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ROCK QUALITY DESIGNATION (ROD) AFTER
TWENTY YEARS

Don U. Deere, Consultant
Gainesville, FL

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19. ABSTRACT

and construction parameters. For obtaining the RQD, the best drilling techniques and prompt core logging in the field by a qualified engineering geologist or geotechnical engineer should be used. The RQD is not a design parameter that stands alone, but must be used together with an appreciation of the detailed geology and the geotechnical aspects.

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PREFACE

This report was written by Don U. Deere, an independent international consultant on dams, tunnels, and underground powerplants, from Gainesville, Florida, and Don W. Deere, geotechnical engineer and principal of Rocky Mountain Consultants, Inc. of Longmont, Colorado.

The work was done under the sponsorship of the US Army Corps of Engineers, Waterways Experiment Station (WES), Geotechnical Laboratory (GL), Vicksburg, Mississippi, under Contract No. DACW39 86M 4273, under date 86 SEP 02 and Amendment P00001 dated 86 OCT 22.

The project was conducted under the general supervision of Dr. Don C. Banks, Chief, Engineering Geology and Rock Mechanics Division; and Dr. W.F. Marcuson III, Chief, GL, WES. Col. Dwayne G., Lee, EN, was the Commander and Director of WES. Dr. Robert W. Whalin was the Technical Director.



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TABLE OF CONTENTS

| | <u>Page</u> |
|---|-------------|
| PREFACE | i |
| PART I: INTRODUCTION. | 1 |
| Background | 1 |
| Purpose. | 1 |
| Approach | 2 |
| PART II: DEVELOPMENT OF THE RQD CONCEPT | 3 |
| The 1963 RQD Precursor | 3 |
| The 1964-65 Developmental Period | 6 |
| The 1966-69 Testing Period | 8 |
| PART III: RECOMMENDED TECHNIQUES OF RQD LOGGING | 11 |
| Core Diameter. | 11 |
| Length Measurement of Core Pieces. | 13 |
| Assessment of Soundness. | 16 |
| Length of Coring Run | 19 |
| PART IV: RQD CORRELATIONS | 21 |
| Tunnel Support/Reinforcement Design. | 21 |
| Prediction of In-Situ Modulus. | 26 |
| Foundation Settlement Correlations | 30 |
| Fracture Frequency | 31 |
| Linear fracture frequency | 32 |
| Volumetric fracture frequency | 32 |
| PART V: UTILIZATION OF THE RQD IN LATER ROCK CLASSIFICATION SYSTEMS. | 35 |
| Bieniawski's Rock Mass Rating System (Geomechanics Classification). | 35 |
| Bartons Q System (Norwegian Geotechnical Institute) | 37 |
| PART VI: PERTINENT QUESTIONS OF RQD IN PRACTICE | 40 |
| Mechanics of Determining RQD (1) | 40 |
| Core diameter (1A). | 40 |
| Length measurement of core pieces (1B). | 42 |
| Length of coring run and of RQD interval (1C) | 44 |

| | |
|--|----|
| Special RQD Logging Problems (2) | 46 |
| Drilling equipment and techniques (2A). | 46 |
| Prompt logging of core (2B) | 47 |
| Applicability to various rock types (2C). | 47 |
| General problems | 47 |
| Shales, claystones, interbedded sedimentary rocks. | 48 |
| Limestone with solution cavities | 49 |
| Volcanics and metamorphics | 50 |
| Orientation Effects (2D). | 51 |
| Desirability of Additional Geological Observations (3) | 52 |
| Joint conditions (3A) | 52 |
| Local geology, weathering, fracture frequency (3B). | 52 |
| Applications to Engineering and Construction (4) | 53 |
| General (4A). | 53 |
| Excavation, dredging, underwater blasting (4B) | 54 |
| Foundations, in-situ modulus (4C) | 55 |
| Tunnels (4D). | 55 |
| Erosion resistance, roughness coefficient (4E). | 56 |
| General Usefulness of RQD (5). | 57 |
| Favorable experience (5A) | 57 |
| Shortcomings, limitations (5B). | 59 |
| PART VII: CONCLUSION. | 61 |
| REFERENCES. | 64 |
| APPENDIX A: COMMENTS AND QUESTIONS ON THE RQD FROM THE US ARMY CORPS OF ENGINEERS | |

| <u>LIST OF TABLES</u> | <u>Page</u> |
|--|-------------|
| TABLE 1 - ROCK QUALITY CLASSIFICATION | 22 |
| TABLE 2 - GUIDELINES FOR SELECTION OF PRIMARY SUPPORT FOR 20-FT TO 40-FT TUNNELS IN ROCK | 23 |
| TABLE 3 - CORRELATIONS OF MODULUS RATIO WITH RQD AND VELOCITY INDEX. | 28 |
| TABLE 4 - ALLOWABLE CONTACT PRESSURE q_c ON JOINTED ROCK. | 30 |

LIST OF FIGURES

| | <u>Page</u> |
|--|-------------|
| FIGURE 1 - RQD LOGGING. | 12 |
| FIGURE 2 - LENGTH MEASUREMENT OF CORE FOR RQD | 14 |
| FIGURE 3 - ROCK QUALITY AND SUPPORT REQUIREMENTS FOR TUNNELS OF VARYING DIMENSIONS. | 24 |
| FIGURE 4 - RQD VERSUS MODULUS RATIO | 27 |
| FIGURE 5 - RQD VERSUS FRACTURE FREQUENCY | 33 |

PART I: INTRODUCTION

Background

The Rock Quality Designation (RQD) was developed as an index of rock quality and was first used on a design and construction job in 1964, and on two additional jobs in 1964-1965. Research continued at the University of Illinois over the next several years under the sponsorship of the US Air Force and US Department of Transportation. The RQD was also used during this period on several consulting jobs involving tunnels and shafts.

The publication that first brought the RQD to the attention of the engineering and geology profession was the 1967 paper by Deere and his colleagues at the University of Illinois (Deere et al., 1967). The following year a chapter by Deere (1968) in the rock mechanics book by Stagg and Zienkiewicz (1968) introduced the concept to an international audience and led to its acceptance and growing use in many countries.

The later rock classification systems for engineering purposes developed by Bieniawski (1973) and by Barton et al., (1974) both include the RQD as an input parameter. Because these systems are increasingly being used, there is interest in the RQD logging techniques and applications.

Purpose

The purpose of the study was to evaluate twenty years of experience by the senior author with the RQD in which many rock types at a great number of engineering projects in many countries have made their contribution. Conversations and correspondence

with many field engineering geologists and geotechnical engineers have raised questions regarding the origin of the RQD, the different techniques of measuring and logging, the optimal core diameter and length of coring runs, and problems with core breakage during drilling and handling, as well as questions regarding its use in engineering design. The junior author brings his own experience and questions after having logged a variety of cores, managed geotechnical investigations, and utilized RQD design correlations on many sites in the United States and overseas over the past decade and a half.

Approach

The approach to the study was to organize the background material relating to the early development in Part II, to discuss and state the recommended RQD logging techniques in Part III, to present and evaluate RQD correlations in Part IV, and to discuss briefly in Part V the Bieniawski (1973) and Barton rock mass classification systems (Barton et al., 1974).

Part VI is concerned with questions of RQD in practice as posed by engineers and geologists of the US Army Corps of Engineers and by some of their geotechnical consultants. Conclusions are given in Part VII.

During the studies for this report, a shorter, preliminary version entitled, "The Rock Quality Designation (RQD) Index in Practice" was presented to the ASTM Symposium on Rock Classification Systems for Engineering Purposes" (Deere and Deere, 1988).

PART II: DEVELOPMENT OF THE RQD CONCEPT

The 1963 RQD Precursor

During the development of rock mechanics in the United States in the early 1960's, there was considerable interplay with the European engineers and geologists and particularly with the Salzburg School of Rock Mechanics in Austria, under the leadership of Leopold Muller. Many of the senior author's concepts were formulated from papers given and discussions held at several of the annual Proceedings, Salzburg Colloquia on Rock Mechanics. It was therefore with appreciation and satisfaction that he accepted the invitation to author a paper for the first volume of the new journal Felsmechanik und Ingenieurgeologie (Rock Mechanics and Engineering Geology) edited by Dr. Muller, an outgrowth of the journal Geologie und Bauwesen.

That paper was entitled, "Technical Description of Rock Cores for Engineering Purposes" (Deere, 1963). The ideas presented were based not only on the background of the Salzburg connection but also on the author's consulting practice in foundation engineering, engineering geology and mining engineering, and his program of graduate courses and research in rock mechanics being developed at the University of Illinois.

The RQD concept was not presented in the 1963 paper as it had not as yet been conceived in its entirety. However, the important geological features that influence rock engineering were emphasized, as was the information that could be obtained from study of rock cores. A number of the passages are quoted in the following paragraphs because (1) the published article is not

readily available, and (2) the ideas expressed formed a direct precursor to the development of the RQD the following year:

...Technical Description of Rock Cores. A careful study of rock cores from boreholes can yield valuable information concerning the nature of the in-situ rock mass. The significant geological features are those that influence the homogeneity of the rock mass and include the occurrence of (1) surfaces of discontinuity and (2) zones with materials of different hardnesses. Detailed observations of these features should be made and recorded on the boring logs. Complete and accurate descriptions are necessary for rock mechanics studies and for allowing the contractor to appraise the nature of the in-situ rock and to plan and carry out his construction procedure.

...Emphasis is given in this paper to those geological features which can be observed in rock cores, and which appear to the author to be significant in rock engineering. The significant features include those which have a direct bearing, almost overwhelmingly so, on the homogeneity of the rock mass with respect to (1) variations in hardness, and (2) physical discontinuities. The pertinent features when observed in the rock cores should be carefully described and recorded in the boring logs in such a manner so as to present a factual record containing a minimum of interpretation. From such boring logs interpretations may be made concerning the character of the rock mass.

...Physical discontinuities are present in all rock masses in the form of planes or surfaces of separation. Geologically, these discontinuities are recognized as joints, faults, bedding planes, or rock cleavage planes. Terzaghi has referred to such features as mechanical defects of rock. The permeability, shear strength, and deformability of a rock mass are all influenced by the number and kind of discontinuities existing in the mass. Engineering projects involving dam foundations, tunnels, underground chambers, and cut slopes may be adversely affected unless the discontinuities are evaluated and their influence taken into account during design and construction.

...A critical examination of rock cores can yield valuable data concerning the occurrence and nature of the mechanical defects in the rock mass from which the cores were obtained. The various types of observations

that can be made are discussed in the following paragraphs.

The article goes on to describe types of discontinuities (joints, bedding planes, cleavage planes, faults) and proposed terminology for describing joint spacing and the thickness of bedding units [e.g., moderately close joint spacing, 1 ft. - 3 ft. (30 cm - 1 m); and medium thick bed, also 1 ft. - 3 ft. (30 cm - 1 m)]. Probably of more significance in the development of the RQD was the following statement:

...In describing the rock cores it is advised that the length of the pieces of the core obtained in each coring run be measured and recorded (e.g., 1 piece of 20 cm, 4 pieces of 10-15 cm, and 25 pieces of 2-10 cm, etc.) These lengths are a direct response to the spacing of the joints and fractures and the thickness of the bedding. Unfortunately, they are also influenced by the drilling method and technique. Still, in the author's opinion, they are of sufficient import to warrant describing.

Emphasis was then given to the importance of the surface characteristic of the discontinuities and of filling materials:

...The behavior in an engineering project of a rock mass transversed by discontinuities is probably more influenced by the character of the joint surfaces and the type of filling material along the discontinuities than by the mere presence of the discontinuities. Therefore in describing rock cores particular attention should be given to those observations regarding the tightness and irregularity of the surfaces as well as to the kind of filling material between or along adjacent surfaces.

It was noted that the degree of tightness could be described as tight or open; the degree of planeness by plane, curved, or irregular; the degree of smoothness by slick, smooth, or rough;

and the infilling or altered materials as to thickness, type, and hardness. The paper closes with discussion of lithology and hardness, noting in particular the severe design and construction problems that may arise from differences in hardness:

...Illustrative conditions are those encountered with interbedded shales and limestones; with solution-widened and clay-filled joints, fault zones, and bedding planes in limestone terrain; with altered and weakened rocks along faults and shear zones in any type of rock; and with the varied products of weathering in the weathered rock zone where joint-block remnants (often spheroidal) of fairly hard rock are surrounded by soil-like material resulting from advanced weathering and decomposition of the rock adjacent to the joint. Many of these conditions will become apparent during the geological mapping; however, the extent of the condition can often only be determined by means of boreholes. Consequently, the rock cores should be studied with utmost consideration being given to the detection of significant variations in hardness.

The 1964-65 Developmental Period

While consulting on the siting and design of a shaft, tunnel, and chamber in granite in 1964 at the Nevada Test Site for underground nuclear testing, it became clear to the senior author that the site had poorer quality granite than an alternate site. However, the detailed core logs prepared by well-qualified geologists did not readily reveal the difference, perhaps because of the emphasis on lithology, mineralogy, and alteration and the lengthy descriptions of the jointing.

The attributes of the core that visually indicated poor rock conditions were the great number of small core pieces bounded by weathered joints and sheared surfaces, the presence of numerous

rock fragments, and occasional core pieces of visibly altered granite. By contrast, the rock cores from the alternate site were of hard, nearly unweathered granite in core pieces of much greater length. Even a casual examination showed that the chemical alteration and the amount of jointing and shearing was much less at the alternate site.

In an effort to illustrate this lesser alteration and jointing at the alternate site as compared with the original site and to be able to portray the rock quality graphically, it was decided to use a "modified core recovery" procedure in which only sound pieces of granite of 4 in. (100 mm) in length or longer were counted. Thus, the quality of rock core was downgraded by not counting the rock fragments, the pieces of core less than the requisite length, pieces of altered granite, and unrecovered core. The 4 in. (100 mm) requisite length was chosen after considerable deliberation as being a reasonably lower limit for a fair quality rock mass containing three or four joint sets of close to moderate spacing.

The following day an oral and graphical presentation was made to the designers and managers. Large-scale boring logs were presented for each site with the "modified core recovery" plotted with depth. Where this value was greater than 95 percent (later changed to 90 percent) the interval was colored blue and was designated as excellent quality rock; the 75-95 percent interval colored green and designated good quality; the 50-75 percent interval colored orange and designated fair quality; the 25-50 percent and the 0-25 percent intervals colored red and designated, respectively, poor and very poor. The name Rock

Quality Designation (RQD) was applied to the overall procedure. The visual display and associated descriptions were readily assimilated by the audience and a rapid decision was made to select the alternate site with the indicated good rock conditions. Later construction of the facility corroborated the generally good rock conditions at the selected site.

In the past, the percentage of core recovery had often been used as an indicator of rock quality. However, with better drilling techniques and with advancements in coring bits and barrels, the percentage of core recovery was often nearly 100 percent even in closely jointed zones and fault zones. Therefore, the "modified core recovery" and RQD concept offered the possibility of a more valid technique of indexing the rock quality for engineering purposes that took into account the effects of fracturing, shearing, and alteration.

The concept was next tested on consulting projects in 1964-65 on highway tunnels on the Pigeon River for the North Carolina Highway Department (quartzite, gneiss, and schist) and for the foundation studies for the World Trade Center in New York on massive schist and schistose gneiss. Meaningful results were obtained on the delineation of rock zones of differing qualities that resulted in substantial differences in design and construction (personal files).

The 1966-69 Testing Period

The early success of the RQD on consulting projects indicated that the concept was worthy of additional study and research by the rock mechanics and engineering geology groups at

the University of Illinois. Sponsorship was obtained from the US Air Force on the development of an engineering classification of in-situ rock. Deere et al. (1969b) presented the complete report of that investigation; some of the more pertinent results were presented earlier (Deere et al., 1967; Deere, 1968; Hendron, 1968).

The 1967 reference by Deere and his colleagues at the University of Illinois (Deere et al., 1967) was the first time that the RQD concept had been presented in published form to the engineering and geology profession¹. The published work that introduced the RQD to a wide international audience, and that no doubt was responsible for its rapid acceptance in many countries, was the 1968 book by Stagg and Zienkiewicz "Rock Mechanics in Engineering Practice" that contained one chapter by Deere (1968) and one by Hendron (1968) in which the RQD concept and applications were discussed.

In the US Air Force studies, a number of sites were visited and RQD measurements were made of existing rock core or of cores from borings drilled specifically for that research project. Different requisite lengths for core pieces to be counted for the RQD were tried, as well as a weighting procedure. The weighting procedure involved counting all pieces but giving

¹ An incorrect reference was cited inadvertently in this paper accrediting Deere with the introduction of the RQD in his 1964 paper "Technical Descriptions of Rock Cores for Engineering Purposes." Actually, two mistakes were involved. First, the date of the cited paper should have been 1963, not 1964; and second, the RQD concept was not given in that paper as it was not developed until 1964 and was only available in file copies of consulting reports.

less weight to the smaller pieces by using the square of the lengths for all pieces less than 1 ft. (300 mm). While this eliminated the discontinuity at 4 in. (100 mm), it complicated the procedure and the results did not appear appreciably better. Therefore, the original 4 in. (100 mm) requisite length was retained.

The Air Force study also included correlation with other rock quality indices, with some in-situ rock properties, and with tunnel supports and advance rates. A number of these correlations are discussed in Part IV.

The US Department of Transportation in the late 1960's also sponsored research at the University of Illinois on tunnel support systems that included the RQD as a quality index for predicting type and amount of required support (Deere et al., 1969a; Peck et al., 1969; and Deere et al., 1970).

PART III: RECOMMENDED TECHNIQUES OF RQD LOGGING

In this section several of the techniques for the RQD logging of cores are reviewed. The procedures as given in the original references (Deere et al., 1967; Deere, 1968) are discussed together with some of the problems encountered and modifications proposed by others or by the authors.

The RQD is a modified core recovery percentage in which all the pieces of sound core over 4 in. long (100 mm) are summed and divided by the length of the core run. The correct procedure for measuring RQD is illustrated in Figure 1. The RQD is an index of rock quality in that problematic rock that is highly weathered, soft, fractured, sheared, and jointed is counted against the rock mass. Thus, it is simply a measurement of the percentage of "good" rock recovered from an interval of a borehole.

Core Diameter

The RQD was originally developed using NX-size core (2.155 in. or 54.7 mm diameter¹). Deere (1968) specified that a minimum NX-size core obtained with double-tube core barrels should be used. This minimum size was specified to discourage a common practice of the time of utilizing excessively small core sizes or single barrel coring in geotechnical investigations; both of which can result in poor recovery and excess core breakage.

¹ Core diameters referred to in this report are nominal dimensions. Actual diameters may vary slightly depending upon core barrel manufacturer.

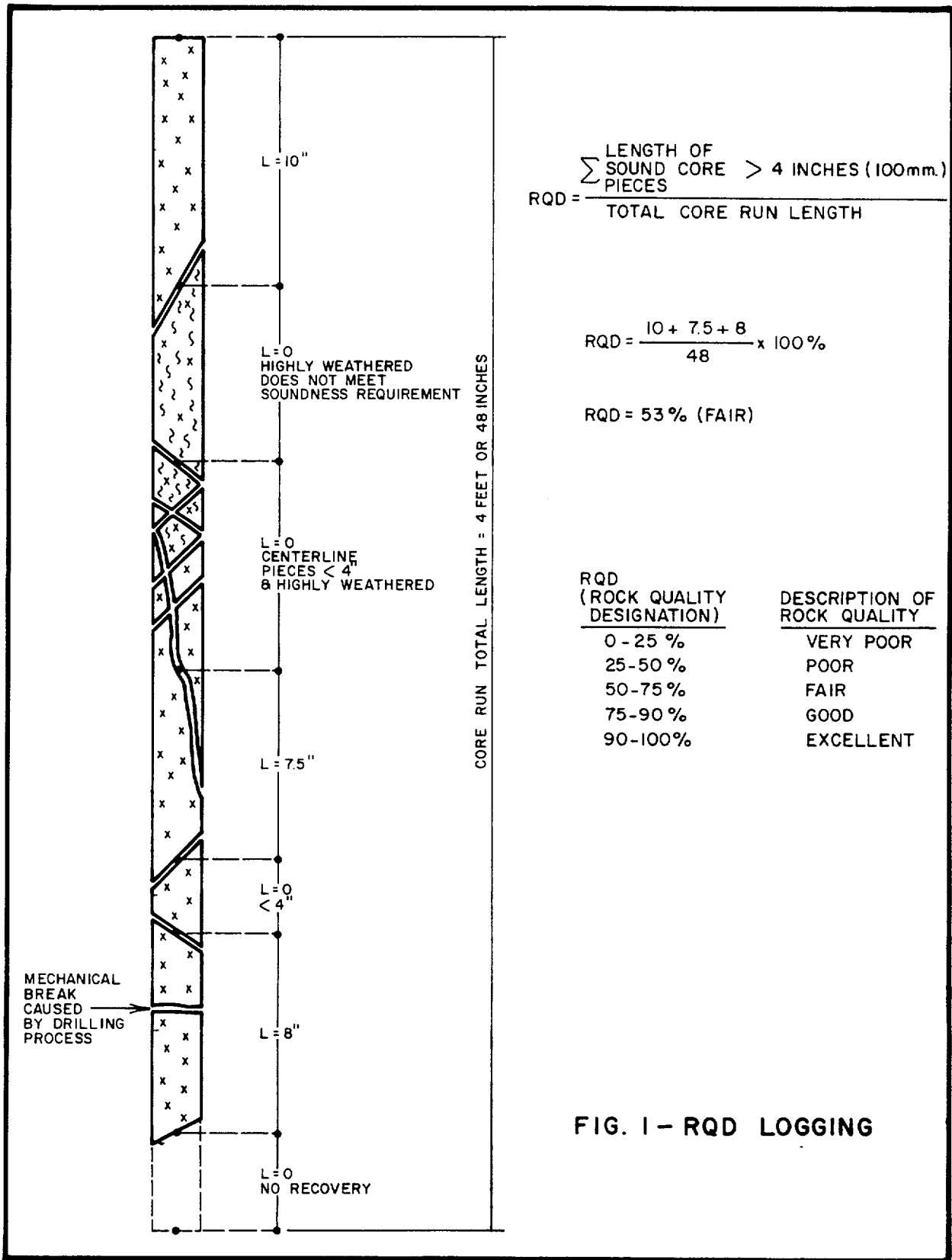


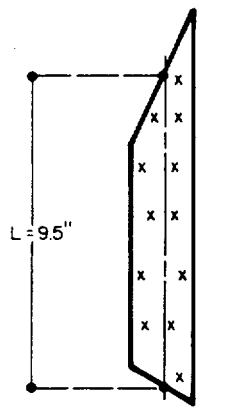
FIG. 1 - RQD LOGGING

Experience in recent years indicates that diameters both larger and slightly smaller than NX may be utilized for computing RQD. The popular wire-line core, NQ (1.875 in., 47.6 mm diameter) is now used extensively and is considered acceptable; so are the larger HQ and PQ of the wire-line series and the 2-3/4 in., 4-in., and 6-in. sizes. The smaller BQ and BX sizes are discouraged because of more potential core breakage and loss. If they are used, a note should be made on the boring log indicating that both core recovery and RQD may be slightly lower than if taken on the preferred NQ size or larger. The topic of core diameter is addressed in more detail in Part VI.

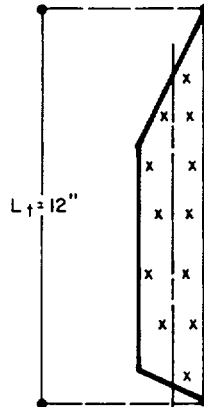
Variable length requirements for RQD measurement have been proposed (Heuze, 1971). For example, instead of using the standard 4-in. (100 mm) requisite length, a length equal to double the core diameter was advocated (such as a 60-mm length when using 30-mm diameter AX core). The authors believe that 4-in. (100 mm) requisite length should be used for all cases for the purposes of standardization and comparison. Moreover, with good drilling techniques, the lengths of the core pieces, at center-line measurement, will be the same regardless of core diameter since the spacing of natural unbonded joints does not change.

Length Measurements of Core Pieces

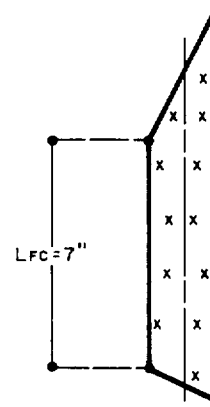
The same piece of core could be measured three ways: along the centerline, from tip to tip, or along the fully circular barrel section (Fig. 2). No specific instructions were given in



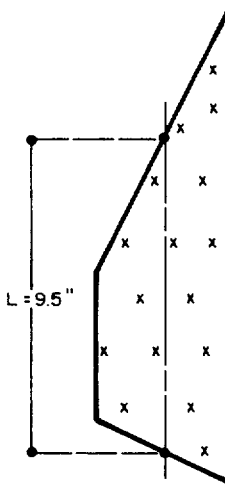
2" Ø CORE



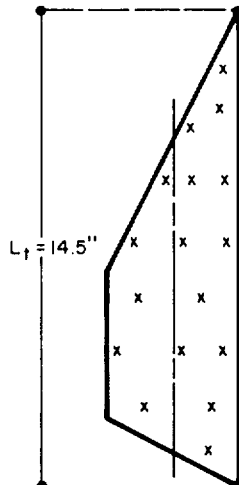
2" Ø CORE



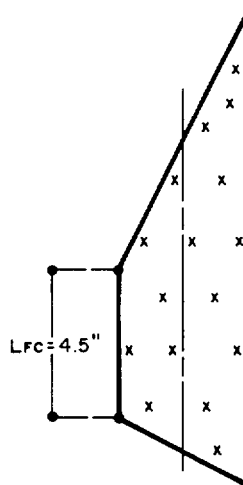
2" Ø CORE



4" Ø CORE



4" Ø CORE



4" Ø CORE

CENTERLINE

A. CORRECT METHOD FOR CORE LENGTH MEASUREMENT
 - LENGTH OF CORE INDEPENDENT OF CORE DIA.

TIP TO TIP

B. INCORRECT METHOD FOR CORE LENGTH MEASUREMENT
 - LENGTH DEPENDENT ON CORE DIA.

FULLY CIRCULAR

C. INCORRECT METHOD FOR CORE LENGTH MEASUREMENT
 - LENGTH DEPENDENT ON CORE DIA.

FIG. 2 - LENGTH MEASUREMENT OF CORE FOR RQD.

Deere's previous papers (Deere et al., 1967; Deere, 1968; Deere et al., 1969b). The recommended procedure is to measure the core length along the centerline (Fig. 1). This method is advocated by the International Society for Rock Mechanics (ISRM), Commission on Standardization of Laboratory and Field Tests (1978, 1981). The center-line measurement is equivalent to a scanline along the core axis. The reasons that the center-line measurement is preferred are that 1) it results in a standardized RQD that is not dependent on the core diameter, and 2) it avoids unduly penalizing the quality of the rock mass for cases where fractures parallel the borehole and are cut by a second set.

Core breaks caused by the drilling process should be fitted together and counted as one piece. Drilling breaks are usually evidence by rough fresh surfaces. For schistose and laminated rocks, it is often difficult to discern the difference between natural breaks and drilling breaks. When in doubt about a break, it should be considered as natural, in order to be conservative in the calculation of RQD for most uses. This practice would not be conservative when the RQD is used as part of a ripping or dredging estimate.

Some rocks, such as shales and claystones, often break up into small discs or chips with time. Rock core with initial RQD of 100 percent may break up in a period of hours or days into core with zero RQD. This phenomenon is due to one or more deleterious processes of slaking, desiccation, stress relief cracking, or swelling. Thus, it is imperative that the RQD be logged on site when the core is retrieved. The breakup of the

core over time, however, should be noted on the drilling logs, as this is evidence of a rock property that may control design of a structure.

Assessment of Soundness

Pieces of core which are not "hard and sound" (International Society for Rock Mechanics, 1978, 1981) should not be counted for the RQD even though they possess the requisite 4-in. (100 mm) length. The purpose of the soundness requirement is to downgrade the rock quality where the rock has been altered and weakened either by agents of surface weathering or by hydrothermal activity. Obviously, in many instances, a judgment decision must be made as to whether or not the degree of chemical alteration is sufficient to reject the core piece.

One procedure, which the authors have used, is not to count a piece of core if there is any doubt about its meeting the soundness requirement (because of discolored or bleached grains, heavy staining, pitting, or weak grain boundaries). This procedure may unduly penalize the rock quality, but it errs on the side of conservatism. A second procedure which occasionally has been used by the authors in recent years is to include the altered rock within the RQD summed percentage but to indicate by means of an asterisk (RQD*) that the soundness requirement has not been met. The advantage of the method is that the RQD* will provide some indication of the rock quality with respect to the degree of fracturing, while also noting its lack of soundness.

Bieniawski (1974) addresses the soundness requirement as follows:

1

...Since only hard, sound core is included in RQD determination, this means that rock core which is highly weathered receives zero RQD. For this purpose "highly weathered rock" means that weathering extends throughout the rock mass. The rock material is partly friable, has no lustre and all material except quartz is discolored or stained. Highly weathered rock can be excavated with a geologist's pick...

The assessment of the soundness requirement merits further consideration. There is no disagreement with Bieniawski's suggestion that "highly weathered rock" receives zero RQD. Using the weathering grades of the International Society for Rock Mechanics (1978, 1981) (I-Fresh; II-Slightly Weathered; III-Moderately Weathered; IV-Highly Weathered; V-Completely Weathered; and VI-Residual Soil), there is no doubt about Grade I-Fresh being included and Grade VI-Residual Soil being excluded from the RQD count. The remaining four categories all represent degrees of weathering where judgment decisions must be made.

Grade II-Slightly Weathered is described as "Discoloration indicates weathering of rock materials and discontinuity surfaces. All the rock material may be discolored by weathering and may be somewhat weaker externally than in its fresh condition." Since the alteration is limited to discoloration, possibly with somewhat lowering of strength, it appears logical to accept this degree of "slightly weathered" Grade II in the RQD count. The Grade V-Completely Weathered state by its very name eliminates any core so described from the RQD count. Its description is, "All rock material is decomposed and/or disintegrated to soil. The original mass structure is still

largely intact" (International Society for Rock Mechanics, 1978, 1981).

The two remaining categories are III-Moderately and IV-Highly Weathered. The latter category, IV-Highly Weathered is the one which Bieniawski (1974) eliminated from the RQD count. The ISRM description is, "More than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a discontinuous framework or as corestones." Little (1969) in his description of residual tropical soils uses the same terminology, Highly Weathered, and states, "Rock so weakened by weathering that fairly large pieces can be crumbled in the hands. Sometimes recovered as core by careful rotary drilling. Stained by limonite." It is clear that Highly Weathered rock should not be included in the RQD count since it has been weathered to the point that it can be crumbled in the hands.

The Grade III-Moderately Weathered category is described (International Society for Rock Mechanics, 1978, 1981) as, "Less than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework or as corestones." Little (1969) states for Moderately Weathered rock, "Considerably weathered. Possessing some strength; large pieces (e.g., NX drill cores) cannot be broken by hand. Often limonite stained. Difficult to excavate without the use of explosives." Because this category is close to the borderline, it is of interest to consider another description (Fookes and Horswill, 1970), "Term-Moderately

Weathered, Grade III, Abbreviation Mw...The rock is discolored; discontinuities may be open and surfaces will have greater discoloration with the alteration penetrating inward; the intact rock is noticeably weaker, as determined in the field, than the fresh rock."

It is recommended that Grade III-Moderately Weathered rock be accepted in the RQD count but that it be identified with an asterisk as being less than sound. However, it possesses sufficient strength, although moderately weathered, to resist hand breakage of core pieces.

In summary, Grade I (Fresh) and II (Slightly Weathered) are included in the RQD count, as is Grade III (Moderately Weathered) but with the asterisk qualifier. Grades IV (Highly Weathered), V (Completely Weathered), and VI (Residual Soil) are disregarded in the RQD count.

Length of Coring Run

The RQD is sensitive to the length of the core run. For example, a 11.8 in. (300 mm) long, highly fractured zone within a massive rock would result in RQD values of 90 percent, 80 percent, and 40 percent, for respective run lengths of 12.9 ft. (3 m), 4.9 ft. (1.5 m), and 1.6 ft. (0.5 m). Thus, the shorter the run length, the greater the sensitivity of the RQD and, in this case, the lower its value [becoming equal to zero for a 11.8 in. (300 mm) run encompassing the fractured zone].

The authors recommend that in general the calculation of the RQD be based on the actual drilling-run length used in the field,

preferably, no greater than 5 ft. (1.5 m) and certainly not more than twice that length. Actual length and nature of zones of poor and good rock should be described in the drilling log and could be supplemented by calculation of RQD on variable "artificial run lengths" to highlight poor quality or good quality zones. Many times this discrimination occurs naturally in the drilling process; as zones of poor rock are encountered, the run lengths are shortened to prevent blockage of the coring bit and to enhance core recovery. The ISRM Commission on Standardization of Laboratory and Field Tests (International Society for Rock Mechanics, 1978, 1981) recommends RQD logging using variable "run lengths" to separate individual beds, structural domains, weakness zones, etc., so as to indicate any inherent variability, and to provide a more accurate picture of the location and width of zones with anomalously low or high RQD values.

PART IV: RQD CORRELATIONS

The original development of the RQD was for use in early site evaluation to predict tunneling conditions. The difference in rock quality could be easily visualized between borings and between different depth zones. Zones of poor rock within a mass could be easily "red flagged." Shortly after its development, correlations were made between RQD and tunnel support requirements. This application was expanded to correlate the RQD with rock mass modulus and rock foundation settlement. Since 1970, the RQD has been used as a basic element of rock mass classification systems. Subsequent correlations between RQD and fracture frequency were made so that RQD or fracture frequency could be theoretically calculated when only one of the parameters was measured.

Tunnel Support/Reinforcement Design

The RQD was an early and simple method of classifying rock masses for prediction of tunneling conditions and selection of tunnel support. The US Army Corps of Engineers (1978) discuss the use of the RQD method in their publication "Tunnels and Shafts in Rock."

The RQD support criteria relate RQD and construction methods to alternate support systems of steel sets, shotcrete, or rockbolts. The method was developed utilizing numerous actual consulting cases and published case histories. Detailed discussions of the use of the RQD for tunnel support design are

provided in papers by Deere et al., (1969a, 1969b), Peck et al., (1969), Deere et al., (1970), Cecil (1970), Cording and Deere, (1972), and Merritt (1972).

The RQD can be generally correlated to the common tunnelers' classification as follows in Table 1 (after Deere et al., 1970):

TABLE 1

ROCK QUALITY CLASSIFICATION

| <u>Rock Quality</u> | <u>RQD (%)</u> | <u>General Tunnelers' Classification</u> |
|---------------------|----------------|--|
| Excellent | 90-100 | Intact |
| Good | 75-90 | Massive, moderately jointed |
| Fair | 50-75 | Blocky and Seamy |
| Poor | 25-50 | Shattered, very blocky and seamy |
| Very Poor | 0-25 | Crushed |

Guidelines (Deere et al., 1970) for the selection of tunnel support/reinforcement systems based on the RQD for tunnels between 20 and 40 ft. (6.1 m and 12.2 m) in diameter are given in Table 2. Reduced support is shown for machine bored tunnels over conventionally excavated drill-and-blast tunnels due to less rock disturbance.

Merritt (1972) prepared correlations between RQD and required tunnel support (no support or local bolts; pattern bolting; or steel sets) for various sized tunnels. His correlation is presented in Figure 3, together with the recommendations of Cecil (1970) which include shotcrete.

Although the RQD does not take directly into account important rock mass characteristics such as joint infillings,

TABLE 2

GUIDELINES FOR SELECTION OF PRIMARY SUPPORT FOR 20-FT TO 40-FT TUNNELS IN ROCK

| Rock Quality | Construction Method | Alternative Support Systems | | | | | | | |
|--|-----------------------|-------------------------------|--------------------------|-------------------------|--|---|---|---------------|--|
| | | Steel Sets | | | Rock Bolts (a) (Conditional use in poor and very poor rock) | | Shotcrete (b) (Conditional use in poor and very poor rock) | | |
| | | Rock Load (B-Tunnel Width) | Weight of Sets | Spacing (c) | Spacing of Pattern Bolts | Additional Requirements and Anchorage Limitations (a) | Total Thickness | | Additional Support (b) |
| | | | | | | Crown | Sides | | |
| Excellent (d) RQD > 90 | Boring machine | (0.0-0.2)B | Light | None to occasional | None to occasional | Rare | None to occasional local application | None | None |
| | Drilling and blasting | (0.0-0.3)B | Light | None to occasional | None to occasional | Rare | None to occasional local application | None | None |
| Good (d) RQD = 75 to 90 | Boring machine | (0.0-0.4)B | Light | Occasional to 5 to 6 ft | Occasional to 5 to 6 ft | Occasional mesh and straps | Local application 2 to 3 in. | None | None |
| | Drilling and blasting | (0.3-0.6)B | Light | 5 to 6 ft | 5 to 6 ft | Occasional mesh and straps | Local application 2 to 3 in. | None | None |
| Fair RQD = 50 to 75 | Boring machine | (0.4-1.0)B | Light to medium | 5 to 6 ft | 4 to 6 ft | Mesh and straps as required | 2 to 4 in. | None | Provide for rock bolts |
| | Drilling and blasting | (0.6-1.3)B | Light to medium | 4 to 5 ft | 3 to 5 ft | Mesh and straps as required | 4 in. or more | 4 in. or more | Provide for rock bolts |
| Poor RQD = 25 to 50 | Boring machine | (1.0-1.6)B | Medium circular | 3 to 4 ft | 3 to 5 ft | Anchorage may be hard to obtain. Considerable mesh and straps required. | 4 to 6 in. | 4 to 6 in. | Rock bolts as required (approx. 4-6 ft. cc.) |
| | Drilling and blasting | (1.3-2.0)B | Medium to heavy circular | 2 to 4 ft | 2 to 4 ft | Anchorage may be hard to obtain. Considerable mesh and straps required. | 6 in. or more | 6 in. or more | Rock bolts as required (approx. 4-6 ft. cc.) |
| Very Poor RQD < 25 (excluding squeezing and swelling ground) | Boring machine | (1.6-2.2)B | Medium to heavy circular | 2 ft | 2 to 4 ft | Anchorage may be impossible. 100% mesh and straps required. | 6 in. or more on whole section | | Medium sets as required |
| | Drilling and blasting | (2.0-2.8)B | Heavy circular | 2 ft | 3 ft | Anchorage may be impossible. 100% mesh and straps required. | 6 in. or more on whole section | | Medium to heavy sets as required |
| Very Poor, squeezing or swelling ground | Both methods | up to 250 ft | Very heavy circular | 2 ft | 2 to 3 ft | Anchorage may be impossible. 100% mesh and straps as required. | 6 in. or more on whole section | | Heavy sets as required |

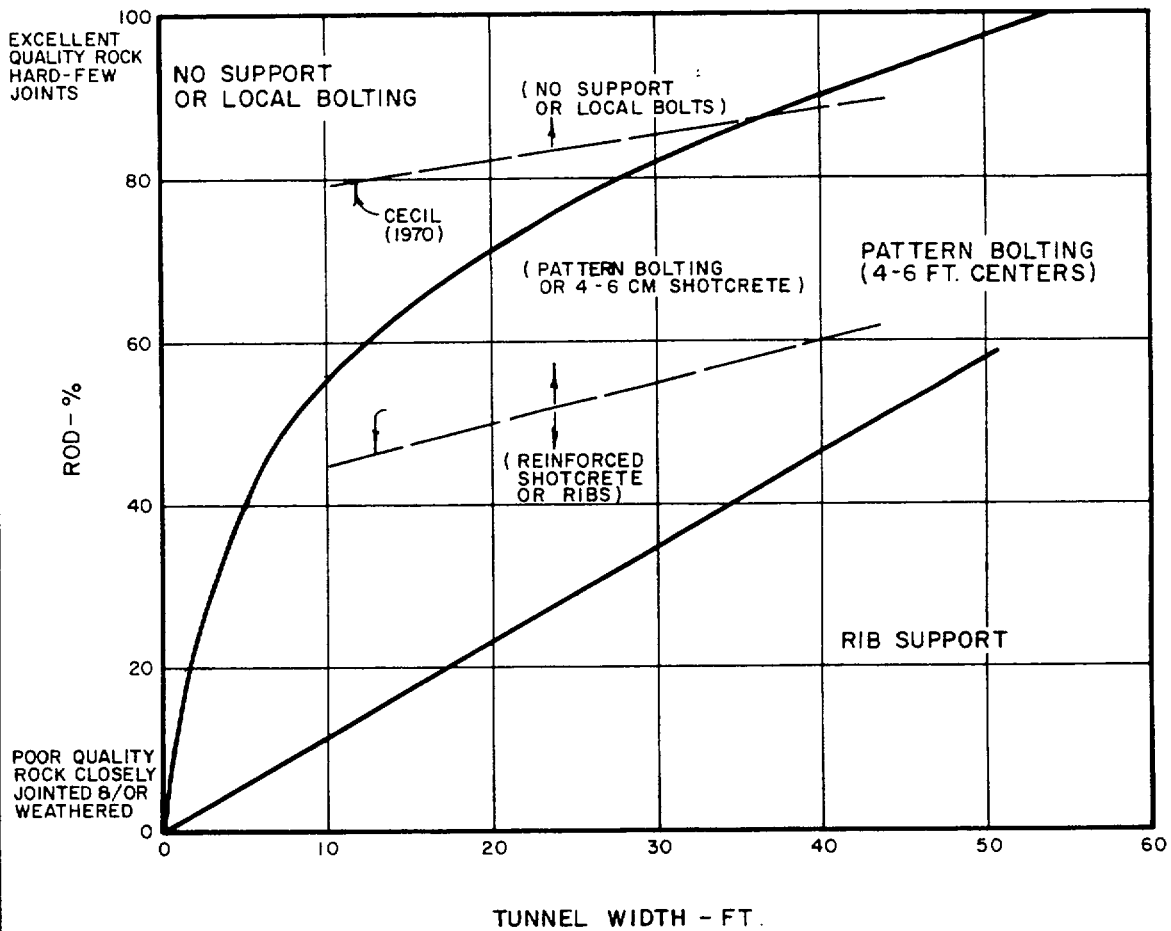
NOTE: Table reflects 1969 technology in the United States. Groundwater conditions and the details of jointing and weathering should be considered in conjunction with these guidelines particularly in the poor quality rock. See Deere et. al. (1969a) for discussion of use and limitations of the guidelines for specific situations.

a Bolt diameter = 1 in. length = 1/3 to 1/4 tunnel width. It may be difficult or impossible to obtain anchorage with mechanically anchored rock bolts in poor and very poor rock. Grouted anchors may also be unsatisfactory in very wet tunnels.

b Because shotcrete experience is limited, only general guidelines are given for support in the poorer quality rock.

c Logging requirements for steel sets will usually be minimal in excellent rock and will range from up to 25 percent in good rock to 100 percent in very poor rock.

d In good and excellent quality rock, the support requirement will in general be minimal but will be dependent on joint geometry, tunnel diameter, and relative orientations of joints and tunnel.



AFTER MERRITT
1972

NOTE: SUPPORT DATA FROM IGNEOUS AND METAMORPHIC ROCKS WHERE REAL ROCK PRESSURES OR SWELLING/SQUEEZING GROUND DID NOT EXIST.

1M = 3.28 FT.

FIG. 3 - ROCK QUALITY AND SUPPORT REQUIREMENTS FOR TUNNELS OF VARYING DIMENSIONS

roughness, orientation, or state of stress, the authors believe it is still a useful tool in predicting ground conditions and support requirements for tunnels. The analysis is quick and inexpensive and may be used as the sole design method for experienced tunnel engineers or geologists or simply be used as a check guide on other more comprehensive design methods.

The authors have encountered cases where the RQD did not correlate well with required tunnel support. For example, there are cases where the RQD was in the good to excellent range yet considerable tunnel support was required. Two examples of this are as follows:

- o Open solution-widened joints in a massive limestone. Tunnelling through this rock mass resulted in shifting of large rock blocks bounded by the solutioned joints.
- o Small clay-filled joints or shears that were moderately spaced but adversely oriented within a generally massive rock mass. Tunneling through this rock resulted in very blocky ground requiring more support than predicted by RQD.

Cases where very low RQD's have overpredicted support/reinforcement requirements include the following:

- o Highly fractured volcanic (or granitic) rocks -- the joints or fractures were rough, tight, discontinuous, well-interlocked, and under sufficient stress to prevent loosening.

Prediction of In-Situ Modulus

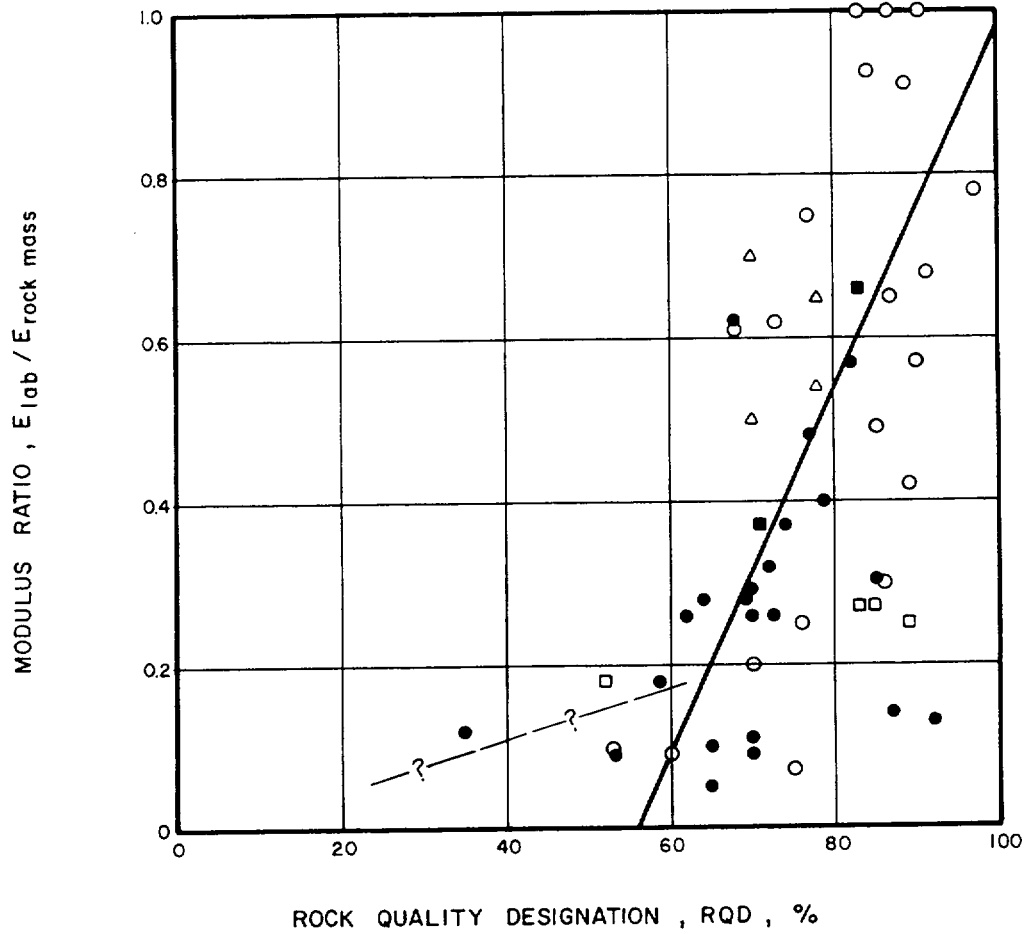
Another aspect of the University of Illinois RQD research in the late 1960's was the correlation of the RQD (or velocity ratio) with the in-situ modulus of deformation. Obviously, the greater the fracturing and alteration the lower the RQD and, also, the lower the modulus; correlations showed this to be true (Deere et al., 1967; Hendron, 1968; Deere et al., 1969b; Coon and Merritt, 1970).

The modulus or elasticity of an intact rock specimen can be measured in the laboratory by plotting stress versus strain in the unconfined compression test. The laboratory modulus of an intact rock specimen may be defined by E_{t50} (the slope of a line tangent to the stress-strain curve taken at 50 percent of failure stress).

This modulus of elasticity in the lab is, of course, higher than the modulus of deformability (static modulus of elasticity) of the rock mass because the in-situ rock mass has discontinuities or joints. The ratio of intact lab modulus (E_{t50} or E_{lab}) to the in-situ rock mass modulus (E_d or $E_{rock\ mass}$) correlates in a general way with the RQD.

The relationship of the modulus ratio to the RQD as developed by Coon and Merritt (1970) is shown on Figure 4. The correlation is useful above RQD>60 percent but insufficient data exist for the low RQD range.

The junior author has used this correlation on small projects where it is not economically feasible to perform large scale in-situ testing. For example, the correlation has proved



- DWORSHAK DAM, GRANITE GNEISS, SURFACE GAGES
- " " " " " , BURIED "
- TWO FORKS DAMSITE, GNEISS
- YELLOWTAIL DAM, LIMESTONE
- △ GLEN CANYON, SANDSTONE

AFTER COON & MERRITT
1970

FIG. 4 - RQD. VERSUS MODULUS RATIO

quite useful in evaluating the safety of existing concrete dams subject to loading from flood-overtopping, where the modulus of deformation of the foundation is required as an input factor. Drill cores of the rock foundation are tested for lab moduli and then corrected by the modulus ratio reduction factor.

The Velocity Index can be substituted for RQD where RQD information is not available or only limited borings are performed. The Velocity Index is defined as the square of the ratio of field in-situ seismic compressional velocity (V_f) to the laboratory compressional sonic velocity (V_l) or $(V_f/V_l)^2$. The field velocities may be taken via seismic refraction, cross-hole, or downhole techniques. Laboratory sonic velocities are measured on core specimens loaded to 3000-psi (211-kg/cm²) stress levels. The correlation is nearly one to one between RQD and Velocity Index. Table 3 displays the correlation between RQD, Velocity Index, and the Modulus Ratio (after Coon and Merritt, 1970).

TABLE 3
CORRELATIONS OF MODULUS RATIO WITH RQD
AND VELOCITY INDEX

| <u>Classification</u> | <u>RQD</u> | <u>Velocity Index</u> | <u>Modulus Ratio</u> $E_{rock-mass}/E_{lab}$ |
|-----------------------|------------|-----------------------|---|
| Very Poor | 0 - 25 | 0-0.20 | < 0.20 |
| Poor | 25 - 50 | 0.20-0.40 | < 0.20 |
| Fair | 50 - 75 | 0.40-0.60 | 0.20-0.50 |
| Good | 75 - 90 | 0.60-0.80 | 0.50-0.80 |
| Excellent | 90 - 100 | 0.80-1.00 | 0.80-1.00 |

Kulhawy (1978) expounded on the RQD/Modulus Ratio or Reduction Factor by including an additional parameter of joint stiffness. He developed a series of curves that allowed estimation of the modulus reduction if RQD was measured and joint

stiffness was estimated from a table of representative measured values for different rock types. The estimated modulus was then proposed for use in a rational estimation of settlement on rock foundations.

Bieniawski (1978) proposed a method for estimating the modulus of deformation based on his RMR ratings of which RQD is a parameter. His preliminary work showed reasonably good correlation. The correlation was given as:

$$E_{\text{rock mass}} = 2 \times \text{RMR} - 100 \quad (1)$$

where $E_{\text{rock mass}}$ = in-situ static modulus of deformation in GPa

RMR = rock mass rating in accordance with the Geomechanics Classification - for RMR >50.

$$\text{and } E_{\text{rock mass}} = 10^{(\text{RMR}-10)/40} \text{ for RMR} < 50 \quad (2)$$

(Serafim et al., 1983)

The senior author over the last decade has not used the RQD correlation extensively but has employed for preliminary estimates the unpublished correlation of seismic P-wave velocity or seismic modulus and the in-situ modulus ($E_{\text{seismic}}/E_{\text{static}}$ of rock mass = 1.5 to 10, often 4 to 5), or the correlation with the shear wave frequency of Schneider as given by Bieniawski (1978). For critical cases, the authors prefer large-scale in-situ testing where the loading direction in the testing approximates that in the prototype structure so that the significant rock joints can be appropriately tested.

In summary, the RQD - Modulus Reduction correlation is useful for obtaining a rough estimate of in-situ modulus of deformation. The authors recommend that it be used in conjunction with other modulus estimating techniques.

Foundation Settlement Correlations

Peck et al., (1974) proposed allowable foundation contact pressures on jointed rock on the basis of the RQD. They stated with respect to settlement on unweathered rock:

Unless the strength of the intact rock is extremely low, roughly equal to or less than that of plain concrete, the allowable contact pressure beneath foundations is governed exclusively by the settlement associated with the defects in the rock, and not by strength. The compressibility is closely related to the spacing and direction of the joints, whether they are tight or open, and whether they are filled or coated with softer materials. If the joints are tight or are not wider than a fraction of an inch, the compressibility is reflected by the RQD (Art. 5.3).

Table 4 presents the maximum allowable contact pressure for different RQD values for a total maximum settlement of 0.5 in. (12.7 mm) proposed by Peck et al., (1974). The tabulated value of allowable pressure should not be used if it exceeds the unconfined compressive rock strength.

TABLE 4

ALLOWABLE CONTACT PRESSURE q_a ON JOINTED ROCK

| <u>RQD</u> | <u>q_a</u> <u>(tons/sq ft)</u> | <u>q_a</u> <u>(lb/sq in)</u> |
|------------|--|--|
| 100 | 300 | 4170 |
| 90 | 200 | 2780 |
| 75 | 120 | 1660 |
| 50 | 65 | 970 |
| 25 | 30 | 410 |
| 0 | 10 | 140 |

Peck (1976) in a later paper presents the same table and notes, "...This correlation can give useful results if tempered

by a detailed knowledge of the geology of the deposit. However, it is only a first crude step..."

Kulhawy (1978) reviewed this concept in his paper and agreed that "It does provide a convenient starting point for evaluating foundations on rock masses." He proposed a method for providing a quantitative estimate of rock foundation settlement based on RQD, Modulus Reduction or Ratio, and joint stiffness, as previously noted.

Fracture Frequency

There are instances where it is useful to convert fracture frequency to RQD or vice versa. For example, use of rock mass classification systems usually require RQD as an input, and if RQD has not been directly measured in core, measurement of fracture frequency from outcrop scanline surveys can be converted. Various conversion factors have been derived and are discussed below.

A word of caution should be noted; there is not a direct or totally appropriate conversion available since RQD is a much more general measure of rock mass or rock core quality than fracture frequency. RQD discounts for core loss and highly weathered or soft rock zones (soundness requirement). Fracture frequency and RQD are closely related, however, for an unweathered rock mass that is degraded only by fracturing.

There have been various publications that discuss the fracture frequency/RQD correlation. Chronologically these include, Deere et al., (1967); Priest and Hudson (1976);

Kulhawy (1978); Goodman and Smith (1980); Wallis and King (1980); Priest and Hudson (1981); Palmstrom (1982); Hudson and Priest (1983); Sen (1984); Sen and Kazi (1984); Kazi and Sen (1985).

Linear fracture frequency

Priest and Hudson (1976) define the correlation between linear fracture frequency and RQD as randomly distributed

$$\text{RQD} = 100e^{-0.1\lambda} (0.1\lambda + 1) \quad (3)$$

where λ = mean discontinuity frequency per meter.

or

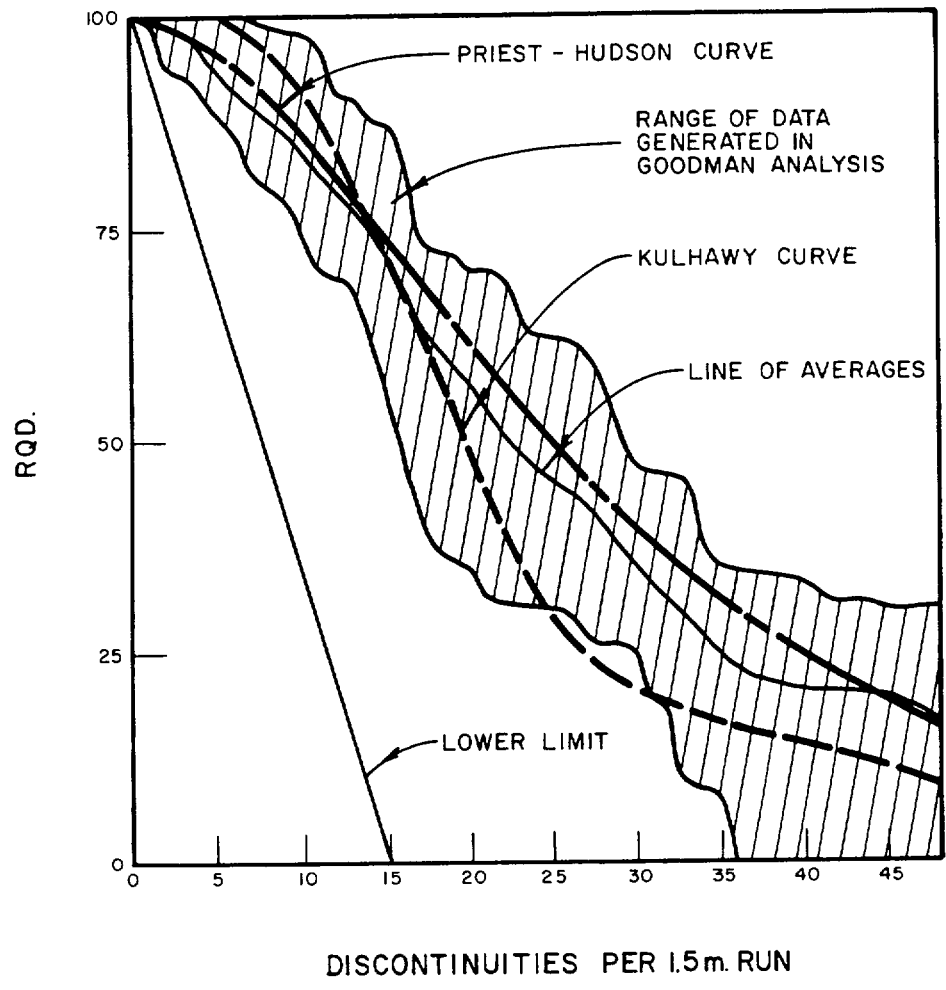
$$\text{RQD} = 110.4 - 3.68 \lambda \text{ when } 6 < \lambda < 16 \quad (4)$$

These appear to be reasonable correlations for use in rock outcrop scanline surveys and were confirmed by 27 surveys in chinks and mudstones. This randomly distributed theoretical relationship was also confirmed in the field by Wallis and King (1980) at a site within granite.

Goodman and Smith (1980) explored the theoretical models and bounds of possibility in the correlation. The relationships between RQD and fracture frequency are shown in Figure 5. The Priest and Hudson relationship (1976), as presented above, approximates the line of averages shown in Figure 5 and appears to be a preferred formula.

Volumetric fracture frequency

Palmstrom (1982) developed the concept of volumetric joint count (Jv). This is a simple measure of the degree of jointing and refers to the number of joints per cubic meter. Palmstrom



AFTER GOODMAN & SMITH
1980

FIG. 5 - RQD. VERSUS FRACTURE FREQUENCY

derived the theoretical correlation between J_v and RQD as

$$RQD = 115 - 3.3 (J_v) \text{ for } J_v \geq 4.5 \quad (5)$$

This conversion factor has been advocated by Barton et al., (1974) for use in the Q System Rock Mass Classification as well as by the International Society of Rock Mechanics (1978).

Kazi and Sen (1985) proposed a rock mass parameter termed volumetric RQD (V. RQD). The V. RQD is calculated by summation of the volumes of intact blocks bigger than 0.001 m^3 [i.e., for a cubic block with 4 in. (100 mm) sides] divided by the total rock mass volume, expressed as a percentage.

The volumetric joint count (J_v) and volumetric RQD (V. RQD) are refinements on linear fracture frequency and RQD that account for 3-dimensionality of discontinuities. They may prove useful in cases where oriented coring and 3-D rock exposures are available for inspection and when one has case history experience with these parameters.

PART V: UTILIZATION OF THE RQD IN LATER ROCK CLASSIFICATION SYSTEMS

In the early 1970's a number of rock classification systems were introduced. Two that have gained international acceptance and that are increasingly being used are those of Bieniawski (1973) and Barton et al., (1974). Both systems use the RQD as an input parameter.

Bieniawski's Rock Mass Rating System (Geomechanics Classification)

Bieniawski (1973) in the presentation of his classification of jointed rock masses notes:

...Deere's very practical and simple approach⁷ has a considerable potential in relating his rock quality designation (RQD) to tunnel support²¹ as well as in estimating deformability of rock masses²². However, the RQD method disregards the influence of joint orientation, continuity and gouge material which may all be of great importance in some cases.

Bieniawski proposed (1973) that for his Geomechanics Classification the following parameters should be incorporated:

- o Rock Quality Designation (RQD);
- o State of weathering;
- o Uniaxial compressive strength of intact rock;
- o Spacing of joints or bedding;
- o Strike and dip orientations;
- o Separation of joints;
- o Continuity of joints; and
- o Groundwater inflow.

With respect to the RQD he notes:

...The state of the rock cores recovered in a drilling program is a valuable indication of the in-situ condition and probable engineering behavior of a rock mass¹⁰. Various criteria may be used for quantitative description of the rock quality in the cores, such as core recovery, fragment size, fracture frequency or rock quality designation (RQD). While the actual choice is largely a matter of personal preference, the Author advocates the use of RQD because it has been found particularly useful in classifying rock masses for selection of tunnel support systems^{2, 20, 21}.

...It should be noted that for RQD determination, core of at least 50 mm in diameter should be used and double tube N size core barrels (75 mm OD) with non-rotating inner barrels are strongly recommended²⁴.

With respect to the limitations of RQD and its practical advantages Bieniawski (1973) states:

...The limitations of the RQD are that it disregards the influence of joint orientations, continuity and gouge material. On the other hand, the RQD procedure is simple, inexpensive and reproducible. As a result it is used extensively in the U.S.A. and Europe and is currently quickly gained acceptance in South Africa.

...If the RQD method is used in core logging, there is no need for determination of also fracture frequency (i.e. the number of fractures over an arbitrary length) or the fragment size, as this would be duplication of effort.

The RQD parameter was given a rating in the classification procedure which in the 1973 article ranged from 3 for very poor rock to 16 for very good rock. Ratings for the other parameters were obtained and summed to give the total rating. The value of the total rating then defined the rock mass class; for example, a rating of 70 to 90 indicated Class No. 2, good rock.

Over the years, as more experience was obtained, several changes were made to the classification system. The reader is referred to Bieniawski's recent paper given at the ASTM Symposium on Rock Classification Systems for Engineering Purposes held in June 1987 in Cincinnati (Bieniawski, 1988) for current classification procedures and utilization of the method. The term Rock Mass Rating System (RMR) appears to be gaining preference over the previous name of Geomechanics Classification.

Barton's Q System (Norwegian Geotechnical Institute)

A group from the Norwegian Geotechnical Institute (NGI) proposed an engineering classification of rock masses for the design of tunnel support (Barton et al., 1974). The rock mass quality Q was proposed, being the result of six classification parameters: the RQD index, the number of joint sets J_n , the roughness of the weakest joints J_r , the degree of alteration or filling along the weakest joints J_a , the degree of water inflow J_w , and a stress reduction factor SRF. With respect to the RQD they note:

...The RQD index happens to be one of the better single parameters since it is a combined measure of joint frequency and degree of alteration and discontinuity fillings, if these exist. However, it is relatively insensitive to several important properties of rock masses, in particular the friction angle of altered joint fillings (Cording and Deere, 1972), and the roughness or planarity of joint walls.

Barton et al., (1974) modified the RQD by multiplying the value by appropriate factors that were considered indicators of:

1. Relative block size, (RQD/Jn)
2. Inter-Block shear strength, (Jr/Jn)
3. Active stress, (Jw/SRF)

The overall quality Q is given by the product:

$$Q = (RQD/Jn) (Jr/Ja) (Jw/SRF) \quad (6)$$

Nine ranges of Q were identified with the following descriptive terminology (eliminating herein the lowest and highest ranges for simplicity and as being of lesser interest): Extremely poor, 0.01-0.1; Very poor, 0.1-1; Poor, 1-4; Fair, 4-10; Good, 10-40; Very good, 40-100; and Extremely good, 100-400.

Barton et al., (1974) stated that when borecore was unavailable, the RQD could be estimated as follows (Barton quotes personal communication with Palmstrom, 1974):

$$RQD = 115 - 3.3 Jv \quad (7)$$

where Jv = total number of joint per m³

(RQD = 100 for Jv < 4.5)

For details of the methodology and the application to selecting tunneling support the reader is directed to the recent publication by Barton (1988).

Hoek and Brown (1980) in their book state:

The large amount of information contained in . . . [the instruction table] . . . may lead the reader to suspect that the NGI Tunneling Quality Index is unnecessarily complex and that it would be difficult to use in the analysis of practical problems. This is far from the case and an attempt to determine the value of Q for a typical rock mass will soon convince the reluctant user that the instructions are simple and unambiguous and that, with familiarity . . . [the tables] . . . become very easy to use.

Bieniawski (1976) made a comparison of his RMR ratings and Barton's Q rock quality for 111 cases and found a reasonably good correlation with the following relation:

$$\text{RMR} = 9 \ln Q + 44 \quad (8)$$

Bieniawski (1976) states, ". . . the author has found the NGI system is relatively easy to apply once the user is fully familiarized with its principles." He recommends that both the Geomechanics Classification (RMR) and the NGI Classification (Q) be used on each project for cross-checking purposes. The authors agree that this is worthwhile in order to accumulate experience, not only in the correlation of the two classifications but also in the correlation with design parameters and construction experience.

PART VI: PERTINENT QUESTIONS OF RQD IN PRACTICE

Each District and Division of the US Army Corps of Engineers submitted comments and questions about the RQD to Dr. Don C. Banks, Chief, Engineering Geology and Rock Mechanics Division, Geotechnical Laboratory, US Army Waterway Experiment Station, Vicksburg, Mississippi. A total of 28 letters were received in December 1986 and January 1987 from the Corps as well as from a number of geotechnical consultants to the Corps.

The authors of this report have placed each question or comment into one of five general categories that have been established as follows:

1. Mechanics of Determining RQD,
2. Special RQD logging Problems,
3. Desirability of Additional Geological Observations,
4. Applications to Engineering and Construction, and
5. General Usefulness of RQD.

The categorized questions and comments as excerpted from the 28 letters of response are presented in the Appendix. This section presents the authors' replies. The number following each topic heading corresponds to the outline in the Appendix.

Mechanics of Determining RQD (1)

Core diameter (1A)

The topic of core diameter proved to be one of the more popular subjects for comments and questions. Thirteen responses addressed this item. The principal question was if diameter

larger or smaller than NX size could be used and if correlation coefficients would be necessary. Several Corps of Engineer Districts use NQ, HQ, and PQ wire-line coring and/or 4 in. (100 mm) coring.

As noted in Part III, the original work on RQD was done almost exclusively on NX-size core. Deere (1968) recommended that cores of at least NX size obtained by double-tube core barrels be used together with proper drilling supervision.

Experience of the last decade has shown that the wire-line series of core bits and barrels is increasingly being used, particularly for the deeper holes. The NQ core of 1-7/8-in. diameter¹ (1.875 in., 47.6 mm) is now perhaps as common as NWX (or NWM) size (2.155 in., 54.7 mm) and the RQD is being taken on either size, interchangeably without any correlation coefficient, which appears to be acceptable practice.

The question then arises as to the next size smaller in both categories [BWX, or BWM, of diameter 1.655 in. (42.0 mm); and BQ, of diameter 1-7/16 in. (1.438 in., 36.5 mm)]. Experience has shown that in good quality rock these sizes give similar results to those obtained with the larger sizes. However, in weathered and heavily fractured rock, and in weak sedimentary and foliated and schistose metamorphic rocks, there is a tendency for more core breakage and, perhaps, more core loss. Attempts can be made to fit the core breaks back together for core measurements to

¹ Core diameters referred to in this report are nominal dimensions. Actual diameters may vary slightly depending upon core barrel manufacturers.

compensate for some of the breakage. The authors believe that the RQD should be taken on the BWX and BQ cores but that a note should be added to the boring log pointing out that both core recovery and RQD values may be slightly lower than if taken with the recommended NQ size or larger. The AWX-AWM and AQ sizes (1.185 in., 30-mm diameter; and 1-1/16 in., 27.0 mm, respectively) are considered too small to be used for RQD because of their potential for core breakage, grinding, and loss.

At the other end of the scale the larger diameter HQ (2-1/2 in., 63.5 mm); the 2-3/4 in. (2.690 in., 68.3 mm); the PQ (3-11/32 in., 3.343 in., 85.0 mm); the 4 in. (3.970 in., 100.8 mm); and the 6 in. (5.970 in., 151.6 mm) are all acceptable for the RQD. The HQ and 2-3/4-in. sizes are quite common now, particularly for the upper portion of a borehole. In using the larger diameter cores the RQD measurements must be taken along the core axis centerline as described in the following section. The 4-in. (100 mm) requisite length for a core piece to be counted still would apply.

Length measurement of core pieces (1B)

Included among the ten comments and questions received on this topic were three different items: (1) the position of the measurement, (2) the recommendation (by others) of using a requisite length of twice the core diameter, and (3) the problem of distinguishing between natural and induced fractures. A discussion of these items is also presented in Part III.

The original RQD papers by Deere and his colleagues at the University of Illinois never specifically outlined where the length measurement should be taken on a core and thus clarification is needed. Experience has shown that the length should be measured at the core axis or centerline advocated by the International Society of Rock Mechanics (1978, 1980). This method of measurement is equivalent to a scanline and thus is independent of core size and is less sensitive to joint angle.

Confusion as to the requisite length measurement arose due to publications by others (Heuze, 1971; Goodman, 1981) that defined RQD as "percentage recovery of core in lengths greater than twice its diameter." This statement is approximately correct for the N-sized core only. The 4-in. (100 mm) requisite length, measured at centerline, should be used for all applicable core sizes. The spacing of natural unbounded joints does not change with core size.

It is often very difficult to distinguish between natural and induced fractures. A committee of the International Society of Rock Mechanics (1978, 1981) addressed the problem as follows:

...When estimating frequency or RQD from drillcore it is necessary to discount fresh artificial breaks (fractures) clearly caused by the drilling process, and also those made deliberately when fitting core into the core boxes. The following criteria are suggested:

- (i) A rough brittle surface with fresh cleavage planes in individual rock minerals indicates an artificial fracture.
- (ii) A generally smooth or somewhat weathered surface with soft coating or infilling materials such as talc, gypsum, chlorite,

mica or calcite obviously indicates a natural discontinuity.

- (iii) In rocks showing foliation, cleavage or bedding it may be difficult to distinguish between natural discontinuities and artificial fractures when these are parallel with the incipient weakness planes. If drilling has been carried out carefully then the questionable breaks should be counted as natural fractures, to be on the conservative side.
- (iv) Depending upon the drilling equipment part of the length of core being drilled may occasionally rotate with the inner barrels in such a way that grinding of the surfaces of discontinuities and fractures occurs. In weak rock types it may be very difficult to decide if the resulting rounded surfaces represent natural or artificial features. When in doubt the conservative assumption should be made, i.e. assume that they are natural.
- (v) It may be useful to keep a separate record of the frequency of artificial fractures (and associated lower RQD) for assessing the possible influence of blasting on the weaker sedimentary and foliated or schistose metamorphic rocks.

Length of coring run and of RQD interval (1C)

A total of five questions or comments were received regarding the appropriate interval or run length over which to measure the RQD. This concept is discussed in Part III with further discussion below.

The RQD is highly sensitive to core-run length or interval, providing more delineation of anomalously "poor" or "good" rock zones with shorter lengths. The authors advocate the following procedure:

1. Log RQD as the core comes out of the ground based on the actual drill-run lengths and record on the drilling logs. The length of coring-run should preferably not exceed 5 ft. (1.5 m) but in more massive rocks where recovery is 100 percent, 10-ft. (3 m) runs are acceptable.
2. During drilling, the actual length of poor and good rock zones should be described by prose in the drilling log and should be supplemented by calculation of RQD on "variable artificial run lengths" to highlight poor quality or good quality zones, changes in lithology, etc. This is analogous to the standard practice of performing packer permeability tests on 20-ft. (6 m) intervals within a boring, followed up by select tests on smaller intervals in areas of high water "takes."
3. After one has gathered the proper information in the field by the logging procedures described above, the RQD values can then be assembled for different areas, depths, etc. by calculation of weighted averages. For example, a weighted average for RQD can be calculated for each boring to compare one area of the site with another. The weighted average of RQD for core taken within 2 or 3 tunnel diameters of a tunnel alignment could be assembled and used for classification of the tunnelling rock. Weighted averages can also be calculated for each rock type encountered, each structural domain, and for the upper weathered zone.

Special RQD Logging Problems (2)

Drilling equipment and techniques (2A)

Three comments were submitted with respect to the questionable reproducibility of RQD since it is dependent on human factors (skill and attitude of the drill operator) and on the equipment used. The authors agree that these can be a serious problem. It is important in all aspects of geotechnical investigations to obtain the best information possible, not just for RQD measurement. The engineering geologist or geotechnical engineer can reduce the influence of these operational factors by: (1) specification of proper drilling equipment in the bid documents (e.g., double- or triple-tube core barrels, etc.) and (2) providing for trained technical supervisory personnel on-site during drilling.

In addition, correct measurement of RQD calls for discounting mechanically induced core breaks, although there are not always easily discerned. The junior author has had some success reducing drilling breakage and core loss by specifying a two-tiered payment system, whereby footage was paid for at one scale for recovery above 95 percent, and at a second lower scale for poorer recovery. This system of payment helps counter the traditional system whereby the drill operator receives daily footage bonuses from his company, which may result in overzealous hole advance.

Prompt logging of core (2B)

The problem of core deterioration with time and handling was pointed out, especially when drilling thinly bedded argillaceous rocks.

The authors advocate logging of the core immediately after it is removed from the ground. Valuable information is lost every time the core is handled. This requirement is paramount when dealing with shales that undergo time-dependent slaking, desiccation, stress-relief cracking, or swelling.

Applicability to certain rock types (2C)

By far, the greatest number of comments and questions received were with respect to the applicability of RQD to certain rock types. A total of 16 comments were received on this subject and are tabulated in the Appendix, Section 2C. The comments have been subdivided into (1) General Problems; (2) Shale, Claystone, Interbedded Sedimentary Rocks; (3) Limestone with Solution Cavities; and (4) Volcanics and Metamorphics.

General problems. Six comments or queries were received that have been lumped together under this heading. The principal question appears to be if the RQD procedure is applicable to all rock types. Yes, it has been applied to all lithologies. Difficulties often arise with thinly bedded, laminated sedimentary rocks and schistose or foliated metamorphic rocks. Such rocks are prone to breakage along the incipient weak surfaces during drilling and handling. Good drilling techniques with minimum vibration and large diameter cores (HQ or larger)

can yield intact cores. These must be logged immediately before they break up due to handling, drying, and stress-relief cracking. When drilling subparallel to the weakness direction, it is very difficult to obtain cores without breakage or core loss. Boreholes should be drilled at various orientations to investigate the directional sensitivity.

Another problem is the artificial discontinuity in the RQD count at the 4-in. (100 mm) requisite length. Such a break penalizes too heavily the hard, thin-bedded siltstone, limestone, etc. that have bed thicknesses (and bedding plane joints) at say 3 in. (76 mm). In retrospect, it might have been better to have chosen some form of weighted average so that all core pieces could contribute to the RQD count. At the present state of usage, however, it seems best to retain the requisite length and to note on the boring log the reason for the low RQD. Employing larger diameter drill bits, best drilling techniques, and short runs will reduce core breakage along the incipient bedding plane joints and will lead to higher, and more realistic, RQD values. Such would not apply, of course, to pre-existing bedding joints formed in nature by stress-relief and weathering.

Shale, claystones, interbedded sedimentary rocks. Five queries have been assigned to this category. There is some overlap with the previous comments. The argillaceous rocks present the most trouble because they are weak and susceptible to breakage during drilling, handling, and storage due to vibration and moisture changes. Routine drilling and logging will not give good samples or correct RQD values. The more careful

technique mentioned in the previous section must be employed to obtain optimal results.

The senior author recalls examining cores on a hydro project in Columbia many years ago. The shale cores had broken into disks (poker chips) and RQD logging appeared next to impossible. However, when going to the drill site and examining the cores as they were retrieved, the cores were seen to be intact across the lightly bonded bedding planes and the cross-cutting joints could easily be recognized. RQD logging was possible.

The applicability of the RQD to shales or claystones interbedded with hard limestone or sandstone was of common concern in several of the inquiries. This is a common condition in many parts of the United States as well as elsewhere. There is a tendency for the harder core pieces to spin on the softer shale and vice versa. Shorter runs, 2-1/2 ft. to 5 ft. (0.75 to 1.5 m), and larger core diameter usually result in improvement.

It would be of value for the different Districts that have this interbedded geology to conduct a series of field tests in which adjacent holes are drilled with variations in core diameter, run length, and drilling techniques to isolate the most important variables.

Limestone with solution cavities. Four comments dealt with this condition. The RQD should not be isolated from the site geology. The presence of a cavity within a core run should be duly recorded on the boring log. In addition to the overall RQD, partial "artificial" run lengths can be shown with the appropriate RQD for each, including zero for the cavity.

Volcanics and metamorphics. One comment dealt specifically with basalts and metamorphics, noting that these strong rock masses may receive lower ratings than they deserve because of the elimination of short core pieces. The authors agree. Rock masses that contain tight, interlocked, irregular discontinuous joints may be quite strong, impervious, and of high modulus.

At a recent project in Argentina, a wide, highly fractured zone in andesite between two small faults was questionable as a foundation for two blocks of a high concrete gravity dam because of its fractured nature (mostly small pieces in the muck pile following blasting; highly fractured appearance in-situ; and RQD of about 25 in several of the short borings that had been recently made to investigate the zone). Seismic traverses were performed and surprisingly high P-wave velocities were obtained, around 13,000 to 15,000-ft/sec. (4,000 to 4,500-m/sec.), values similar to those for the adjacent less fractured andesite that contained hard rhyolite intrusions. A closer examination was made of the highly fractured zone and it was noted to be very tight, difficult to remove with a pick, and the joints were rehealed with hard epidote coatings. The thin hard coatings were sufficient to improve the rock mass quality and make it acceptable foundation rock; the coring and the blasting, however, had broken the bonding of the joints, resulting in small pieces.

This example is one of many, no doubt, where the RQD gives values too low for the rock with respect to bearing capacity and modulus. But, for production of aggregate or riprap one might say the RQD gave values consistent for those uses.

Orientation effects (2D)

Three questions or comments were received regarding the bias in RQD that may result from differing borehole orientations with respect to joint orientation. The problem is not severe where 3 or 4 joint sets exist, although, even then, there can be some bias when the boreholes parallel one of the sets.

The major problem is created when there is a predominant joint set, such as foliation or schistosity joints in metamorphic rocks, or one or two vertical joint sets in horizontally bedded sedimentary rocks. For best results from the viewpoint of good core recovery, less breakage, and crossing the predominant joints at their true spacing, the borehole orientation should be normal to the joints. Such orientation is often not practical but an intersection of no greater than 45 degrees to 55 degrees should be attempted.

Where the intersection is at a steep angle, say 60 degrees to 90 degrees, in addition to the greater potential for core breakage, there can be a considerable bias in one of two ways. A borehole may miss the predominant jointing altogether or only cross it once or twice, leading to a higher RQD. On the other hand, the borehole may hit a joint from the beginning and follow it for a considerable distance, leading to core breakage and to no pieces of cylindrical core. So as not to penalize the rock quality too greatly, the center-line or axis measurement is recommended, as previously discussed.

A recommended procedure that has been used on more than one occasion by the writers, where a predominant joint set exists, is

to drill the boreholes at both favorable and unfavorable crossing angles so as to determine the directional bias. Notes can be added to the boring logs pointing out this fact.

Desirability of Additional Geological Observations (3)

The importance of observing and recording other rock mass characteristics was commented on by eight inquirers. The authors certainly agree that RQD does not stand alone when attempting to describe or characterize rock mass behavior (Deere, 1963). The RQD may be characterized as a simple index, analogous to the SPT blow count for soils, that has not only many useful design correlations but also many limitations.

Joint conditions (3A)

It was recognized in the development of the RQD that many of the important joint characteristics would not be included in the RQD procedure and that additional engineering geological observations and description would be necessary. The later rock mass classification systems of Bieniawski (1973) and Barton et al., (1974) do include most of the important joint characteristics, in fact, an important contribution of their systems was to provide check lists of joint characteristics to be determined from the core logging and field mapping.

Local geology, weathering, fracture frequency (3B)

The many excellent comments received on these topics speak for themselves. The RQD is only one of several tools or

techniques that help in understanding the site geology, siting structures, and selecting foundation depths or tunnel supports. It should not be used without a good knowledge of the local geology including weathering, lithology, stratigraphy, and structural features.

Applications to Engineering and Construction (4)

General (4A)

Two comments or queries were assigned to this category. One asks for revision and expansion of the RQD - Rock Quality Table to have, "...built in restrictions to prevent misinterpretation of the rock quality descriptions (very poor - excellent) for qualifying the meaning of the terms as applied to different rock types and to the design of various types of structures, tunneling, excavations and foundations."

The suggestion is good but because the two new classification systems of Bieniawski (1988) and of Barton (1988) have improved on the RQD and have more recent and more comprehensive case histories relating to various design and construction experience, it appears advisable to use their relationships.

The second comment relates to the use of the RQD as a design aid without the consideration of other factors. Certainly, the site geology with all of its pertinent factors must be considered. As noted above, the newer classification systems of Bieniawski and of Barton are recommended. They include the RQD but as only one of several other important factors.

The RQD in itself should not be modified, in the authors opinion; the usefulness of the RQD is in its simplicity. The low RQD values act as a "red flag" to the engineering geologist and rock engineer who must investigate the cause of the low values -- rock weathering, shear zone, thin bedding, etc., or poor drilling techniques. The RQD is not an end in itself but an indicator of conditions to be investigated and explained.

Excavation, dredging, underwater blasting (4B)

Three queries were received on the general subject of excavation. The RQD can not stand alone as a correlation tool with excavatability, but has been used as one of the parameters in excavatability prediction. The junior author has made his own successful predictions of excavatability on projects using: (1) RQD measured on short intervals and unconfined compressive strength for a prediction of excavatability of a slurry wall with a clamshell, and (2) the RQD, unconfined compressive strength, and seismic refraction velocity for prediction of single-tooth rippability with a D-8 dozer, all correlated by field rippability tests.

Recently, two excavatability prediction systems using RQD as a parameter have been published. Correlations have been developed using several case histories. Smith (1986) utilizes the RMR System to estimate rippability. Kirsten (1988) characterizes excavatability for trenching, digging, dozing, and ripping using a modified Q System.

For any type of underwater excavation, it is important to have a sufficient number of well controlled borings so that a realistic geologic profile can be prepared with appropriate descriptions and parameters for each geotechnical unit.

Foundations, in-situ modulus (4C)

Approximately one-third of the respondents queried the usefulness of the foundation bearing or in-situ modulus correlations with RQD. These topics are described within Part IV.

Both correlations are useful as starting points and should be utilized in conjunction with other correlations or as checks with field tests. Kulhawy's (1978) model for rock foundation settlement and Bieniawski's (1978) correlation with deformation modulus both improve on the RQD concept by including joint properties.

The senior author's primary use of RQD for foundations is for project siting when comparing depths of excavation to acceptable rock for high concrete dams.

Tunnels (4D)

In response to a query on the applicability of RQD to openings at great depths, the authors believe it is still applicable for its primary use for project siting or "red flagging" of zones of poor quality rock. Core diskings due to high in-situ stress may occur which would preclude the use of the RQD. The ratio of in-situ stress to the intact unconfined

compressive strength controls the core diskings as it would tunnel wall stability. Reference should be made to Barton (1988) for more on this topic.

Horizontal borings along the tunnel line would be most helpful in intersecting the steep structural features of shears, faults, and closely jointed zones and allowing the RQD to be determined for each. During the construction of several tunnels horizontal "feeler" or probe holes have been drilled from the face of the tunnel to give advance warning of weak zones and any contained groundwater.

Occasionally, horizontal holes from the tunnel portal area have been drilled during the exploratory phase. For practical purposes, however, most of the exploratory drilling for tunnels will be vertical with some angled holes to cross suspected weak fractures and to give a 3-dimensional picture of the bedding and the jointing.

Erosion resistance, roughness coefficient (4E)

Two interesting questions were received regarding erosion of rock masses caused by flowing water in hydraulic tunnels and in channels. The senior author has inspected numerous unlined diversion tunnels, pressure tunnels, trailrace tunnels, and rock channels after a few months to a few years of operation.

Pressure tunnels have low flow velocities of perhaps 13 ft. to 16 ft. (4 m to 5 m) per second maximum and fair to good quality rock has resisted erosion very well. In these cases the zones of weak and heavily fractured rock and shear zones had been

protected by concrete or by reinforced shotcrete and rock bolts. Diversion tunnels during flood will be subjected to higher velocities, perhaps 36 ft. to 46 ft. (11 m to 14 m) per second, and some erosion has been noted in both the invert and lower side walls in unprotected weak zones and heavily fractured zones. Similar velocities and even higher may occur in spillway channels; weak zones have been eroded considerably (schistose zones, within a more massive gneiss in one case).

While the RQD can be helpful in detecting the presence of the weak zones and in delineating the more massive rock areas, it probably can do no more than could good engineering geology descriptions in predicting erodibility or roughness.

General Usefulness of RQD (5)

Many comments were received on both the favorable experiences and the shortcomings of the RQD. This discussion summarizes the comments received and attempts to place the use of the RQD in perspective.

Favorable experience (5A)

Three comments were singled out from the responses that specifically indicated the RQD has been helpful. One comment noted that the index had been found to be a practical parameter for estimating rock core quality and no problems had been experienced with its application as an engineering index. Another, while noting its shortcomings, felt that it had allowed coordination of the nature of the rock mass to engineering

characteristics in a quick and simple manner -- and any modification that would detract from its simplicity would be a disservice. And, further, "...What the RQD system does is add the experience factor for the inexperienced people." A third comment noted that the RQD was one tool available, like other index properties, for the evaluation of rock behavior in various engineering applications.

The authors believe that the usefulness of the RQD can be divided into these basic categories:

- o The "Red Flag" effect. The RQD directs the attention of the engineering geologist and design engineer to areas of rock with poor engineering properties. These are areas that may control the design of a project and should be avoided or have sufficient means available to cope with them.
- o Design guidance. Correlations of RQD with rock properties and project performance provide preliminary design guidance for structures on rock.
- o Stimulation of profession. The RQD was developed at a time when the field of Rock Mechanics was in its infancy. RQD helped focus the attention on the importance of rock weathering and discontinuities and on obtaining information from rock cores regarding them. The RQD concept stimulated others, no doubt, to related studies of fracture frequency, scan-line surveys, and to the development of modern engineering classifications systems.

Shortcomings, limitations (5B)

The shortcomings and limitations of the RQD were popular subjects and 10 comments or queries specifically addressed this (See Appendix). The authors appreciate the many thoughtful comments that were presented in the letters and are in general agreement with the majority of them.

Perhaps the most common complaint was not against the RQD per se but the manner in which it is often used in design as the sole parameter without considering the geologic details and the overall geologic evaluation of the site. Certainly, the core logging should be done at the site by a qualified engineering geologist or geotechnical engineer at the time of the drilling and not left to the driller or technician, or done in the laboratory days or weeks later after the core has been transported, dried, stress-relieved, and otherwise disturbed.

The structural, hydraulic, or highway design engineer could well misuse the correlation tables without the input of the engineering geologist, geotechnical engineer, or rock mechanics specialist who has knowledge not only of the critical geologic details but also of the precedent in engineering design and construction. The RQD can not stand alone. Its inclusion into the later classification systems that include other geological factors (Barton, 1988; Bieniawski, 1988) was a logical progression in use.

One comment noted that the RQD was not very helpful in selecting foundation depth in weathered rock. This experience is contrary to the authors' experiences where such application has

had excellent results (Deere and Deere, 1988), not only for foundation depth but also for tunneling and selection of dam excavation depths.

A few comments dealt with the simplicity of the method, which is both favorable and unfavorable, and the misuse that may result from the qualitative terminology of good, fair, etc., that may not always apply to the specific site or a specific engineering problem. The authors agree and recommend that the more comprehensive classification systems noted above be applied -- as they are developing a good base of case histories.

PART VII: CONCLUSIONS

Twenty years' experience with the RQD logging and application of the RQD index to engineering has been discussed in the previous parts of this report. The main conclusions may be summarized as follows:

1. Core diameters for RQD logging should normally be of NQ or NWX (NWM) size; for weak argillaceous or foliated rocks, larger sizes are preferred; and the smaller BQ and BWX sizes should be discouraged and; when used, should be identified with a disclaimer.
2. Length measurements of the core pieces should be made along the centerline (axis) as advocated by the ISRM (1978, 1981); core breaks caused by drilling and handling should be fitted together and counted as one piece; and the requisite length should be retained as 4-in. (100 mm) for all size cores.
3. Fresh and slightly weathered rock should be used in the RQD count; moderately weathered rock that resists hand breakage should be included but an asterisk used with the RQD (RQD*); and highly weathered rock (that breaks under hand pressure), completely weathered, and residual soil should not be included.
4. Length of coring run ideally should be 5 ft. (1.5 m) but realistically may be longer or shorter; for good quality rocks which give 100 percent core recovery, 10-ft. (3-m) runs are acceptable; for difficult

schistose, laminated, soft and hard interbedded, and rocks with unfavorable joint or bedding orientations, short run lengths of 2-1/2 ft. to 5 ft. (0.75 to 1.5 m) or less are recommended; short "artificial" run lengths, or intervals, may be created when logging the core to identify zones of vastly different RQD.

5. RQD correlations with tunnel support requirements, in-situ modulus, allowable bearing pressure, and fracture frequency are available in the literature, some of which have been included herein; these are still considered helpful in preliminary studies. Perhaps the most important use of the RQD in practice is in early delineation or "red flagging" of zones of poor rock.
6. More recent classification systems (Bieniawski RMR, Barton Q) have included the RQD together with other parameters that broaden the scope and more closely define the rock quality for engineering purposes; these have gained international acceptance and are recommended herein.
7. Pertinent questions and comments regarding the RQD logging procedures and utilization within the various Districts and Divisions of the US Army Corps of Engineers have been reviewed and discussed under five categories; many of the concerns were the same as those noted in the first six conclusions herein; of particular concern were the additional topics: first, the need for drilling supervision and prompt logging in

the field by a qualified engineering geologist or geotechnical engineer of cores obtained by the best drilling equipment and techniques; second, the possible misuse of RQD in design by using it as the sole parameter without the necessary geological and geotechnical input; and third, the difficulties of obtaining intact cores and reliable RQD values in shales and in interbedded hard and soft rocks.

8. A research program is recommended wherein the Corps of Engineers does comparative studies in bedded soft and hard rocks of recoveries and RQD's in adjacent borings drilled at differing angles, core sizes, lengths of drill run, and drilling techniques.

The authors acknowledge the interest, questions, and comments of the users of the RQD in the various Districts and Divisions of the US Army Corps of Engineers which have helped in focusing on critical issues.

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APPENDIX A

**COMMENTS AND QUESTIONS ON THE RQD
FROM THE US ARMY CORPS OF ENGINEERS**

APPENDIX A

COMMENTS AND QUESTIONS ON THE RQD FROM THE U.S. ARMY CORPS OF ENGINEERS

CONTENTS

1. MECHANICS OF DETERMINING RQD
 - 1A. CORE DIAMETER
 - 1B. LENGTH MEASUREMENT OF THE CORE PIECES
 - Position of the Measurement
 - Core Length of Twice the Diameter
 - Distinguishing between Natural and Induced Fractures
 - 1C. LENGTH OF CORING RUN AND RQD INTERVAL
2. SPECIAL RQD LOGGING PROBLEMS
 - 2A. DRILLING EQUIPMENT AND TECHNIQUES
 - 2B. PROMPT LOGGING OF CORES
 - 2C. APPLICABILITY TO VARIOUS ROCK TYPES
 - Problems
 - Shale, Claystone; Interbedded Sedimentary Rocks
 - Limestone with Solution Cavities
 - Volcanics and Metamorphics
 - 2D. ORIENTATION EFFECTS
3. DESIRABILITY OF ADDITIONAL GEOLOGICAL OBSERVATIONS
 - 3A. JOINT CONDITIONS
 - 3B. LOCAL GEOLOGY, WEATHERING, FRACTURE FREQUENCY
4. APPLICATIONS TO ENGINEERING AND CONSTRUCTION
 - 4A. GENERAL
 - 4B. EXCAVATION, DREDGING, UNDERWATER BLASTING
 - 4C. FOUNDATIONS, IN-SITU MODULUS
 - 4D. TUNNELS
 - 4E. EROSION RESISTANCE, ROUGHNESS COEFFICIENT

5. GENERAL USEFULNESS OF RQD

5A. FAVORABLE EXPERIENCE

5B. SHORTCOMINGS, LIMITATIONS

1. MECHANICS OF DETERMINING RQD

1A. CORE DIAMETER

Question

- 1A 1: RQD was based upon use of NX, double tube, core sampling which has not been used by Mobile District for a number of years. Has any correlative work been done between NX, NQ wire line and/or other sizes and types of sampling?
- 1A 2: Is it valid to apply RQD to cores greater than NX-size by increasing the length of core used in determining the Modified Core Recovery to twice the core diameter (i.e., count only 12-inch long pieces for 6-inch diameter core)?
- 1A 3: Are RQD values applicable to other than NX size core?
- 1A 4: RQD is based on NX core - how can RQD be used, measured, correlated on larger or smaller diameter cores?
- 1A 5: I would like to see the RQD table revised by including information on applying this system to different rock lithology, in-situ geology, core size, etc...
- 1A 6: ...It does not provide for core diameters larger or smaller than NX and does not give an indication of highly fractured zones within core runs...
- 1A 7: ...In recent years, this District has utilized 4" core barrels almost exclusively though we are now making considerable use of HQ wire line equipment. Due to the nature of our rocks, highly fractured in Puerto Rico and weak limestones in Florida, we do not use NX size core equipment. When the question arose among field geologists as how to measure fragment length in core other than NX, we decided to piece the core run together and use the top center of core as a reference line. It was apparent we could not measure the long or short side of individual pieces and have a direct correlation between 4" and NX core. We decided a center reference line would produce a medium length width would be representative regardless of the core diameter...
- 1A 8: The "Geotechnical Handbook" being prepared should include a discussion comparing RQD values taken on similar rock, but cored with a different size or type of core barrel. I have been told that Dr. Deere intended RQD's to be used with only NX size cores. Several texts discuss the determining of RQD values on

core 50 mm and larger. As you know a larger diameter core results in better core recovery and in most cases a higher RQD values.

- 1A 9: Can RQD be reasonably extended to core sizes other than NX? If so, which ones and why, or why not?
- 1A 10: Is there any experience of relating RQD to diameter of the core. It is our understanding that RQD was developed for NX core and length of solid core divided by the core diameter equal to 2. With 3-inch core this would result in RQD based on solid pieces being 6 inches rather than 4 inches as in NX core. It is believed that common practice is to using four inch solid pieces in all core sizes. This should be clarified.
- 1A 11: RQD is of extremely limited use in today's core drilling work when NX is only one of the choices for processing the work in the most cost-efficient and/or highest rock recovery/quality manner. More and more we are using wire line systems. Will this re-study address correlations of RQD to other sizes of core besides NX? In particular, correlation should be made for large diameter (4", 2-3/4") as well as wire line sizes such as PQ, HQ, etc. and triple tube c.b.
- 1A 12: One of the major drawbacks of RQD is its relationship to core size, i.e., the larger the core diameter, the smaller the RQD. To be useful as a true index property of a rock mass, RQD should be independent of hole size. Can compensation be made for this problem?
- 1A 13: ...We have had much discussion recently about the definition and use of RQD, and we would like to relay our feelings on the following three areas: (1) As we understand it, RQD is calculated counting only those pieces of drill core greater than 4 inches in length. This does not seem to be the appropriate method since it is not a true reflection of the condition of the rock mass in place; (2) the use of RQD by the Corps of Engineers is confined only to NX core. This is very restrictive since a major portion of the drill holes in the Northwest are larger diameter (HQ) than NX...

1B. LENGTH MEASUREMENT OF THE CORE PIECES

Question

Position of the Measurement:

- 1B 1: Measuring RQD needs clarification - where on core?

1B 2: ...When the question arose among field geologists as to how to measure fragment length in core other than NX, we decided to piece the core run together and use the top center of core as a reference line. It was apparent we could not measure the long or short side of individual pieces and have a direct correlation between 4" and NX core. We decided a center reference line would produce a medium length which would be representative regardless of the core diameter...

1B 3: Fractures parallel to the axis of coring need to be accounted for. TVA uses the rule that if a section of core is split into two longitudinal halves of length "x" that is more than 4" in length, the value of x/2 is counted in the summation of intact pieces of core.

Core Length of Twice the Diameter:

1B 4: Is it valid to apply RQD to cores greater than NX-size by increasing the length of core used in determining the Modified Core Recovery to twice the core diameter (i.e., count only 12-inch long pieces for 6-inch diameter core)?

1B 5: Is there any experience of relating RQD to diameter of the core? It is our understanding that RQD was developed for NX core and length of solid core divided by the core diameter equal to 2. With 3-inch core this would result in RQD based on solid pieces being 6 inches rather than 4 inches as in NX core. It is believed that common practice is to use four solid pieces in all core sizes. This should be clarified.

1B 6: Based on the original data available, the 4-inch core length was adopted for RQD determinations. Does the data from the last 20 years support this, or would some other length be better?

1B 7: ...If the RQD of the core is measured using only natural breaks, it should be close to the value obtained using downhole photographic methods... Many of the drill holes presently drilled here in the Northwest are HQ-sized which, by the Corps of Engineers' policy, cannot be used in the calculation of RQD. If the above method of calculating RQD were to be used, there would be no difference in the results of calculations made in NX holes or 6-inch holes since they are both a measure of what is in the ground. The present method of RQD calculation would probably arrive at different values because of differing mechanical stresses on the drill core during drilling causing

differing degrees of breaks along healed fractures, bedding planes, or foliations. Again, counting only

those naturally occurring breaks allows any size of drill hole to be used in the calculation of RQD.

Distinguishing Between Natural and Induced Fractures:

- 1B 8: Clarification on natural vs. mechanical break needed.
- 1B 9: Are there techniques other than fitting core pieces, which can be used by a field geologist or technician, to differentiate between natural (in-situ) separations and drilling induced separations in shales or shaley siltstone, sandstone sequences? This determination is vital to an accurate definition of the RQD.
- 1B 10: Stress relief discing of deep cores does occur. Stress relief discing is a larger problem with smaller cores than with larger cores. Stress relief discing should not be included in RQD counts of core breaks. Some geologists could confuse discing as joints. Some guidance on field logging techniques would be helpful.
- 1B 11: The definition of RQD, according to Technical Report GL-85-3, Geotechnical Descriptions of Rock and Rock Masses, is a method used to describe the condition of the rock mass from core borings. It is assumed that the condition of the rock mass refers to those naturally occurring breaks and fractures within it. This is not what is described when the RQD is calculated counting only those pieces of core greater than 4 inches in length. In describing the rock mass in-situ, one has to look at only the spacing between the unhealed fractures in the rock mass intersected by the drill hole. If the core could be obtained without the mechanical forces that drilling and handling places on the core, the only breaks would be the open and closed fractures and shear zones for faults. None of the healed fractures would be broken and bedding of foliation parting would not take place as occurs during normal drilling operations. The RQD would then be the measure of all the cores containing natural breaks with spacings of 4 inches or greater. This is a concern in the Walla Walla District because an RQD measured looking at the core differs greatly from a RQD measured downhole with the NX borehole camera, or the borehole analysis package. If the RQD of the core is measured using only natural breaks, it should be close to the value obtained using downhole photographic methods.
- 1B 12: In the New York District rock drilling is mainly limited to the first 5 feet encountered during shallow borings. As a geologist who subsequently examines rock core, I have found that general rock descriptions, of which RQD's are not always given, can often underestimate the rock quality, due to the difficulty for

inspectors in distinguishing between natural and mechanical breaks. The Districts can be faced with claims for excavating equipment not being able to remove "highly fractured" rock. Consequently I would appreciate it if Dr. Deere would consider this problem in his evaluation of RQD and possible ways to avoid it.

I am familiar with the different rock coring methods and ways that core can be broken mechanically. I at times have trouble identifying natural breaks but can usually eliminate 3/4 of the breaks as mechanical. Besides odd fractures I do not include tight fractures which were opened by the coring process.

I have recently completed a 1-1/2 year deep-hole coring program along a proposed flood diversion tunnel for the Passaic River Basin in New Jersey. It is the first time in recent years that extensive rock coring has been done in the New York Districts. Rocks encountered were shale and sandstone with 10°-20° bedding joints and basalt with 10°-20° stress release and 80°-90° columnar joints. I took RQD values for only the 3 tunnel diameter zone which was usually at least 100 feet below the rock surface. The rock quality was good to excellent though the cores themselves were highly fractured. Fortunately because of the rock quality, after eliminating mechanical breaks, I estimated the RQD for most cases without measuring the rock core. One day the consultants who were going to get the rock data came out to inspect the drilling. They were shocked to look at a highly fractured 10 foot core and hear me give it a 95% RQD value. Another case of not being able to detect the mechanical breaks. To satisfy myself and reassure the consultants I made some graphs for the GDM report using my drilling logs and downhole camera photographs of undisturbed rock. Bill Tanner's camera from the Southwestern Division lab was used mainly to determine structures yet individual natural fractures were also detected on the film.

Enclosed are copies of my graphs. I first totalled the joints from both data sources and divided them into 10° intervals. As you can see I missed many natural breaks (400). Part of the large discrepancy can be attributed to my not logging each joint from a highly fractured (ex. 2 joints per inch) zone on my drilling logs. The percentage of missing joints can not be determined.

The enclosed graph comparing the undisturbed rock data (photography) and the disturbed rock data (core logs) show that the addition of missing natural breaks does not reduce the RQD values. Instead, for the most part, the undisturbed rock had higher RQD values than I determined. The missing natural breaks add an average

of 1 joint per 11 feet which does not reduce RQD values based on RQD measuring requirements eliminating rock core less than 4 inches.

1C. LENGTH OF CORING RUN AND OF RQD INTERVAL

Question

- 1C 1: Only one question really comes to mind, did Dr. Deere have any set dimensions such as core run, footage of core box or total core hole footage for computation of the index? For convenience and uniformity of intervals, we used the total footage of a core box to determine RQD.
- 1C 2: Clarification needed if RQD should be measured as a % over every 5 feet, 10 feet, length of run, core box, etc.
- 1C 3: No guidelines are uniformly followed in selecting intervals for reporting RQD. For example, arbitrary and varying lengths of core run up to 10 feet may be given an average RQD. An average RQD of 50 over 10 feet does not satisfactorily reflect field conditions where the upper 5 feet of rock has an RQD of 0 and the lower 5 feet has an RQD of 100. Where abrupt changes occur in rock quality, RQD values should be reported separately for each interval.
- 1C 4: Since RQD is based on the total length of rock drilled, the results are affected by the quality of not only the rock but also the drilling process. Inappropriate bit types, feed rates, water pressures, barrel adjustments, core size and other factors can greatly affect the percent rock recovered and its condition. These influences are particularly problematic in shales . . . RQD could be based on the length of core recovered; however, the wealth of experience and "feel" for ranges would be jeopardized by such a change.
- 1C 5: . . . We follow the guidelines in the South Atlantic Division Geotechnical Manual which is as described by Dr. Deere in his original paper. We divided the total length of sound, fresh pieces of rock over 4" long recovered during the run by the length of the run. The contractor's position was that you should only use the length of the run in rock not total run. Our position was, and still is, that unless you get 100% recovery (uncorrected) you have no way to know what was "soil" or what was "rock". I use the quotes because in our case it was not a soil in the true meaning, but rather a soft zone or layer of unconsolidated material within harder, consolidated layers. Using the contractor's technique, losses experienced were considered "soil"

and all soft zones were also called "soil". In effect you always get 100% recovery (uncorrected) in "rock".

Your RQD's are then computed based on this total length, counting all pieces 4" or longer in length. It naturally results in a much higher RQD.

2. SPECIAL RQD LOGGING PROBLEMS

2A. DRILLING EQUIPMENT AND TECHNIQUES

Question

- 2A 1: A factor that seems to be ignored in the application of RQD is the skill of the drill operator. This seems to be an important factor. How should it be evaluated?
- 2A 2: Since no two drillers, rigs or equipment will produce the same results in sampling identical materials, what "Mickey Mouse" factor(s) are to be applied to provide comparable data? . . . The bit type, "stone" size and distribution, rotational speed, tool weight, drilling fluid type, pressure and volume, core barrel length, use of drill collars and or "trash baskets" and length of core runs are also factors which contribute to recovery and condition of samples.
- 2A 3: Since RQD is based on the total length of rock drilled, the results are affected by the quality of not only the rock but also the drilling process. Inappropriate bit types, feed rates, water pressure, barrel adjustments, core size and other factors can greatly affect the percent rock recovered and it's condition. These influences are particularly problematic in shales.

2B. PROMPT LOGGING OF CORES

Question

- 2B 1: If the sample condition is not observed upon removal from the core barrel, during handling and boxing and immediately logged by a qualified person, the data presented may be far from the original characteristics. We often have core samples which are not logged until after transportation and sometimes days or weeks after obtained.
- 2B 2: In the Huntington District, we work almost exclusively in thin-bedded sedimentary shales and sandstones. We have found, particularly in shales, that RQD becomes dependent on drilling techniques, core handling and rapid deterioration due to fissility. We feel that RQD is, at best, only a vary general indicator of quality for shales, indurated clays and poorly consolidated claystones.

2C. APPLICABILITY TO VARIOUS ROCK TYPES

Question

General Problems

- 2C 1: ...I would like to see the RQD table revised by including information on applying this system to different rock lithology, in-situ geology, core size, etc...
- 2C 2: Has sufficient experience developed to indicate that RQD is more or less applicable to different rock categories - igneous vs. sedimentary vs. metamorphic - or even within a given category, i.e., shale vs. sandstone vs. limestone?
- 2C 3: The following would all tend to reduce the RQD: foliated zones, fault zones, shale, cavernous limestone, and thinly bedded competent rocks such as limestone. Although the rock units above and below the above-mentioned zones may be of substantial strength and competence, the RQD would appear low. Would it be possible to increase the RQD based on each in-situ case?
- 2C 4: RQD does not distinguish between fractures, broken rock, and thin interbedded formations with minimal fracturing and weathering if the beds are less than 4 in. thick.
- 2C 5: Should there be a way to account for influence of features such as bentonite seams in shale or micaceous layers in igneous rocks, which are intact but represent definite planes of greatly reduced strength, using RQD.
- 2C 6: Several problems have been encountered in the field application of RQD during core logging:
- a. Difficult to use in soft rock formations where drilling action causes separation along incipient fracture planes.
 - b. Weak, brecciated-type rocks often don't break along natural fractures, and therefore, rate high in RQD when in reality they are often very poor in rock mass quality.

Shale; Claystones, Interbedded Sedimentary Rocks

- 2C 7: Are RQD values applicable for soft rock cores such as compaction type clay shales or in interbedded clay shale and harder limestone?

- 2C 8: The Vicksburg District has not used the RQD method and does not anticipate having to work in an area where it can be utilized anytime in the near future. The Vicksburg District has worked with RQD information gathered by other districts and was of the opinion that it was inappropriate due to the soft nature of the rock.
- 2C 9: Very little documentation is available regarding RQD, application in various rock types. For example, thin bedded limestone or even massive soft shale may have similarly poor RQD values or opposite RQD values depending upon when the shale is logged or who logs it. QUESTION: Can more specific guidance be provided for this aspect?
- 2C 10: The original correlations did not include weak rocks such as some sandstones and shales. Can correlations for these now be developed?
- 2C 11: Irrespective of the potential misuse of RQD, the procedure itself has some inherent problems. For certain types of lithology, the use of RQD can result in a gross misunderstanding of the engineering properties of the rock in-situ. Particularly troublesome are the thin-bedded shaley limestones common to much of Middle Tennessee, for example. Many of these rocks, even though cored by experienced drillers, tend to break along shaley laminations which cannot be reliably designated as in-situ or drilling-induced to the extent that RQD for any length of core run will be very low. The erroneous implication then being that the rock is of poor engineering quality. However, the presence of lamination in the bedrock does not significantly influence the capability of these rocks to sustain very high compressive loads. Owing to the high degree of anisotropy in the mechanical properties of these types of rock, reliance on the RQD to any degree can be highly misleading in making an engineering evaluation.

Limestone with Solution Cavities

- 2C 12: In addition, solution activity in carbonate rocks often produces cavities and corresponding low RQD's and core recoveries. However, if the cavities are isolated and surrounded by hard continuous limestone, the low values may misrepresent the quality of the continuous rock for support of loads.

For these reasons, an alternate parameter such as fracture frequency can be a better indicator of rock quality than RQD.

- 2C 13: Weathering features such as solutioning and open seams, voids, mud seams, etc. can not be distinguished from fracturing or thin bedding.
- 2C 14: Another problem with using RQD to describe the engineering qualities of limestone or other soluble bedrock is that the RQD procedure does not consider the impact of the thickness or location of cavities within the bedrock mass on its structural integrity. For instance, a ten-foot run of core that is essentially sound except for a two-foot thick void in the middle of the run would have an RQD of 80%, which is described as "good." In this case, even though the majority of the rock is hard and competent, the presence of a void comprising twenty percent of the mass cannot be overlooked. In fact, it is the nature and location of the void, not the condition of the recovered core, that would be the most important issue affecting the engineering properties of that bedrock.
- 2C 15: In addition, solution activity in carbonate rocks often produces cavities and corresponding low RQD's and core recoveries. However, if the cavities are isolated and surrounded by hard continuous limestone, the low values may misrepresent the quality of the continuous rock for support of loads.

For these reasons, an alternate parameter such as fracture frequency can be a better indicator of rock quality than RQD. RQD could be based on the length of core recovered; however, the wealth of experience and "feel" for ranges would be jeopardized by such a change.

More practically, it may be valuable to simply note the conditions which can affect RQD and suggest the use of another parameter if conditions are suspect.

Volcanics and Metamorphics

- 2C 16: Problems have been inherent with the system since its inception and prevent our wholehearted adoption. First, the elimination of short core pieces from determining rock quality causes some strong rock masses, such as, basalt and metamorphics to receive lower ratings than they deserve. Good examples are the local diced basalt units which stand in vertical cliffs (even overhanging) due to the irregular nature of the fracture planes.

2D. ORIENTATION EFFECTS

Question

- 2D 1: Drill hole orientation can, and often does, result in considerable bias in the RQD values, i.e., holes that parallel major fracture sets could indicate a misleading high RQD value. How can this shortcoming be addressed?
- 2D 2: There is a difference in RQD based on the orientation of joints and bedding in relation to the bore hole. Is there some correlation that can be used or should the procedure contain some warning.
- 2D 3: How can RQD measurements on core from vertical borings hope to give an accurate prediction of the effects of vertical and high angle joints on the engineering properties of a rock mass?

3. DESIRABILITY OF ADDITIONAL GEOLOGICAL OBSERVATIONS

3A. JOINT CONDITIONS

Question

- 3A 1: Continuity, planarity, mineral alteration along joints and shear planes are properties of rock discontinuities that have primary affect on rock mass properties. RQD frequently does not reflect these important features.
- 3A 2: There should be some way to connect RQD to fracture roughness or infillings, such as clay, etc. How can RQD reflect the significant contribution of fracture nature toward overall rock mass quality?
- 3A 3: Will RQD systems, such as rock mass classifications, be expanded - will joint conditions, joint sets, water, etc. have an increased role?

3B. LOCAL GEOLOGY, WEATHERING, FRACTURE FREQUENCY

Question

- 3B 1: In regard to your inquiry about our use of RQD measurements, we use it routinely in core drilling. However, I do not think it is useful in our practice. Generally, I am trying to estimate the average depth of weathering into rock for foundation design and cost estimating. That usually involves looking at each core carefully and trying to pick the depth where any significant rock weathering stops. RQD does not help much in that regard.
- 3B 2: We have found that RQD, although a neat number to calculate, is not always the best method to use in evaluating the drill core. RQD is not meant to be a stand alone method of evaluating core and is best used in the calculation of geomechanical properties of rock masses. For other situations a fracture frequency plot of the core is more useful since one can visually see at once where the fractured areas occur in the drill hole. We also make a fracture frequency plot of the healed fractures, since they are typically healed with chlorites and tend to part when excavated, as a part of the evaluation for possible quarry material.
- 3B 3: Anyone who uses RQD as a tool to understanding the engineering properties of bedrock must also understand the limitations inherent in such a simplistic approach to assessing the engineering properties of bedrock. When considered by itself, outside the context of the local geology, i.e., the lithology of the rock, the geologic structure of the bedrock and the potential

influence of bedrock weathering, RQD becomes a meaningless number. Deere (1968)* certainly recognizes the limitations of the RQD system and the necessity for considering the overall geology of a site when designing engineering projects that interact with the bedrock. Therefore, to be properly used, RQD must be considered as only one small part of the overall geologic evaluation and cannot be used as the sole basis for determining the engineering qualities of bedrock.

3B 4: ...Most of my experience with the use of RQD has been favorable but I have noticed through the years an increase in the misuse and misinterpretation of the system by engineers not trained in the geotechnical field. As most of us know, the RQD method is one of many tools which must be used with other factors to determine the suitability of the total rock mass. There is a growing number of engineers and architects (structural and highway) that have locked on to the RQD table without regard to the many factors that went into the system or the many geological conditions that must be considered when designing foundations, tunnels, or excavation slopes.

An increasing number of firms are using inexperienced core drill inspectors who are not trained in good descriptive logging techniques which results in poor rock descriptions and total dependence on RQD values. I suspect the AE regards the RQD method as a panacea to the rising cost of detailed geotechnical investigations and rock testing.

3B 5: ...We do not require use of the RQD system, but many of our geologists use it because of certain benefits. We do not mind the use, as long as additional information which is not provided by the RQD is given in their logs or reports. Its benefits are simplicity as a logging tool, universal fame and published correlation charts containing engineering design parameters, such as, modulus, shotcrete thickness needed, etc.

* References in this appendix can be found at the end of the main text.

4. APPLICATIONS TO ENGINEERING AND CONSTRUCTION

4A. GENERAL

Question

- 4A 1: I would like to see the RQD table revised by including information on applying this system to different rock lithology, in-situ geology, core size, etc. The table should have built in restrictions to prevent misinterpretation of the rock quality descriptions (very poor-excellent) by qualifying the meaning of the terms as applied to different rock types and to the design of various types of structures, tunneling, excavations and foundations.
- 4A 2: RQD is a tool that has been widely used. It can also be misused by the fact that a lot of design aids have been developed using RQD along with other information on rock properties. With these aids some designers can take RQD alone to use in design. A discussion on the intended use and limitations should be included if a report is prepared.

4B. EXCAVATION, DREDGING, UNDERWATER BLASTING

Question

- 4B 1: I would appreciate it if you would include among your questions to Dr. Deere whether he has had any experience in correlating RQD values with the use of particular kinds of capacities of excavating and dredging equipment (backhoe, clamshell, dipper, dredge, etc.) without blasting.
- 4B 2: May I add for underwater blasting. Please add it to my previous submission.
- 4B 3: We would like Dr. Deere's thoughts on the utility of RQD in determining rock excavatability for both dredging projects and surface construction projects.

4C. FOUNDATIONS, IN-SITU MODULUS

Question

- 4C 1: Some propose the use of RQD to arrive at allowable bearing values for foundations bearing in bedrock. Are such methods realistic or valid?
- 4C 2: It is our understanding that RQD was originally developed as a method for tunnel design evaluations. Over the past several years, it has become a generic guide to rock foundations quality. As such, RQD is now

being applied to all types of foundation design by some. At the present time, it is assumed that the use of the RQD value by the engineer/geologist is based on experience together with other known parameters or when correlated to allowable contact pressures as referenced in Table 22.2 of Peck, Hanson and Thorburn, "Foundation Engineering" and other rock quality indices. However, when supplied to an unknowing or inexperienced engineer or contractor who looks at the RQD recorded on a raw boring log, the resulting interpretation can be misleading. QUESTION: Can the method of describing the rock core be modified or the quality designations be better defined for specific uses?

- 4C 3: In summary, RQD serves a purpose and can be a useful tool to describe certain properties of rock core. However, its design application is severely limited. The fact that RQD is correlated with such terms as "excellent", "good" and "poor", and is sometimes even correlated with allowable bearing capacities (Peck, Hansen, Thornburn, 1974), affords much opportunity for its misuse. Designers must not rely on RQD alone as a basis for foundation design decisions. At best, it can only serve as a tool of limited use in the assessment of the engineering qualities of bedrock.
- 4C 4: The original correlations between RQD and rock modulus or deformation ratio did not appear to be exceptionally good. Does more data verify these correlations or do they need revision?
- 4C 5: RQD is an index of in-situ rock quality, but the information provided by it affords only a rough qualitative measure of rock quality. Attempts have been made to relate RQD with modulus of deformation of rock mass, but the procedure ignores many factors which control the deformation modulus. Therefore, a large number of engineers consider the RQD method of evaluating rock mass modulus unreliable. Is it safe to use the deformation modulus determined by the RQD method for stability analysis of structures on rock foundations?
- 4C 6: The deformation modulus of rock mass not only depends upon the number of discontinuities, but also on their characteristics. RQD does not provide information as to these characteristics; therefore, it is not appropriate to correlate the RQD in its present form with deformation modulus of rock mass. Can the form of the RQD be changed to include the characteristic of discontinuities?
- 4C 7: To perform stability analysis of concrete structures on rock foundations, deformation moduli of rock mass in

three mutually perpendicular directions are required. In addition, shear moduli in these directions are also required. The RQD method provides deformation modulus only in the vertical direction. Can this method be extended to determine modulus in horizontal direction and shear modulus in three mutually perpendicular directions?

- 4C 8: The correlations between a modulus reduction factor and RQD established by Dr. Deere is based on limited field data and it has many shortcomings; i.e., it is not applicable for RQD less than 57 and it is not realistic to use this correlation for rock mass where discontinuity characteristics are significantly different from those in the Deere's correlation. Is it possible to make the correlations realistic by incorporating field test data gathered from sources with different discontinuity characteristics?

4D. TUNNELS

Question

- 4D 1: Has sufficient evidence emerged to recommend RQD applications or interpretations for very deep problems, e.g., for rock openings at depths of the order 1,000 meters (as opposed to 10 or 100 meters)?
- 4D 2: Some engineering geologists have expressed the idea that RQD, when applied to tunneling, should be determined from horizontal holes. Is this correct?
- 4D 3: We have used the RQD index two or three times in past years to determine an appropriate tunnel support system. The index was required for analyzing rock mass behavior with both the Rock Structure Rating Concept and Bieniawski's Geomechanics Classification. These qualitative studies have proved to be a very useful way to describe rock mass quality in addition to practical experience.

4E. EROSION RESISTANCE, ROUGHNESS COEFFICIENT

Question

- 4E 1: A question that seems to come up often on both open channel and tunnel excavations in rock is how to assess the rock in such excavations for its durability against erosion under various velocities of streamflow. The question we propose is: "Can RQD be used as an indicator of the durability of rock against streamflow erosion?" Additionally: "Can RQD be used to predict the maximum stream velocity a rock mass can withstand?"

4E 2: Another problem that seems to come up is on how to estimate the roughness coefficient used in Manning's equation for determination of discharge in an open channel. The problem with an open channel in bedrock is on how to predict what this value might be due to all the variables such as degree of weathering, amount and orientation of discontinuities, etc. Can RQD be used in some way to help estimate what the value of the roughness coefficient may be?

5. GENERAL USEFULNESS OF RQD

5A. FAVORABLE EXPERIENCE

Question

- 5A 1: No problems have been experienced with the application of RQD as an engineering index. In fact, in the use for which it was intended, we have found the index to be a practical parameter for estimating rock core quality.
- 5A 2: These remarks are not intended to belittle the usefulness of the RQD system, but to point out its shortcomings in practical work. The system has allowed coordination of the nature of the rock mass to engineering characteristics in a quick and simple manner. Any modifications that detract, very much, from its simplicity would be a disservice. After all, the natural occurring features of a rock mass are quite simple and easy to note and provide the basic data needed for just about any analysis. When experience in engineering characteristics is added, you have all that is necessary. What the RQD system does is add the experience factor for the inexperienced people. Of course, it does it well, because it draws on a broad experience base.
- 5A 3: Like many other index properties, RQD appears to be one tool available for the evaluation of the behavior of rock in various engineering applications. This new study should set RQD in its proper perspective, including where and how it should be used, and where and how it should not be used.

5B. SHORTCOMINGS, LIMITATIONS

Question

- 5B 1: ...We also found during our survey that some of the largest companies did not use RQD unless specifically requested by their clients. This was due largely to the problems with the method as derived in the field and also with its use in design. Many engineers apparently will design based strictly on the RQD number without regard to other factors.
- 5B 2: ...Most of my experience with the use of RQD has been favorable but I have noticed through the years an increase in the misuse and misinterpretation of the system by engineers not trained in the geotechnical field. As most of us know, the RQD method is one of many tools which must be used with other factors to determine the suitability of the total rock mass.

There is a growing number of engineers and architects (structural and highway) that have locked on to the RQD table without regard to the many factors that went into the system or the many geological conditions that must be considered when designing foundations, tunnels, or excavation slopes.

An increasing number of firms are using inexperienced core drill inspectors who are not trained in good descriptive logging techniques which result in poor rock descriptions and total dependence on RQD values. I suspect the AE regards the RQD method as a panacea to the rising cost of detailed geotechnical investigations and rock testing.

5B 3: RQD is a tool that has been widely used. It can be misused by the fact that a lot of design aids have been developed using RQD along with other information on rock properties. With these aids some designers can take RQD alone to use in design. A discussion on the intended use and limitations should be included if a report is prepared.

5B 4: We have had much discussion recently about the definition and use of RQD, and we would like to relay our feelings on the following three areas: (1) As we understand it, RQD is calculated counting only those pieces of drill core greater than 4 inches in length. This does not seem to be the appropriate method since it is not a true reflection of the condition of the rock mass in place; (2) the use of RQD by the Corps of Engineers is confined only to NX core. This is very restrictive since a major portion of the drill holes in the Northwest are larger diameter (HQ) than NX; and (3) RQD seems to be used more than it should be. In many situations, we feel that a graphical representation of the fracture frequency is more useful. RQD seems best suited for use in rock mass rating schemes such as the Geomechanics Classification System, or the Q system, which is used in estimating the engineering properties of the rock mass.

5B 5: In regard to your inquiry about our use of RQD measurements, we use it routinely in core drilling. However, I do not think it is that useful in our practice. Generally, I am trying to estimate the average depth of weathering into rock for foundation design and cost estimating. That usually involves looking at each core carefully and trying to pick the depth where any significant rock weathering stops. RQD does not help much in that regard.

5B 6: I am not sure a simple index property can account for these problems. Obviously a study of geologic

conditions and core inspection should always be made by a geotechnical designer, and he should never be tempted to circumvent this process by relying on simple parameters prepared by drillers and/or technicians. Therefore any improvements in RQD must be viewed with caution if they take emphasis away from performing a comprehensive evaluation of geologic details that could adversely effect project performance.

5B 7: A rock quality designation as described by Deere (1968) provides a means of communicating certain physical characteristics about bedrock cores. The procedure has been widely used by geologists and engineers to assess, in very general terms, the competency of bedrock as it relates to engineering work. Unfortunately, the simplicity of the procedure together with the common practice of correlating numerical RQD with terms like "poor", "good" and "excellent" often lead to the misuse and misunderstanding of RQD.

Anyone who uses RQD as a tool of understanding the engineering properties of bedrock must also understand the limitations inherent in such a simplistic approach to assessing the engineering properties of bedrock. When considered by itself, outside the context of the local geology, i.e., the lithology of the rock, the geologic structure of the bedrock and the potential influence of bedrock weathering, RQD becomes a meaningless number. Deere (1968) certainly recognizes the limitations of the RQD system and the necessity for considering the overall geology of a site when designing engineering projects that interact with the bedrock. Therefore, to be properly used, RQD must be considered as only one small part of the overall geologic evaluation and cannot be used as the sole basis for determining the engineering qualities of bedrock.

5B 8: In summary, RQD serves a purpose and can be a useful tool to describe certain properties of rock core. However, its design application is severely limited. The fact that RQD is correlated with such terms as "excellent," "good" and "poor," and is sometimes even correlated with allowable bearing capacities (Peck, Hanson, Thornburn, 1974), affords much opportunity for its misuse. Designers must not rely on RQD alone as a basis for foundation design decisions. At best, it can only serve as a tool of limited use in the assessment of the engineering qualities of bedrock.

5B 9: Problems have been inherent with the system since its inception and prevent our wholehearted adoption. First, the elimination of short core pieces from determining rock quality causes some strong rock

masses, such as, basalts and metamorphics to receive lower ratings than they deserve. Good examples are the local diced basalt units which stand in vertical cliffs (even overhang) due to the irregular nature of the fracture planes. The RQD system does not incorporate the attitude of fractures or the presence of clay fillings along fractures. It does not provide for core diameters larger or smaller than NX and does not give an indication of highly fractured zones within core runs. Unfortunately, some geologists have logged only RQD values and thought that they had done a meaningful job of fracture logging. We find that the most meaningful core fracture logging method notes individual fractures with their attitude, fillings, and smoothness. Where fractures are too closely spaced to be treated individually, as they usually are, then marking boring logs with brackets or zones and describing the fractures within the brackets pins down the weak horizons where they actually are and works out the best.

5B 10: If the sample condition is not observed upon removal from the core barrel, during handling and boxing and immediately logged by a qualified person, the data presented may be far from the original characteristics. We often have core samples which are not logged until after transportation and sometimes days or weeks after obtained.

Some of our staff feel that, as presently determined and used, the RQD is nothing more than a statistical exercise with little useful application in the real world. Deere could probably spend another 20 years in developing correction/adjustment values for the variables which are not actually related to rock quality but which can greatly affect the RQD numbers.

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