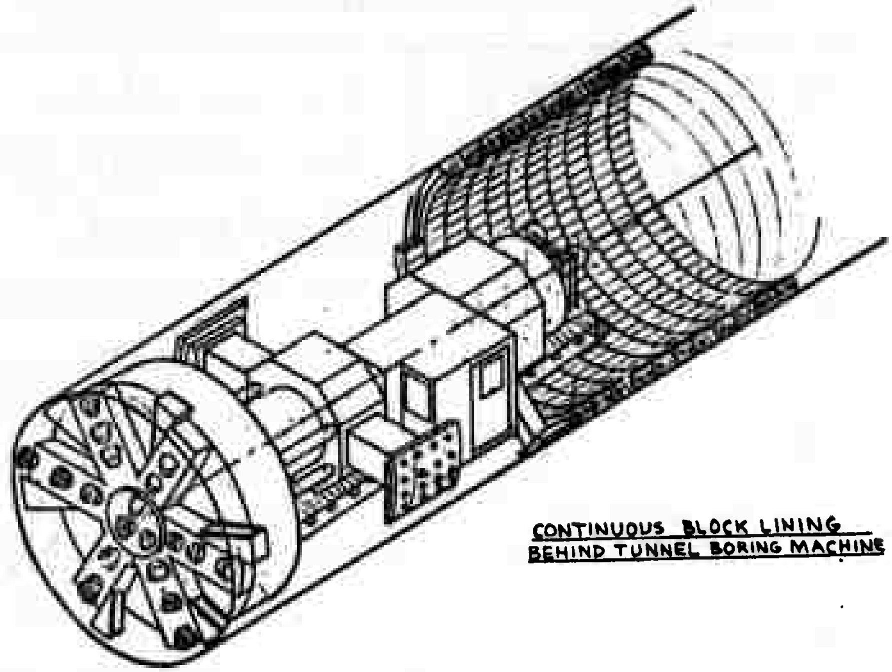
Originators: Williamson & Tiedemann

Description: Automatic machine mounted on back of TBM picks up specially-cast blocks from end of roller conveyor where applicator (not shown) applies mortar to cross joint. Machine places block in continuous spiral advancing at same rate (but partly independent) of TBM. Circular guide holds block for one (or more) complete rings. Applicator (not shown) attached to guide applies mortar to circumferential joint on blocks in place. Preformed sections of rebar are placed in block wells and blocks are grouted using quick couplings cast into arch blocks. Holes cast in back of blocks (see details) permit grout to flow to any voids behind blocks. Various shapes and materials can be used for block.

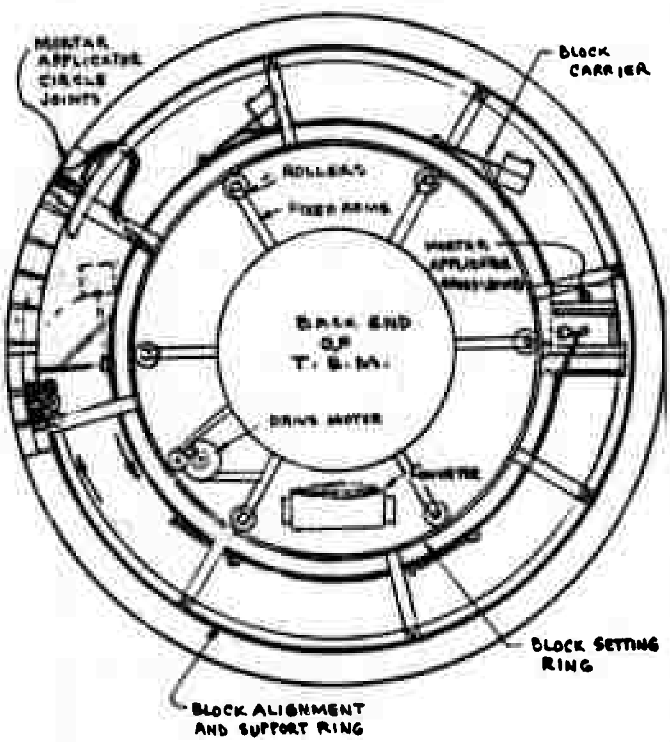
Advantages: Continuous, inexpensive lining placed immediately behind TBM.

Disadvantages: Takes up a lot of space - cannot vary for different rock loads - not applicable for heavy or squeezing ground - creates material handling problem in area of muck train.

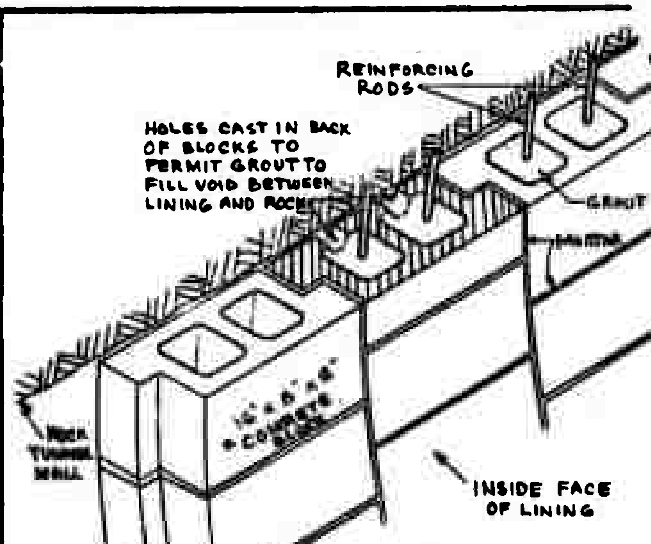
Figure 7.17



CONTINUOUS BLOCK LINING BEHIND TUNNEL BORING MACHINE



CONTINUOUS BLOCK SETTING MACHINE

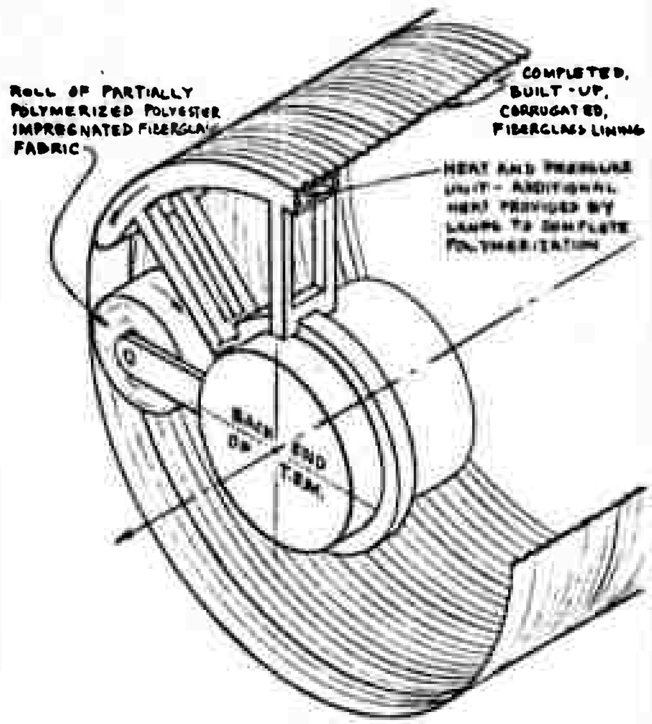


ISOMETRIC VIEW OF CONTINUOUS SPIRAL BLOCK LINING

*NOTE: DETAILS OF BLOCK SHAPE AND MATERIAL MAY VARY. CONCRETE BLOCK SHOWN ONLY ONE OF MANY POSSIBILITIES.

Figure 7.17 (continued)

GROUND SUPPORT CONCEPT SUMMARY



ISOMETRIC VIEW OF CONTINUOUS, SPIRAL WOUND, CORRUGATED FIBERGLASS TUNNEL LINING

No: 15

Title: CONTINUOUS CORRUGATED FIBERGLASS LINING

Purpose: Continuous lining at back of TBM.

AREA OF USE

RSR Range: 30-77

D & B: Face - Behind -

T.B.M.: Face ___ Behind X

Chance of Success: Fair

Patentability: Good

Comments: New concept - needs to be developed.

Originators:

Williamson & Tiedemann

Description: Automatic machine at back end of TBM would apply, heat and press a continuous corrugated fiberglass lining. Segments of preformed corrugated fiberglass would be placed against the rock (see details) as a first layer and back form for subsequent layers. A reel unwinds a flexible layer of partially polymerized, polyester, impregnated fiberglass. This is followed by a heating and pressing unit which forms the corrugations and completes polymerization process. Width of cloth and corrugation size could vary for different size tunnels and desired lining thickness.

Advantages: Continuous lining placed behind TBM which serves as temporary and final support.

Disadvantages: High material cost. Probably not applicable to wet tunnels. Initial (partial) polymerization would probably require a plant set up at job site. Low heat resistance.

Figure 7.18

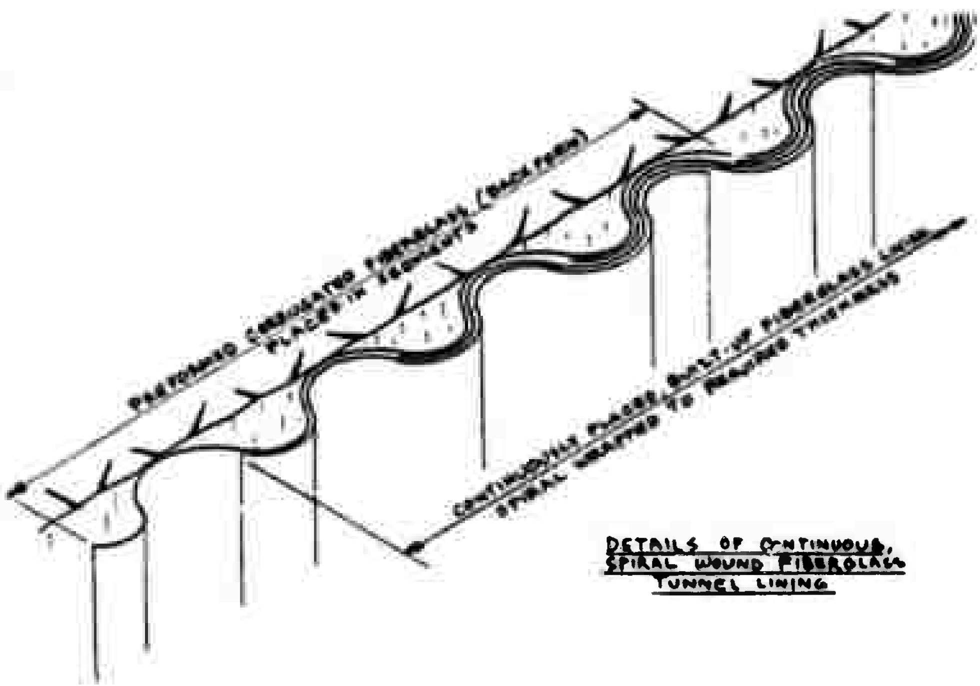
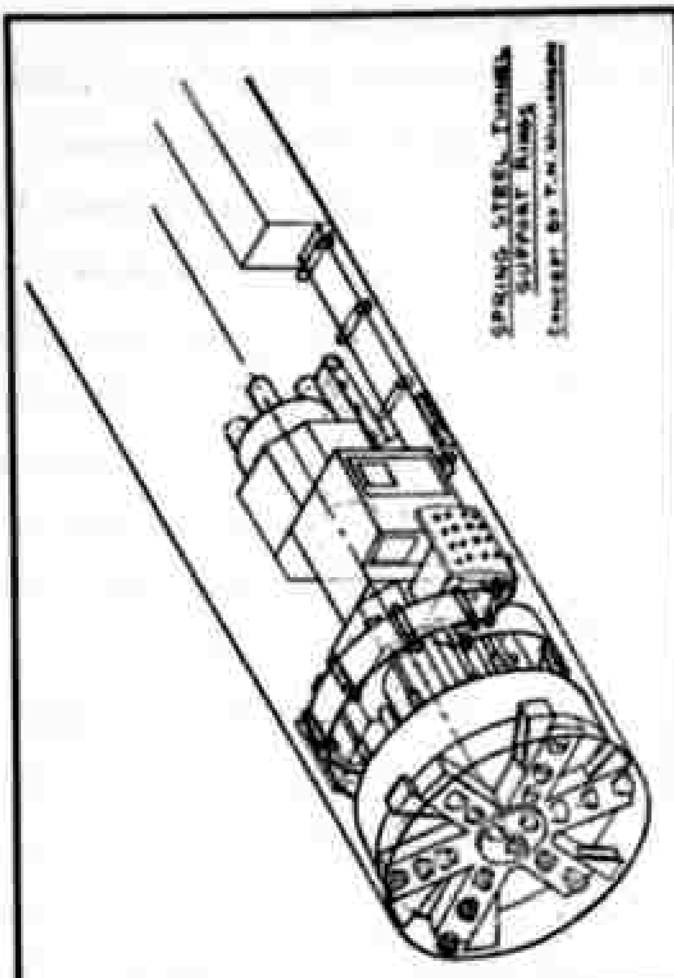


Figure 7.18 (continued)

GROUND SUPPORT CONCEPT SUMMARY



No: 16

Title: SPRING STEEL SUPPORT RINGS

Purpose:

AREA OF USE

RSR Range: 45-77

D & B: Face ___ Behind ___

T.B.M.: Face X Behind ___

Chance of Success: Fair

Patentability: Good

Comments: Might require development of special steel.

Originator: Williamson

Description: Spring steel rings of suitable width are cut to length of circumference and formed to tunnel shape. They are brought to heading in long container, maintained in flat horizontal condition by spring loaded container top. Rings are fed past the machine by rollers and rolled to a circular shape, (smaller than the tunnel) in the plane of the last ring erected. Horizontal jacks mounted behind the cutter head pull the ring forward from the rollers allowing it to spring outward pressing against the rock.

Advantages: Provides support right behind cutter. Automated process reduces labor erection costs.

Disadvantages: High material cost. Not good where heavy or non-uniform loading exists because of lack of stiffeners. Long containers a handling problem.

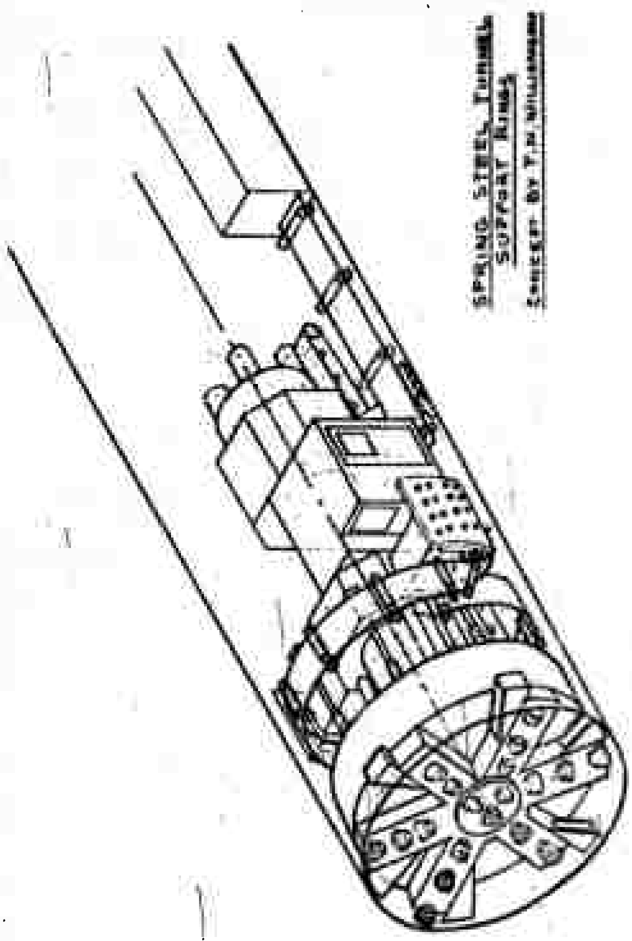
Figure 7.19

7.5 EVALUATION OF GROUND SUPPORT CONCEPTS

For purposes of evaluation, the different concepts have been grouped into four general categories 1) New Materials 2) New Uses of Existing Materials 3) Mechanical Support and 4) Mechanical Placing Concepts. The numerical numbering of the concepts are in accordance with the above rather than as an indication of preference or evaluation. The concepts are compared with respect to eight different parameters or criteria which affect the tunneling process. The parameters are assigned a relative value on basis of an overall evaluation of 100, which, for purposes of this report reflects the optimum system. The individual concepts are rated numerically with respect to each parameter.

Several appraisals using different parameters and values were made before finalizing the matrix shown on Figure 7.20. Each concept was evaluated and rated with respect to its potentiality of fulfilling the requirements for an optimum support system (See paragraph 7.1). Possible cost or time of development which might be required for a new material or concept was not included as a separate parameter. However, a general appraisal of that criterion was considered in the overall evaluation of concepts with respect to parameter A - Feasibility. For example, if present or emerging technologies indicated a high possibility of success within the next few years, a relative high feasibility rating was assigned to the respective concept; if not, a low rating was used. In addition, evaluations for parameter A included other general aspects of the tunneling process such as practicability, size of crews etc. Weighted values assigned for parameters B through H were based on applicable comments and features given for each respective concept on Figures 7.4 through 7.19. They relate to conditions or features usually considered in evaluating tunnel systems.

GROUND SUPPORT CONCEPT SUMMARY



No: 16

Title: SPRING STEEL SUPPORT RINGS

Purpose:

AREA OF USE

RSR Range: 45-77

D & B: Face ____ Behind ____

T.B.M.: Face X Behind ____

Chance of Success: Fair

Patentability: Good

Comments: Might require development of special steel.

Originator: Williamson

Description: Spring steel rings of suitable width are cut to length of circumference and formed to tunnel shape. They are brought to heading in long container, maintained in flat horizontal condition by spring loaded container top. Rings are fed past the machine by rollers and rolled to a circular shape, (smaller than the tunnel) in the plane of the last ring erected. Horizontal jacks mounted behind the cutter head pull the ring forward from the rollers allowing it to spring outward pressing against the rock.

Advantages: Provides support right behind cutter. Automated process reduces labor erection costs.

Disadvantages: High material cost. Not good where heavy or non-uniform loading exists because of lack of stiffeners. Long containers a handling problem.

Figure 7.19

COMPARISON OF SUPPORT CONCEPTS - SHEET 1									
		Support Materials Concepts							
		New Materials				New Uses For Existing Materials			
Parameter	Maximum Values	1 Spray In Place	2 Steel & Polyurethane	3 Fiberglass & Polyurethane	4 Long Hole Polymers	5 Long Crown Bars	6 Shotcrete Ribs	7 Gunite & Shotcrete	8 Rock Pins
A. Feasibility	20	5	12	10	5	3	15	13	10
B. Safety and Environment	15	5	8	10	6	5	8	6	8
C. Adaptability to Rapid Excavation	15	10	8	9	2	1	6	3	4
D. Adaptability to Wide Range of Rock Conditions	10	6	8	8	3	4	8	6	2
E. Proximity of Support to Face	10	8	7	7	3	3	4	3	3
F. Effect on Continuity of Operations	10	6	4	5	3	2	3	2	5
G. Effect on Working Room Near Face	10	1	2	3	2	2	4	4	3
H. Effect on Material Handling	10	4	2	3	1	1	4	3	4
TOTAL	100	45	51	55	25	21	52	40	39

Figure 7-20

COMPARISON OF SUPPORT CONCEPTS - SHEET 2									
Parameter	Maximum Values	Mechanical Concepts							
		Mechanical Support			Mechanical Placing Concepts				
		9 Movable Support	10 Crawler Support	11 Steel Ribbon	12 Gang Drill	13 Shotcrete Applicator	14 Block Laying Machine	15 Corrugated Fiberglass Machine	16 Spring Steel
A. Feasibility	20	16	15	10	12	15	8	2	5
B. Safety and Environment	15	14	12	6	12	12	8	4	3
C. Adaptability to Rapid Excavation	15	13	12	6	9	11	5	3	6
D. Adaptability to Wide Range of Rock Conditions	10	9	7	4	6	8	4	5	3
E. Proximity of Support to Face	10	10	8	6	7	8	4	4	8
F. Effect on Continuity of Operations	10	8	7	5	6	6	4	4	3
G. Effect on Working Room Near Face	10	8	7	5	7	6	3	3	2
H. Effect on Material Handling	10	7	6	6	8	6	2	2	2
TOTAL	100	85	74	48	67	72	38	27	32

Figure 7-20 (continued)

It is difficult to make relative comparisons of basically different support systems, especially those of a conceptual nature, where of necessity, many conclusions are based on assumptions. Although concept #1 has been assigned a relative low rating, it has many theoretical advantages over some of the others. If a suitable plastic material was developed in the near future, the rating for that concept would be significantly increased. Conversely, a mechanical concept with an indicated high rating might have to be downgraded if engineering studies showed technical flaws not now apparent. Concept #8, Rock Pins, would probably have a higher rating if its application were considered with respect to coal mining operations as opposed to conventional tunneling. It is realized that this or similar reasoning might apply to all concepts; that is, it is likely that different ratings would be assigned if each was considered individually with respect to a specific tunneling situation. For purposes of this study, however, all concepts have been rated on basis of present day technologies and requirements for typical civil works tunnels driven through fair to good rock structures.

The optimum system must be capable of providing adequate support for a wide range of rock conditions (RSR values from 27 to 77) which is considered with respect to parameter D. To a certain extent this requirement can be fulfilled by present systems or new concepts which involve the use of existing support materials, i.e. the size and spacing of steel ribs can be varied, different thicknesses of shotcrete can be applied and rock bolts installed in varying patterns. Steel ribs are adaptable to all RSR values; shotcrete and rock bolts would probably not be used for initial support in tunnels with an RSR value less than 40. It is possible that concepts using steel or fiberglass segments with polyurethane backing could be made adaptable to all rock conditions. This might be accomplished by varying the thickness of the segment webs and increasing the load carrying capacity (density) of the polyurethane when injected behind the segments. Varying the thickness of sprayed-in-place or corrugated fiberglass linings would increase their adaptability to a larger range of rock conditions. In all cases, evaluation of parameter D must include also the consideration of 1) how the system could be installed and 2) possible delay or interference with the overall tunneling process. In this respect, concept #9 - Movable Support - has an advantage. It provides complete support for all rock conditions with little or no interference of the heading operation. However, it requires the use of other support systems behind the movable shield.

Although eight different parameters were considered in making the evaluation, it is obvious that each has some effect on the others. This is illustrated to a certain degree by the cost comparisons shown on Figures 7.1, 7.2 and 7.3. Figure 7.20 shows that concepts number 9, 10, 13, 12 and 3 (in order of ratings) offer the greatest potential of fulfilling the requirements of an optimum support system in the near future. An economic analysis and a discussion of various pros and cons of these concepts is given in Section 8.

The development of new support materials or new techniques of tunnel excavation could easily alter the ratings shown on the matrix. Comparing maximum parameter values with respective concept ratings gives an indication of potential improvement which might be made in that specific area or feature of the concept. General appraisals can be made by considering the four different categories. "Mechanical Support" concepts appear to be the most likely candidates for improving the art of tunneling at the present time. "Mechanical Placing" concepts are next, with "New Materials" and "New Uses of Existing Materials" following in that order. Even though ratings for new material concepts have been more or less downgraded due to limitations of existing technology, they show greater potential than concepts using existing materials and about the same as mechanical placing concepts.

Although continued improvements can be expected in all categories, it appears that any significant "breakthrough" in tunnel support systems will be in the area of new materials. This is due to the fact that most of the other concepts presently reflect the results of past research and basic improvements which have been made over a period of time. Additional improvements will probably be more of the nature of a modification as opposed to large advances in technologies.

SECTION 8

COST EVALUATION OF SUPPORT SYSTEMS

8.1 INTRODUCTION

In determining support requirements for tunnels it is usually found that several different support systems could be used; each of which would be adequate to support the surrounding rock mass. Variations of conventional systems; steel ribs, shotcrete and rock bolts, can be made to satisfy the support requirements of most rock structures. Steel ribs can be used in all cases; the use of shotcrete and rock bolts is generally restricted to rock structure having an RSR value greater than 40. Within the intermediate range of fair to good rock structure (RSR values from 40 to 77) the problem always exists as to which system would provide the most optimum solution to the tunneling process. The answer requires a detailed analysis and evaluation of all operations and cost components which are affected by the use of a particular support system. This section of the report indicates how such an analysis and evaluation can be made. It deals primarily with the various conventional support systems as determined for the Donjay example tunnel in Section 6. It considers also, five new concepts of ground support (Section 7) that may have been used in the Donjay Tunnel.

The conventional systems are evaluated with respect to both methods of excavation, the five new concepts only with respect to machine excavation. All situations are analyzed and evaluated in approximately the same manner; consequently, comments made for one are, in general, applicable to the others. It is pointed out that an analysis made to evaluate systems for an actual tunnel project would require considerably more detail than presented in the following paragraphs. The intent is to show the general approach to the problem and give an indication as to possible cost advantages that may be achieved by use of different support systems. Comments and statements pertaining to various aspects of the tunneling process have been made in previous sections. They should be considered within the context of the following discussion.

8.2 RATE OF ADVANCE

The cost per lineal foot of tunnel, which is a measure of the overall efficiency of the tunneling process, is directly dependent on the daily rate of advance of the tunnel heading. It is determined by considering the relative effect and corresponding time requirements for completing all work operations or subsystems occasioned by a particular rock structure and method of excavation. For conventional drill and blast methods, the subsystems (excavation, ground control, logistics and environmental control) are basically sequential in nature. They can be individually analyzed on basis of relevant components of work. For example, the work components or operations pertinent to the excavation subsystem are usually identified as follows:

1. Move-in and set-up drill jumbo.
2. Drill blast holes.
3. Load powder.
4. Blast face - smoke time.
5. Muck out.

Other subsystems can be similarly defined. Each would be evaluated with respect to relative quantities of work involved depending on size of tunnel, rock structure, length of round pulled, etc. Time required to complete each operation is determined by considering the construction capabilities of the particular equipment and labor crew involved. The sum of the separate time requirements is the "cycle time". The maximum or optimum advance per day is obtained by dividing available working hours by cycle time and multiplying by the length of round. This rate is adjusted to allow for lost time and other inefficiencies inherent to tunneling operations so as to arrive at the estimated daily advance rate. The adjustment, or construction efficiency factor, varies with respect to type of operation, length of tunnel, labor regulations and other conditions. Figure 8.1 shows a typical format and the determinations used in estimating daily advance rates for the Donjay example tunnel. It lists the major work operations and their respective time requirements. Length of round pulled, cycle times, number of rounds per day and construction efficiency factors used to determine optimum and estimated advance rates are shown. Separate analyses have been made for each of the four tunnel sections with respect to applicable support system determined for the drill and blast method of excavation (see tabulation on page 6-17). No supports are required for tunnel Section C.

The tabulation illustrates the overall relative dependency of all conditions and work operations pertinent to the drill and blast method of excavation. The need to provide ground support in different sections of the Donjay Tunnel could reduce the anticipated optimum advance rate (57 feet per day in unsupported Section C) by as much as 54%. This applies to Section A where the estimated advance rate is 26 feet per day. Percentage reductions for the other sections and support systems are also given. Another evaluation or comparison could be made by eliminating time required to install supports (work operation #6) from respective cycle times. Using the adjusted cycle times, daily advance rates which reflect all operations except the actual installation of support can be determined. A comparison of these rates with the anticipated rate of advance for Section C shows a reduction of approximately 40% (tunnel Section A) as compared to the previously given 54%. This comparison of percentage reduction in daily advance rates; which reflects the extreme conditions of the Donjay Tunnel, shows that a large portion of the reduction is due to conditions dictated by the inherent properties of the rock structure as opposed to the

PROGRESS ESTIMATE FOR DRILL & BLAST TUNNEL WITH CONVENTIONAL GROUND SUPPORT								
TUNNEL SECTION	A	B			C	D		
SUPPORT REQUIREMENT	10 WF 49 @ 3'	8 WF 40 @ 4'	Rock Bolts @ 2.5'	Shotcrete 4" Thick	No Support	6 H25 @ 6'	Rock Bolts @ 4.5'	Shotcrete 2" Thick
LENGTH OF ROUND PULLED	4'	6'	6'	6'	11'	9'	11'	11'
WORK OPERATION:								
1. Move Jumbo in - set up	0:05	0:05	0:05	0:05	0:05	0:05	0:05	0:05
2. Drill out	0:40	1:05	1:05	1:05	1:30	1:15	1:30	1:30
3. Load and Shoot	0:22	0:23	0:23	0:23	0:25	0:23	0:25	0:25
4. Smoke Time	0:15	0:15	0:15	0:15	0:15	0:15	0:15	0:15
5. Muck out	0:43	1:00	0:55	0:55	1:35	1:20	1:35	1:35
6. Install Supports	0:40	0:38	1:10	0:38	-	0:30	0:32	0:32
7. Miscellaneous	0:10	0:08	0:05	0:05	0:05	0:05	0:05	0:05
Total Cycle Time in Hours	2.91	3.57	3.97	3.45	3.92	3.90	4.45	4.60
No. of Cycles per 22.5 Hr.Da	7.74	6.30	5.67	6.52	5.74	5.77	5.06	4.90
Optimum Advance per Day	31'	38'	34'	39'	63'	52'	56'	54'
Construction Efficiency	85%	85%	87%	85%	90%	86%	87%	86%
Estimated Advance per Day	26'	33'	30'	33'	57'	45'	49'	46'
Reduction in Optimum Rate due to Support Requirements	54%	42%	47%	42%	-	21%	14%	19%
Reduction in Optimum Rate without Operation (6)	40%	32%	26%	28%	-	9%	4%	5%

DONJAY TUNNEL

Figure 8.1

actual installation of supports. It is obvious, however, that all operations and conditions are dependent on each other. For instance, it would not be necessary to use a four foot round for Section A if the rock structure did not require support. This interdependency is most pronounced for the drill and blast method wherein all operations are sequential in nature. It has less effect for machine methods and possibly could be eliminated by development of new technologies or concepts.

Following the same general procedure as outlined on Figure 8.1, estimates were made of daily advance rates for the other tunneling situations considered in this section of the report. Figure 8.2 shows the advance rates determined for similar sections of the Donjay Tunnel based on use of a boring machine and applicable support systems shown on page 6-17. Advance rates which might be achieved by using new support concepts in conjunction with a boring machine have been determined and are shown on Figure 8.3. Tunnel Section C is not included on that figure. Different operations are considered in analyzing the machine method of excavation. Advance rates for boring machines are usually determined by first considering the maximum penetration rate; which is dependent on machine design and rock properties, and then reducing that rate in proportion to anticipated interference or delays caused by other operations.

8.3 COST EVALUATIONS

Having estimated daily advance rates for the various tunneling situations it is now possible to determine applicable costs per lineal foot of tunnel. Costs, such as labor, equipment operation and depreciation, supervision, overhead, etc., are directly related to time requirements. Job materials, small tools and supplies and permanent materials are based on actual requirements or quantities used to complete the work. Plant installations or requirements and contractor's mark-up (profit and contingency) are dependent on the

PROGRESS ESTIMATE FOR TBM TUNNEL WITH CONVENTIONAL GROUND SUPPORT								
TUNNEL SECTION	A		B		C		D	
SUPPORT	10 WF 49 @ 3-1/2'	8 WF 40 @ 5-1/2'	Rock Bolts 3'x3'	Shotcrete 3" Thick	No Support	6H25 @ 7'	Rock Bolts 6'x6'	Shotcrete 1-1/2" Th.
Distance traveled before setting support	3.5'	5.5'	6'	6'	-	7'	6'	7'
Basic Progress (60% of Max. Penetration Rate)	12'/Hr	9'/Hr	9'/Hr	9'/Hr	2.5'/Hr	6'/Hr	6'/Hr	6'/Hr
Cycle Time (Hours)								
A. Setting Support	0.80	0.60	1.75 *3	0.85 *2	-	0.50	1.10 *4	0.60
B. Interference Factor	1.00	0.50	0.50	1.00	-	0.25	0.25	0.50
C. Support Time in Cycle (AxB)	0.80	0.30	0.88	0.85	-	0.13	0.28	0.30
D. Travel at Basic Rate	0.30	0.61	0.67	0.67	-	1.17	1.00	1.17
E. Total Cycle Time (C+D) or A*1	1.10	0.91	1.75 *1	1.85	-	1.30	1.28	1.47
No. of cycles per 22.5 hour day	20.5	24.7	12.9	14.8	-	17.3	17.6	15.3
Total Advance (Ft/Day)	72	135	77	89	56	121	105	107
% of Basic Rate	25%	63%	36%	40%	94%	84%	73%	75%
% of Max. Pen. Rate	15%	38%	21%	24%	56%	50%	44%	45%
Total Crew Size	114	111	123	117	84	111	111	108

*1 Use (A) time for setting support as total cycle time if it is greater than (C+D)
*2 Arch only. Additional shotcrete gun and crew required for invert
*3 Based on five roof bolt crews
*4 Based on two roof bolt crews

DONJAY TUNNEL

Figure 8.2

PROGRESS ESTIMATE FOR TBM TUNNEL WITH NEW SUPPORT CONCEPTS - SHEET 1

TUNNEL SECTION	A			B				
SUPPORT	3 Fiberglass Lining	9 Movable Support	13 Automatic Shotcrete	3 Fiberglass Lining	9 Movable Support	10 Crawler Support	12 Bolt Gang Drill	13 Automatic Shotcrete
Distance travelled before setting support	4'	4'	4'	6'	6'	6'	6'	6'
Basic Progress (60% of Max.Pen.Rate, except*1)	12'/Hr	13.8'/Hr*1	12'/Hr	9'/Hr	10'/Hr*1	9'/Hr	9'/Hr	9'/Hr
Cycle Time (Hours)								
A. Setting Support	0.80	1.13	1.13	1.00	0.77	0.85	1.33	0.77
B. Interference Factor	0.25	0.25	0.50	0.25	0.25	0.50	0.25	0.50
C. Support Time in Cycle (AxB)	0.20	0.28	0.57	0.25	0.19	0.42	0.33	0.39
D. Travel at BasicRate	0.33	0.29	0.33	0.67	0.60	0.67	0.67	0.67
E. Total Cycle Time (C+D) or A *2	0.80*2	1.13*2	1.13*2	1.00*2	0.79	1.09	1.33*2	1.06
No. of cycles per 22.5 hour day	28.1	19.9	19.9	22.5	28.5	20.6	16.9	21.2
Total Advance (Ft/Day)	112	80	80	135	171	124	101	127
% of Basic Rate	39%	24%	27%	63%	71%	57%	47%	59%
% of Max. Pen. Rate	23%	16%	16%	38%	48%	34%	28%	35%
Total Crew Size	120	117	117	117	117	117	111	117

*1 - Basic Rate increased by eliminating time to move and reset grippers.
*2 - Cycle determined by time required to set arch support

DONJAY TUNNEL

Figure 8.3

PROGRESS ESTIMATE FOR TBM TUNNEL WITH NEW SUPPORT CONCEPTS - SHEET 2					
TUNNEL SECTION	D				
SUPPORT	3 Fiberglass Lining	9 Movable Support	10 Crawler Support	12 Bolt Gang Drill	13 Automatic Shotcrete
Distance traveled before setting support	6'	6'	6'	6'	6'
Basic Progress (60% of Max. Pen. Rate, except *1	6'/Hr	6.5'/Hr*1	6'/Hr	6'/Hr	6'/Hr
Cycle Time (Hours)					
A. Setting Support	1.00	0.47	0.60	0.33	0.47
B. Interference Factor	0.25	0.25	0.50	0.25	0.50
C. Support Time in Cycle (A x B)	0.25	0.12	0.30	0.08	0.24
D. Travel at Basic Rate	1.00	0.92	1.00	1.00	1.00
E. Total Cycle Time (C+D) or A*2	1.25	1.04	1.30	1.08	1.24
No. of cycles per 22.5 hour day	18.0	21.6	17.3	20.8	18.1
Total Advance (Ft/Day)	108	130	104	125	109
% of Basic Rate	75	83	72	87	76
% of Max. Pen. Rate	45	54	43	52	45
Total Crew Size	111	108	108	105	108

*1 - Basic Rate increased by eliminating time to move and reset grippers
*2 - Cycle determined by time required to set arch support

DONJAY TUNNEL
Figure 8.3
(continued)

particular project being considered. The same general costing procedure is followed in all cases, regardless of whether or not the work is to be accomplished by conventional drill and blast methods or by use of a boring machine.

As mentioned previously, this report does not include the large amount of detail and calculations which would be required to prepare an actual cost estimate. It does, however, present results which reflect typical procedures used in estimating costs for the different tunneling situations including consideration of all subsystems involved in the respective tunneling processes. A brief discussion of each situation is given in the following paragraphs.

8.3.1 Conventional Systems - Drill & Blast Method

The cost components most affected by support installations are direct labor and support materials. Labor costs are directly proportional to the size of crews and daily advance rate. Typical size of crews (excluding supervision and overhead) for the Donjay Tunnel would vary between 112 and 121 men per day (3 shifts). Assuming an average hourly labor rate of $9.50 in conjunction with the respective daily advance rates given on Figure 8.1, it is possible to determine the direct labor cost per foot of tunnel.

Cost of support material is determined by extending the applicable unit price against the quantity of support material required for one foot of tunnel. Quantity of material for each support system is based on respective requirements such as rib size and spacing, thickness of shotcrete and rock bolt pattern.

Other components of costs such as job materials and supplies, equipment operation (fuel, lube repairs etc.) overhead and general expenses, plant and equipment write-off and mark-up have been determined on the basis of total requirements for constructing the Donjay example tunnel.

Results of the estimate are shown on Figure 8.4. It gives reasonable appraisal of costs per foot of tunnel as occasioned by use of the respective

COST SUMMARY - DRILL & BLAST TUNNEL - CONVENTIONAL SUPPORTS							
TUNNEL SECTION & SUPPORT REQUIREMENTS	DIRECT LABOR	JOB MATERIALS AND SUPPLIES	SUPPORT MATERIALS	EQUIPMENT OPERATION	TOTAL DIRECT COSTS	OVERHEAD P&E AND MARKUP	ESTIMATED BID PRICE PER L. F. TUNNEL
<u>SECTION A</u>							
10 WF 49 (@ 3')	$328	$46	$173	$35	$582	$308	$890
<u>SECTION B</u>							
8 WF 40 (@ 4')	258	43	122	31	454	264	718
Rock Bolts (@ 2-1/2')	306	49	85	32	472	264	736
Shotcrete (4")	272	39	31	33	375	218	593
<u>SECTION C</u>							
Unsupported	149	34	-	27	210	178	388
<u>SECTION D</u>							
6 WF 25 (@ 6')	189	37	61	29	316	203	519
Rock Bolts (@ 4-1/2')	188	37	24	29	278	189	467
Shotcrete (2")	195	36	18	30	279	178	457

DONJAY TUNNEL

Figure 8.4

support system.

Costs per lineal foot of supported tunnel range from 118% to 230% of the cost of the unsupported Section C. This is approximately the same differential as indicated by the analysis of daily advance rates given on Figure 8.1.

On the basis of this evaluation, the most efficient (less costly) support system to be used for tunnel sections B and D would be shotcrete. Section C is unsupported. Due to predicted rock structure rating for Section A, only steel ribs were considered. The other systems would not be adequate. The cost per foot of tunnel for the respective components shown on Figure 8.4 gives an indication of their relative effect on the overall tunneling operation.

8.3.2 Conventional Systems - Machine Method

Figure 8.5 shows results of a similar cost evaluation made by considering conventional support systems and machine method of excavation. The Donjay tunnel sections and support systems are as shown on page 6-17. Costs were determined in the same manner as those for the drill and blast method. Daily advances and crew sizes considered in the evaluation are shown on Figure 8.2. Comparing total cost per lineal foot of tunnel as shown for corresponding tunnel sections on Figures 8.4 and 8.5 shows lower costs for the machine method in all cases except tunnel Section C. These results could be expected due to differences in advance rates (see Figures 8.1 and 8.2). The higher "machine" cost for Section C is due to the fact that hard massive granite (rock encountered in Section C) cannot be economically cut with present day boring machines. A review of Figure 8.5 shows that the relative position of different support systems with respect to total cost are about the same as found for the drill and blast method of excavation. It is also noted that differences in costs for various systems considered for a particular tunnel section are less than shown on Figure 8.4.

COST SUMMARY - TBM TUNNEL - CONVENTIONAL SUPPORT								
TUNNEL SECTION & SUPPORT REQUIREMENTS	DIRECT LABOR	MATERIALS		EQUIPMENT OPERATION		TOTAL DIRECT COSTS	OVERHEAD P&E AND MARKUP	ESTIMATED BID PRICE PER L.F. TUNNEL
		SMALL TOOLS	SUPPORT MATERIALS	GENERAL	CUTTER COSTS			
SECTION A								
10 WF 49 (@ 3-1/2')	$120	$4	$ 175	$ 24	$ 21	$344	$289	$ 633
SECTION B								
8 WF 40 (@ 5-1/2')	62	2	98	22	29	213	245	458
Rock Bolts (3'x3')	121	4	52	22	29	228	250	478
Shotcrete (3")	100	3	27	25	29	184	239	423
SECTION C								
Unsupported	114	3	-	67	140	324	283	607
SECTION D								
6 H 25 (@ 7')	70	2	55	26	46	199	241	440
Rock Bolts (6'x6')	80	2	13	26	46	167	230	397
Shotcrete (1-1/2")	77	2	13	27	46	165	233	398

DONJAY TUNNEL

Figure 8.5

8.3.3 New Support Concepts - Machine Method

Five new support concepts were evaluated with respect to the Donjay tunnel sections and use of a boring machine. Results are shown on Figure 8.6. Concepts #9 and #10 (mechanical support concepts) were considered as having shotcrete lining placed behind the boring machine or movable support system.

In analyzing the costs of these new concepts, they should be considered with respect to the general categories given in Section 7. The fiberglass segmented lining, although the most promising in the new materials field, was very poor in the economic comparison. The cost of labor, which reflects savings due to the light weight-boltless design, is comparatively low, but does not offset the high material cost. Unless there is a major change in material cost, this type of support seems to be too expensive for consideration at this time regardless of its efficiencies. This may not be true in soft ground tunnels where labor constitutes a greater portion of total cost. In this case, potential reductions in labor cost and increases in daily advance rates due to these efficiencies may offset the higher material cost.

The mechanical placing concepts, #12 - Radial Gang Drill and #13 - Automatic Shotcrete Applicator, both show potential savings, if they can be developed. Although a conservative allowance was made in estimating the additional cost of required equipment, they still showed some savings over their conventional counterpart systems.

The mechanical supports considered, #9 - Movable Tunnel Support and #10 - Crawler Support, showed savings over conventional supports similar in magnitude to the mechanical placing concepts. In considering the overall project, the Movable Tunnel Support concept using shotcrete placed behind the machine provides the most efficient solution. This system has other potential savings which is discussed later. Costs were not given for Crawler

COST SUMMARY - TBM TUNNEL - NEW SUPPORT METHODS								
TUNNEL SECTION & SUPPORT METHOD	DIRECT LABOR	MATERIALS		EQUIPMENT OPERATION		TOTAL DIRECT COSTS	OVERHEAD P&E AND MARKUP	ESTIMATED BID PRICE PER L. F. TUNNEL
		SMALL TOOLS	SUPPORT MATERIALS	GENERAL	CUTTER COSTS			
<u>SECTION A</u>								
3. Fiberglass Lining	$81	$2	$651	$24	$21	$779	$352	$1131
9. Movable Support	111	3	53	31	21	219	268	487
13. Autom. Shotcrete	111	3	53	30	21	218	256	474
<u>SECTION B</u>								
3. Fiberglass Lining	66	2	367	22	29	486	290	776
9. Movable Support	52	2	27	28	29	138	241	379
10. Crawler Support	72	2	27	27	29	157	240	397
12. Bolt Gang Drill	84	2	52	24	29	191	245	436
13. Autom. Shotcrete	70	2	27	27	29	155	235	390
<u>SECTION D</u>								
3. Fiberglass Lining	78	2	304	26	46	456	288	744
9. Movable Support	63	2	13	30	46	154	247	401
10. Crawler Support	79	2	13	29	46	169	244	413
12. Bolt Gang Drill	64	2	13	28	46	153	233	386
13. Autom. Shotcrete	75	2	13	29	46	165	239	404

DONJAY TUNNEL

Figure 8.6

Support in Section A. Since the crawlers do not offer the same complete protection as the movable supports, it was felt that in bad ground the crawlers would have to be lowered and supports placed by conventional means closer to the face.

8.3.4 Comparison of Results

The following table shows a comparison of the most efficient support systems (based on total cost per foot of tunnel) as determined for the respective Donjay tunnel sections:

Tunnel Section	Excavation Method	Support System	Cost Per L.F.
A	D&B	Steel Ribs	$ 890
	TBM	Steel Ribs	633
	TBM	*Automatic Shotcrete (13)	474
B	D&B	Shotcrete	593
	TBM	Shotcrete	423
	TBM	Movable Support (9)	379
C	D&B	(none required)	388
	TBM	(none required)	607
D	D&B	Shotcrete	457
	TBM	Rock Bolts	397
	TBM	Bolt Gang Drill (12)	386

*Use of shotcrete questionable in this section even with automatic shotcrete setup.

A review of the table shows that in each of the tunnel sections requiring support (Sections A, B and D), the boring machine method of excavation offers a saving over comparable drill and blast tunnels. In each case, additional savings might be realized through the utilization of one of the envisioned new support concepts.

In Section A, shotcrete support was considered with respect to both the Automatic Shotcrete Applicator and the Movable Support Method. This was done for comparison purposes only. The type of rock described for this section would be a borderline case (RSR value less than 40) and the decision to use shotcrete would have to be made in the field. An estimate based on use of steel ribs erected behind the Movable Support gave a cost of $602 per linear foot. This still shows a potential savings over the use of steel ribs with conventional boring machine method because of the ease of erecting the support in the relatively unencumbered area of the Movable Support shield and reduced interference with the excavation process.

Evaluations for Section B, with an RSR value which is probably typical of most rock tunnels, showed shotcrete as the least expensive support system for both the drill and blast and machine-bored tunnels. Use of the Movable Support in this area reduced the cost per linear foot by 10% over a comparable system using a conventional boring machine.

Section D, requiring a nominal amount of support, showed the smallest variation of costs with respect to the different support systems. The costs of supporting this section with either rock bolts or shotcrete were very close. Less advantage was found in the use of automated support-placing equipment in this section because of the fact that the nominal amount of required support caused little interference with the tunneling process even when placed by hand.

Any use of shotcrete near the face interferes with the excavation process because of environmental and rebound problems associated with present techniques of applying shotcrete. It is possible that methods could be developed wherein the effect of these problems could be substantially reduced by isolating them to a confined area of application. Possibilities would include ventilation hoods encompassing the area; the use of water sprays and wipers to gather rebound, etc. All would probably require more area for operation than available with use of present excavation methods. The Movable Support concept has additional advantages in this respect. It provides continuous support of the rock for a distance sufficiently removed from the cutter head so that it may be possible to incorporate environmental control devices without undue interference with the actual excavation process. This feature of the concept (separating the area of support installation from the excavation area) offers the same advantages when considering other support systems. An example would be the development of a movable slip form for placing concrete lining behind the machine. This concept is discussed in "Innovations in Tunnel Support Systems" (Reference 10). That concept envisions continuous placing of high early-strength concrete lining behind a tunneling machine. If such a system should prove practical, it could be combined with the Movable Support concept to provide the optimum tunneling system. Theoretically, the excavating and support systems would progress simultaneously without interfering with each other. The material cost of the lining would be comparable to shotcrete and the increased production would result in savings of both labor and overhead. The Movable Support System, in addition, is inherently more efficient than a conventional boring machine because it eliminates the necessity of stopping the excavation to reset the side wall grippers. It provides continuous excavation of the face.

8.4 EFFECT OF TUNNEL SIZE ON COSTS

The preceding cost analyses were based on the 24 foot tunnel size specified for the Donjay Tunnel. In an effort to see what effect variations in tunnel size would have on the determined costs, preliminary evaluations were made for 14 and 30 foot tunnels excavated by the drill and blast method. Conventional support systems which could be used were identified from Support Requirement Charts (Figures 4.9 and 4.12)using respective RSR values previously determined for the four Donjay tunnel sections. Comparing results for the 30 foot sized tunnel showed that costs per lineal foot for the supported sections were 124% to 233% more than costs for unsupported Section C. Shotcrete support for tunnel Sections B and D was the most economical. Costs for the supported sections of the 14 foot tunnel were 120% to 192% more than the unsupported section. In this case, however, steel ribs would provide most economical support for Sections B and D. This indicates a possible limitation of tunnel size, wherein certain conventional support systems should or should not be considered with respect to determining the most economical support system. Additional studies would probably show a similar limitation with respect to use of a boring machine and/or new support concepts. Due to this, it is likely that an additional criterion (tunnel size) should be established and used in future consideration of new support concepts.

SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

The reliability of predicting sub-surface conditions could be materially increased by 1) better utilization of available geologic data pertaining to tunnel construction and 2) establishing standards as to the type, recordation and interpretation of geological information needed to predict and describe the anticipated rock structure. Due to limitations of present techniques for making geological investigations, it is likely that in the foreseeable future, predictions of subsurface conditions will depend to a large extent on personal judgments and empirical evaluations made by qualified individuals in the fields of engineering geology and tunnel construction.

Continued improvement of methods and procedures used with respect to conventional support systems (steel ribs, rock bolts and shotcrete) can be expected, but they have limited potentials in meeting the established goals of underground rapid excavation (Reference 17). New concepts of ground support systems must be developed before the goal can be achieved.

9.1.2 ROCK STRUCTURE RATING & RIB RATIO CONCEPTS

The empirical relationships pertaining to rock structure ratings, rib ratios, rock loads and support systems developed in this research effort will provide a useful tool to be used in determining support requirements for future tunnels. They are based on and reflect case histroy data, geologic information that could be provided with existing techniques, and the practical aspects and requirements of tunnel construction. The concepts could be revised or modified as need be to reflect findings of continued research or results obtained from actual construction.

9.1.3 GROUND SUPPORT SYSTEMS

Of the conventional support systems, shotcrete appears to have the greatest potential of improving the overall tunneling process. At the present time, new materials which could be used for ground support are either too expensive or have other restrictive charateristics which would probably exclude them from immediate consideration. A merchanical support system such as depicted as concept #9, "Movable Tunnel Support System" in this report appears to be the most likely candidate for achieving the goal of underground rapid excavation.

9.2 RECOMMENDATIONS

Based on findings and results of this research effort the following recommendations are made:

A) Additional research and study be made to develop and verify the RSR and RR concepts of predicting subsurface conditions and support requirements. Areas of concern would be:

1. Investigate additional case history projects to supplement and expand the amount of data used in the initial development of the concepts. Tunnels for both civil work and mining developments should be included. Projects to be studied should provide data pertaining to a variety of situations, such as tunnel size, support systems, method of excavation etc. The proposed methodology will be modified as required and finalized for practical usage to civil and/or mining applications.

2. Solicit advice and comments pertaining to the proposed methodology from individuals qualified in the fields of geology, construction

and mining. The support and/or concurrence of these industries is essential in the final evaluation and acceptance of the concepts.

3. The practical application and reliability of the proposed methodology should be evaluated by actual usage for several on-going tunnel projects. This will include initial determination of RSR values based on available pre-construction geology, the prediction of support requirements and subsequent correlation with actual conditions.

4. Findings and results as determined from the above, plus any additional information pertaining to geological investigations or ground supports which might be developed concurrently with the proposed research effort, will be incorporated in final report emphasing the use of the methods.

B) Additional time and effort should be spent to investigate the feasibility and potentialities of the five most promising concepts of new ground support systems as presented on Figure 7-20 and discussed in this report. Work would include preliminary engineering designs, evaluation of the physical adaptability to varied tunnel conditions, appraisals of environmental and safety considerations and a more detailed cost analysis. Results would indicate one of the following: 1) the concept should not be considered in future evaluations 2) potentiality of a concept is such as to warrant additional research 3) field application of a concept or developed prototype is justified.

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