SEMI-ANNUAL REPORT

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

prepared by

JACOBS ASSOCIATES
500 Sansome Street
San Francisco, California 94111

Sponsored by Advanced Research Projects Agency
ARPA Order No. 1579, Ammendment No. 2
Program Code 1F10

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Bureau of Mines under Contract No. HO210038

Effective Date of Contract: February 26, 1971
Contract Expiration Date: February 26, 1972

Amount of Contract: $60,981.00

Principal Investigator and Project Engineer
Mr. G. E. Wickham (415) 434-1822

September 26, 1971

Unclassified
Security Classification

3200.8 (Att 1 to Encl 1)
Mar 7, 66

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Jacobs Associates 500 Sansome Street San Francisco, Calif. 94111	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP NA

3. REPORT TITLE
RESEARCH IN GROUND SUPPORT AND ITS EVALUATION FOR COORDINATION WITH SYSTEM ANALYSIS IN RAPID EXCAVATION

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Semi-Annual Technical Report 26 Feb. '71 to 26 Aug. '71

5. AUTHOR(S) (First name, middle initial, last name)
George E. Wickham
Henry R. Tiedemann

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
26 Sep. '71	26	2

8a. CONTRACT OR GRANT NO. HO 210 038 b. PROJECT NO. ARPA Order No. 1579, Amendment 2 c. Program Code 1F10 d.	9a. ORIGINATOR'S REPORT NUMBER(S) none 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) none

10. DISTRIBUTION STATEMENT
Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
none	Advance Research Projects Agency Washington, D. C. 20301

13. ABSTRACT

A method of ground support requirement prediction for rock tunnels is described. This prediction is based on the investigation of the pre-bid geology of case studies of 32 tunnel projects.

A method of evaluating a rock mass structurally has been developed based on the interrelationship of 7 geologic factors. The relative evaluation of factors are based on the geologic data obtained from the case studies. The method, called Rock Structure Rating, is a numerical value that can vary on a scale of 0 to 100.

The actual ground support provided in the case studies has been evaluated by comparing the supports to a common datum. This method is called the Support Index and also varies numerically from 0 to 100.

The method for correlating these factors is discussed, both as a means for refining the values of the Rock Structure Rating and for future use in predicting support requirements based on pre-bid geological investigations.

DD FORM 1 NOV 65 1473

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ground Support						
Rock Tunnels						
Case Studies						
Geological Investigation						
Temporary Support						
Support Requirement Prediction						
Empirical Data						

TABLE OF CONTENTS

SECTION	ITEM	PAGE
1.0	SUMMARY	1
2.0	RESEARCH PROGRAM	3
3.0	ACCOMPLISHMENTS	7
3.1	ROCK STRUCTURE RATING	7
3.2	RIB RATIO AND SUPPORT INDEX	15
3.3	CORRELATION OF ROCK STRUCTURE RATING AND SUPPORT INDEX	18
3.4	DRAFT OF FINAL REPORT	21

LIST OF FIGURES

FIGURE NO.	SUBJECT	PAGE
1.	CASE HISTORY STUDY PROJECTS (1-20)	4
1a.	CASE HISTORY STUDY PROJECTS (21-32)	5
2.	DEVELOPMENT OF ROCK STRUCTURE RATING CONCEPT (#1 & 1A)	9
3.	DEVELOPMENT OF ROCK STRUCTURE RATING CONCEPT (#2 THRU #2D)	10
4.	ROCK STRUCTURE RATING - PARAMETER "A"	12
5.	ROCK STRUCTURE RATING - PARAMETER "B"	13
6.	ROCK STRUCTURE RATING - PARAMETER "C"	14
7.	TYPICAL RSR vs. RR CURVE	19
8.	TYPICAL RIB SUPPORT CURVES	19

LIST OF FIGURES

FIGURE NO.	SUBJECT	PAGE
1.	CASE HISTORY STUDY PROJECTS (1-20)	4
1a.	CASE HISTORY STUDY PROJECTS (21-32)	5
2.	DEVELOPMENT OF ROCK STRUCTURE RATING CONCEPT (#1 & 1A)	9
3.	DEVELOPMENT OF ROCK STRUCTURE RATING CONCEPT (#2 THRU #2D)	10
4.	ROCK STRUCTURE RATING - PARAMETER "A"	12
5.	ROCK STRUCTURE RATING - PARAMETER "B"	13
6.	ROCK STRUCTURE RATING - PARAMETER "C"	14
7.	TYPICAL RSR vs. RR CURVE	19
8.	TYPICAL RIB SUPPORT CURVES	19

1.0 SUMMARY

The research program for this contract concerns:

Phase I - Dealing with methods of geological prediction with respect to ground support requirements for tunnels.

Phase II - Dealing with new methods and materials for safe, efficient and economical support.

Work done to date is primarily Phase I.

The purpose of Phase I is to evaluate the various geological and construction factors, and their relationship to each other, in order to evolve a prediction method for temporary ground support.

The geological prediction is based on the investigation and analysis of thirty-two case history tunnel projects in the western United States. A method of evaluating a rock mass structurally has been developed based on the interrelationship of seven geological factors such as rock type, joint pattern, ground water flow, etc. The relative evaluation of factors are derived from the data obtained from the case history studies such as core analysis, area geology, geological plan and profile. This method has been called the Rock Structure Rating (RSR). Values of RSR vary on a scale of 0 to 100. As the ability of rock to support itself increases, the RSR value increases.

A method for evaluating the actual support provided in the case history tunnels has also been developed. This evaluation is called the Support Index. A tunnel requiring no support would have a Support

Index of 0. As the ability of rock to support itself decreases, the need for support increases and the Support Index increases in value on a scale of 0 to 100.

An empirical relation has been drawn between Rock Structure Rating and the Support Index to give a method of support prediction which, hopefully, will prove a useful tool in tunnel planning and construction. The nature of these evaluations permit future modification or verification as the case may be with improvements made in methods for measuring the various parameters used.

2.0 RESEARCH PROGRAM

The study team researched thirty-two tunnels in the western United States to form the basis for the analysis and evaluation of the methods of prediction for tunnel support, which will be described in Chapter 3.

These thirty-two tunnels were divided into one hundred and twenty-seven separate geologic sections. The case studies include examples of tunnels in the three major basic rock type (igneous, sedimentary and metamorphic) and several subdivisions of each. They include tunnels driven for seven different owners and range in size from 8' diameter to 34' diameter and include tunnels driven by drill and blast method and by tunnel boring machines. The list of these tunneled projects are given in Figure 1 and 1a.

For each of these sections the study team investigated the information supplied to the bidders in the form of pre-construction geology. This information was analysed with respect to the following:

(a) Surface geology
(b) Historical geology
(c) Site inspection
(d) Topography maps
(e) Geologic profile
(f) Borings
(g) Seismic investigation
(h) Other

These were reviewed with respect to the geologic factors detailed in Chapter 3. In addition, all available information was gathered pertaining to the actual temporary support used in each section of the

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 1

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.	17x15 HS	240	10,900	4	D&B
32	Caribou No. 2	Calif.	17x16 HS	240	8,700	4	D&B

Figure 1a

case history tunnels.

It was found in many of the case history records that pre-construction geology was insufficient to evaluate factors which the study team felt were important. In some instances as-built geology of the tunnel bore had been prepared and where this information was available, it was used to augment the pre-construction geology.

It was also found in some cases that records were not available in sufficient detail to evaluate the actual support. This was particularly true in tunnels with rock bolt support which usually gave only a total number of pounds of support without giving the location or spacing of this support. In like manner some of the tunnels using steel ribs did not give the size and location of the support. This limited the number of sections which could be analysed effectively and was in part responsible for including many more case studies than was originally anticipated.

3.0 ACCOMPLISHMENTS

3.1 RSR (Rock Structure Rating) Method of Evaluating Rock Structure with Respect to Support Requirements

The study team decided to use a numerical evaluation to describe the rock structure in the case studies under investigation. A list was made of factors which affect the ability of the rock to support its own weight after the tunnel section is excavated. The varying degrees of importance placed on these factors were made based on the accumulated experience of the study team, and engineers and geologists who were consulted in connection with the study being made.

Two basically different approaches were used in formulating the concept of the Rock Structure Rating. The first consisted of a series of relationships between the rock properties of the sample tunnel section being used. Comparative values were assigned to these relationships giving a maximum total of 100. The Rock Structure Rating in this case consisted of an arithmetic addition of all values. The second approach attempted to establish interrelationships between various parameters. This concept acknowledged the fact, for instance, that the effect of ground water flow is also related to joint pattern, joint orientation, etc. Although it was realized that a numerical evaluation of these interrelationships would be more difficult to derive, the study team decided on this method of approach because they felt it was basically more realistic.

The initial approach considered nine basic factors which tend to describe the quality of the rock structures; they are -

A. Core analysis
B. Seismic Velocity Ratio (Ref. 1)
C. Joint orientation
D. Rock mass foldings and/or discontinuities
E. Major faults
F. Joint seal
G. Cover over tunnel
H. Water flow
I. Rock Modulus Ratio (Ref. 1)

After assigning weighted value to these factors they were used in analysing the one hundred and twenty-seven geologic sections of the thirty-two case studies.

During the course of this analysis the study team had the opportunity to note the varying effects on the overall RSR values contributed by the different factors or parameters. The proposed method of determining RSR value evolved through several variations and its development is shown graphically in Figures 2 and 3. The basic data which was used to establish a relative value for these parameters between zero and the maximum value as shown in Figures 2 and 3 was the pre-construction geology information defined in Section 2 and augmented by as-built geologic information.

The case history studies were used for determining Rock Structure Rating values during each stage of its development. The final development of the Rock Structure Rating was RSR #2D. Figure 3 shows the interrelationship of parameters for this determination. Parameter "A" shows the

DEVELOPMENT OF ROCK STRUCTURE RATING CONCEPT

RT - Rock Type

CA - Core Analysis

SV - Seismic Velocity Ratio

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

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
+ RT ↔ RM	15
RSR #1A	100

Figure 2

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_s ↔ CA	("D")	(Var.)
=		
RSR		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		100

RSR #2B & 2C*

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

RSR #2D

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

* For differences not shown - see text.

Figure 3

relationship between the basic rock type and rock mass folding and discontinuities. Parameter "B" is the relationship between the joint spacing and the joint orientation, both dip and strike. Parameter "C" shows the relationship between water flow and joint seal and is also effected by the sum of Parameters "A" and "B". The charts giving the values used for these parameters are shown in Figures 4, 5 and 6.

Details of Revisions to Rock Structure Rating:

In developing the Rock Structure Rating, the study team envisioned this concept as a tool which would be refined to the extent possible within the limits of the information available, and reflecting the existing state-of-the art of geological surveying and tunnel support. Keeping this in mind, the first Rock Structure Rating encompassed as many of the geological factors as the team considered useful. As the values for these relationships were computed for the various tunnel sections, and as more case studies were added to the list, the teams' consideration of these factors were altered as follows: A) In the 32 case studies investigated, the team found little factual information on some of the proposed factors such as Seismic Velocity Ratio. As a result for each section, average values had been assigned to these factors, so it was decided it would be more realistic to delete them at this time. B) It was recognized that the immediate area of a tunnel affected by major faults consists of rock crushed to varying degrees, which often more closely resembles a soft ground condition than the unaffected rock of the same geologic formation on either side of the fault.

It was decided, therefore, to delete this factor and treat such areas independently. C) Most of the tunnels investigated were reasonably close to the ground surface as compared to some mining tunnels. Within this range the depth of cover does not materially affect the load imposed on the tunnel so this factor was also deleted. The remaining parameters were adjusted to give a maximum value of 100, resulting in Rock Structure Rating, RSR #1A.

The factors remaining were basically the same that were used in Rock Structure Rating #2 when it was decided to change to this basic form of inter-relationship of parameters. Each of the Rock Structure Ratings used, were computed for all of the sections of the case studies involved and were analyzed for consistency of results by comparison with actual tunnel supports used in these tunnels. A more complete description of this correlation is given in Section 3.3.

In revising Rock Structure Rating No. 2 through steps 2A, 2B and 2C, the basic parameters remained the same. The values of these inter-relationships were altered to give more consistent results. Parameter "D", for instance, consisted of a family of curves of core analysis represented by the Rock Quality Designation (RQD) of Don Deere (Reference 1). These curves were plotted on a graph whose horizontal axis was the sum of Parameters "A" + "B" + "C" and whose vertical axis was the Rock Structure Rating value 0 to 100. This graph was altered at each step of the development of this Rock Structure Rating because of the difficulty of correlation with all of the other parameters. This graph was deleted in Rock Structure Rating #2D. This does not in any way reflect on the usefulness of this important tool.

It can be noted that several of the factors disclosed by a core analysis are also represented in the other three more general parameters. It is, therefore, recommended that the information gathered from core analysis be used in the evaluation of these other factors.

In addition to redefining the importance of various factors in computing Rock Structure Rating, the team also simplified the total number of values given in each chart. As an example, the earlier Rock Structure Ratings had a breakdown of 15 types of rock which were compared in Parameter "A" to the geologic structure. It was decided that there was not sufficient detailed information available to justify such a fine breakdown and this factor was reduced in Rock Structure Rating 2D to the 3 basic rock types shown in Figure 4.

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 4

ROCK STRUCTURE RATING PARAMETER "B" JOINT PATTERN DIRECTION OF DRIVE								
AVERAGE JOINT SPACING FEET	STRIKE ⊥ TO AXIS					‖ TO AXIS		
	DIRECTION OF DRIVE					DIRECTION OF DRIVE		
	BOTH	WITH DIP		AGAINST DIP		BOTH		
	SLOPE OF JOINTS (DIP)					SLOPE OF JOINTS		
	FLAT	DIPPING	VERTICAL	DIPPING	VERTICAL	FLAT	DIPPING	VERTICAL
<.5	14	17	20	16	18	14	15	12
.5-1.0	24	26	30	20	24	24	24	20
1.0-2.0	32	34	38	27	30	32	30	25
2.0-4.0	40	42	44	36	39	40	37	30
>4.0	45	48	50	42	45	45	42	36

Flat $0^\circ - 20^\circ$
Dipping $20^\circ - 50^\circ$
Vertical $50^\circ - 90^\circ$

Figure 5

ROCK STRUCTURE RATING
PARAMETER "C"
GROUND WATER
JOINT CONDITION

ANTICIPATED WATER INFLOW	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	17	12	7	19	15	10
MODERATE	12	9	6	18	12	8
HEAVY	8	6	5	14	10	6

1 - Tight or Cemented
2 - Slightly Weathered
3 - Severely Weathered or Open

Figure 6

3.2 RR (Rib Ratio or Support Index)

In analysing the results of defining the rock for a particular tunnel section by use of a Rock Structure Rating, it was necessary to compare these results with the actual tunnel supports used. The ideal comparison would be one of an empirical mathematical relationship, providing a numerical evaluation could be made of the actual tunnel support.

It must be recognized first that there may be a difference between the support required and the actual support used. In some cases this difference may be small, in other cases it may be considerable. The only thing that is certain is that on the average, the actual support used is conservative, as evidenced by the fact that the tunnel sections are not collapsed. Any numerical values therefore based on this method of approach will be empirical and conservative. It should be possible in the future by more use of advanced methods of measuring stresses in support members, to not only check the accuracy of predictions of rock loads, but also to distinguish between required support and actual support. In the meantime, until such refinements are made, it is preferable to use a margin of safety based on known results. Even within a given area of apparently uniform rock loads, variations exist which impose considerably different loads even on adjacent and nearby supports.

To place a numerical value on tunnel supports, the study team developed a concept which was designated as the Rib Ratio. The majority of the tunnels studied had steel rib supports. It was decided to use as a common datum the support that would be required under the worst static soft ground conditions based on an empirical formula by Terzaghi (Ref. 2) for a cohesionless sand under water. This formula was used to compute the load on a tunnel of the same size as each case study tunnel. Using tables provided in "Rock Tunneling With Steel Supports" by Proctor and White, the spacing of ribs of the same size actually used in any given tunnel section was computed for the theoretical "worst condition datum" tunnel. The Rib Ratio is the numerical value of the theoretical spacing of ribs in feet divided by the actual spacing and multiplied by 100. For instance, if the theoretical spacing of 6H25 ribs for the datum tunnel is two feet and the actual spacing of 6H25 ribs is five feet, the Rib Ratio would be 2 divided by 5 multiplied by 100, or a value of 40. Thus a tunnel in "poor" ground requiring much support would have a high value; a tunnel in relatively "good" rock requiring little support, would have a low Rib Ratio and a tunnel requiring no support would have a Rib Ratio of zero. These numbers are not absolute quantities, but rather relative numbers based on a common datum.

Values of these Rib Ratios are computed for each of the case study sections where sufficient detail of actual supports was given to enable such calculations to be made. In sections where timber ribs were used, equivalent steel rib sizes were calculated using combined bending and axial stresses to compare these sections on the same basis. It is proposed to expand this evaluation of support to include types of tunnel support other than steel ribs. This more general relationship would still use the same numerical values but will be called the Support Index. The relationship between certain supports as compared to steel supports is not as simple as that between timber supports and steel supports. The relationship of shotcrete lining must take into account that it is only capable of taking load in compression. The problem becomes even more complex when considering the theory of rock bolts, and it is possible that only a very casual and approximate relationship can be given in this instance.

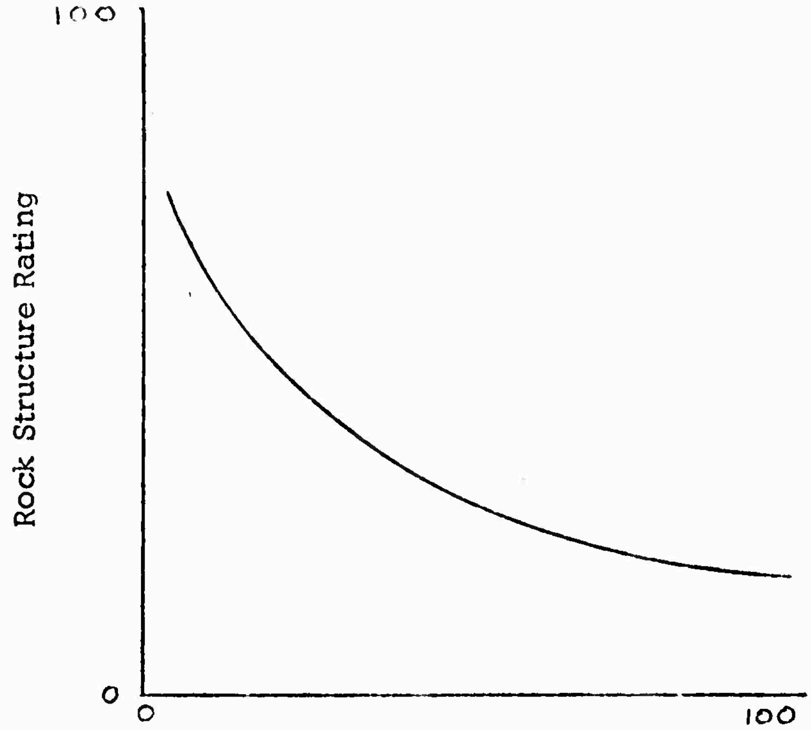
In the development of the Rock Structure Rating and Support Index concept and its use in assigning values to actual tunnel supports, no attempt has been made by the study team to include conditions of swelling ground or squeezing rock. These conditions, while quite serious in tunnel construction, are even more difficult to define than the more normal loads imposed by static rock. Hopefully these conditions can be treated more fully in the future if methods of measurements can be developed to determine in advance possible loads imposed by these conditions.

3.3 CORRELATION OF ROCK STRUCTURE RATING AND SUPPORT INDEX

One aid in developing the values assigned to the parameters of Rock Structure Ratings consisted of plotting points in a graph with a vertical axis for the Rock Structure Ratings and a horizontal axis showing Rib Ratio values. These values were shown to have an inverse proportion relationship to one another. Figure 7 shows a typical graph plotted from the average of these points. After each set of values for the various Rock Structure Ratings were established, a new graph was plotted and a series of "enveloped" consisting of lines parallel to the average graph line were plotted and the number of points falling within these envelopes were counted. By noting the number of points falling close to the average and those at some distance from the average, it was possible to see if certain values of the parameters appeared to have undue effect on the values achieved.

In addition to using the graph to refine the numerical values of the parameters, the graphs were also used to study the effect of other variables. As one example, the points were color coded based on the size of the tunnel section that the point represented. It was found on this particular graph that each of the sizes had approximately the same number of points above and below the average curve. This confirmed the fact that size, as a construction factor did not affect the value of the Rock Structure Rating.

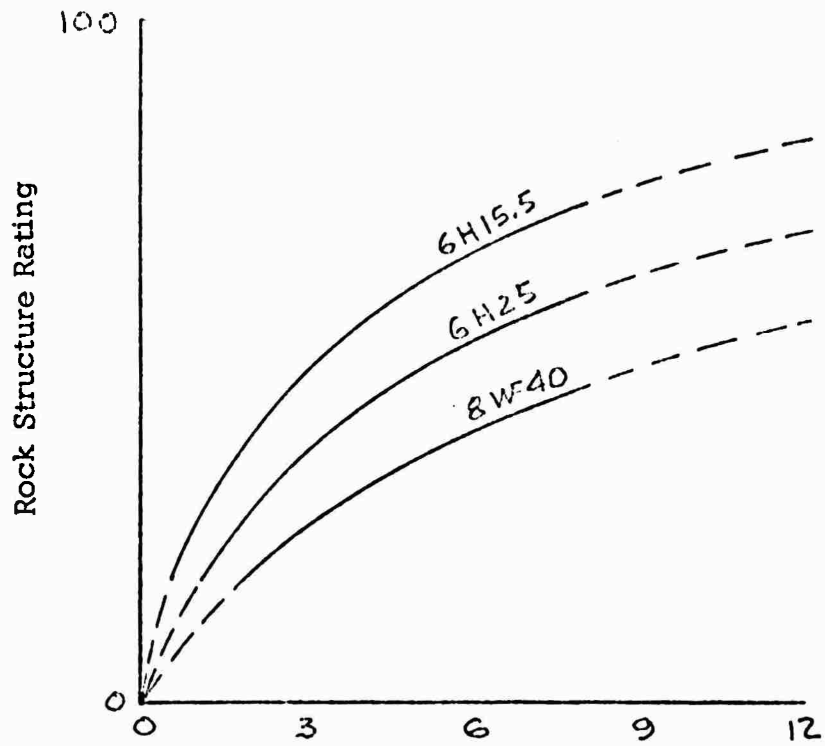
After the development and refinements of a curve representing the



Rib Ratio

TYPICAL RSR VS. RR CURVE

Figure 7



Spacing for Steel Ribs
For 18' Tunnel

TYPICAL RIB SUPPORT CURVES

Figure 8

relationship between the Rock Structure Rating and the Support Index has been finalized, it will then be possible to develop a series of curves that can be used to predict required support for any given size tunnel and a calculated Rock Structure Rating. This family of curves could show size and spacing of various type supports for a particular size of tunnel. This would give options on comparable supports and can be developed from the relationship of Rock Structure Rating and Support Index as defined by the empirical formula of the average curve for these values. A typical example for steel ribs is shown in Figure 8.

3.4 WORK ON FINAL REPORT

Based on the analysis of the case studies in question, together with the development of the Rock Structure Rating Concept and Support Index, a draft has been composed of the first four sections of the final report.

These are as follows:

1. FACTORS EFFECTING GROUND SUPPORT

This section will detail more fully the factors investigated by their research study team.

2. ROCK STRUCTURE RATING

This section will explain the development of this concept and the comparison with its historical predecessors.

3. CASE HISTORY STUDIES

This section will more fully detail how each of the case histories presented pre-construction geology to prospective bidders and how it affected the ability to arrive at meaningful values for the various factors investigated.

4. ROCK STRUCTURE RATING VERSES SUPPORT INDEX

This section will show in detail how these two concepts are related empirically and how they can be used to predict support requirements for future tunneling projects. In accordance with the contract requirements the study team held a two day briefing conference with the Contracting Officer Eugene Skinner on August 5 and 6, 1971. The work to date was reviewed and the work remaining under this contract was discussed. It was decided that the study team would continue with their investigations along the same basic lines as outlined in the contract. It is anticipated from these investigations that the following remaining sections will be added to the final report.

5. NEW CONCEPTS OF GEOLOGIC INVESTIGATIONS

6. COMPARISON OF CONVENTIONAL AND NEW SUPPORT CONCEPTS

7. FEASIBILITY OF SUPPORT SYSTEMS

8. ECONOMIC COMPARISON

9. CONCLUSIONS AND RECOMMENDATIONS

REFERENCES:

REF. 1 - Deere, D. V. (1968) "Geologic Considerations" Chapter 1 in "Rock Mechanics in Engineering Practice", K. G. Stagg and O. C. Zienkiewitz, ed., New York, John Wiley and Sons

REF. 2 - Terzaghi, K. (1946) writing in "Rock Tunneling With Steel Supports" , by R. V. Proctor and T. L. White. The Commercial Shearing and Stamping Co., Youngstown, Ohio