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Contents

List of Tables

Preface

This report contains the results of an investigation by Ms. M. E. Glynn, Mr. J. B. Warriner, and Dr. J. L. Wibowo, U.S. Army Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory (GSL), Vicksburg, MS. They were assisted by Dr. G. A. Nicholson, Geotechnical Associates Network, Inc., Vicksburg, MS. Funds for this study were provided by the U.S. Army Engineer District, Jacksonville, FL.

This study was performed in FY 97 and FY 98 under the direction of Dr. R. D. Bennett, Acting Chief, Soil and Rock Mechanics Division, GSL. Dr. Michael J. O'Connor was Director, GSL.

During the preparation of this report, Director of ERDC was Dr. James R. Houston and Commander was COL James S. Weller, EN.

Conversion Factors, Non-SI to SI (Metric) Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
pounds per square inch	6.894	pascals

1 Introduction

The U.S. Army Engineer District (USAED), Jacksonville, requested the assistance of the U.S. Army Engineer Research and Development Center (ERDC) to develop detailed estimates of deformation moduli for the foundation materials of the Portugués Dam, Poncé, Puerto Rico. Previous efforts by USAED, Jacksonville, have produced moduli estimates for 20-ft[1] lengths of core, without explicit regard to geology or rock structure. This report presents new estimates of deformation moduli using the original boring logs from Design Memorandum Number 22 (DM22) (USAED, Jacksonville 1988a), in addition to logs from more recent borings in weathered rock. These new estimates of rock mass moduli have been developed with explicit regard to rock type and structure and have been projected to 14 geologic cross sections along the dam axis.

Background

The USAED, Jacksonville, incrementally divided the dam axis into 69 radial sections associated with the structure and arched footprint of the dam (Figure 1). Thirty (30) sections define the structure along the left abutment, and 39 sections define the structure along the right abutment, which include the riverbed. Each section line represents a line of constant elevation that extends approximately 30 ft either side of the dam axis and is relatively perpendicular to the axis. The District selected 14 of these section lines (7 along each abutment) for an in-depth foundation and structural materials analyses. Geologic cross sections were constructed by the District to represent geologic conditions at the selected section lines. Section locations are shown on Figure 1 with the 14 analyzed sections highlighted in bold. The 69 section lines are numbered in ascending order, from the top of each abutment toward the riverbed. The number and elevations associated with the analyzed sections are provided in Table 1. In addition, a surface profile of the foundation showing the relative locations of the 14 sections is illustrated by Figure 2.

1 All logs in DM22 (USAED, Jacksonville 1988a) were documented using feet.

Table 1 List of Geologic Cross Sections (Radial Sections) Analyzed			
Right Abutment	**Elevation, ft**	**Left Abutment**	**Elevation, ft**
Section R 12	547	Section L 11	537
Section R 18	487	Section L 12	527
Section R 22	447	Section L 13	517
Section R 25	417	Section L 18	467
Section R 27	397	Section L 19	457
Section R 29	377	Section L 21	437
Section R 33	337	Section L 25	397

Description of the site geology and foundation materials at the Portugués dam site is discussed in detail in DM22 (USAED, Jacksonville 1988a). The foundation materials defined by the District geologist include meta-sandstone, meta- conglomerate, meta-siltstone, thin shears, wide shear zones, dikes, and highly weathered zones. Competent, yet moderately to highly fractured, meta-sandstone and meta-conglomerate are the most prevalent rock types sampled at the site. The rock units, including the shears and dikes, are steeply dipping and strike near perpendicular across the dam axis. Thin shears are ubiquitous at the site and large shear zones are often continuous across the dam axis. The site geology is described as complex (DM22 (USAED, Jacksonville 1988a)).

The current study was conducted in two phases. The first phase, completed in September 1998, examined the left abutment, and the second phase, completed in March 1999, examined the right abutment. Geologic cross sections were provided by the District and the authors interpreted and computed rock mass modulus for the specified rock units. This report describes the procedures used to determine those moduli, and the appendix discusses accuracy of the methods used.

Purpose and Scope

The main purpose of this investigation was to estimate the rock mass modulus of the lithologic units at the locations listed in Table 1 and highlighted in Figure 1. The results of this study will be used by USAED, Jacksonville, to determine a two-dimensional equivalent modulus for each cross section through finite element (FE) analyses. Finally, these equivalent moduli will be used as input to simulate three-dimensional stresses in the structure and foundation, also through FE analyses.

Determination of rock mass modulus was accomplished in four major tasks:

a. The first task involved division of boring log information into depth intervals of similar rock type and quality.

b. The second task required that the Rock Mass Ratings (RMR), according to the Geomechanics Classification System (GCS) (Bieniawski 1973, 1990), be assigned to each designated boring interval.

c. The next task compared boring logs to proximate cross sections (Table 1), and the RMR values were projected from the logs to the sections. In general, data from borings 5 to 20 ft away from a section line were used to characterize each section.

d. The RMR values assigned to each lithology in the sections were correlated to a rock mass modulus of deformation (Serafim and Pereira 1983), for input to the District's FE analyses.

Each geologic cross section (Figures 3 through 16) represents a generalized view of a unique portion of the foundation generated from surface and subsurface data. These sections were interpreted by District personnel primarily from surface maps and secondarily through core boring logs. Surface mapping provided orientation of lithologic features at section lines, which were extrapolated in depth to develop the geologic sections. However, surface and cross section data were not sufficient to calculate modulus of the rock units, therefore boring data were required. It was assumed that borings nearest to the section being analyzed were the most representative of that section because of the steeply dipping and complex geologic structure of the site. Therefore, rock mass moduli for the geologic sections were compiled primarily by projecting data only from proximate borings to each cross section line. For these reasons, the moduli presented on the given cross sections are not exact values but considered engineering estimates of lithologic conditions within close proximity to these cross sections.

2 Rock Mass Properties

RMR Classification Parameters

RMR is the primary output data of the GCS as described by Bieniawski (1973, 1990). The GCS is a means of classifying rock masses for various engineering purposes according to inherent features such as joint wall strength, Rock Quality Designation (RQD) (Deere 1963, 1989), joint characteristics, and groundwater conditions. These inherent features are referred to as classification parameters. Each classification parameter is assigned a rating, and ratings are summed to equal the RMR for the selected rock interval. Table 2 provides the range of values possible for the classification parameters and their ratings. The method followed in this study to obtain RMR was compliant with the definition of RMR (Bieniawski 1973, 1990) and the assumptions were similar to those used previously by the District (USAED, Jacksonville 1998b). The following paragraphs describe the procedure and assumptions used for obtaining ratings for each classification parameter specifically for the Portugués Dam site.

In general, the District's initial procedure consisted of:

a. Subdividing the core boring logs (DM22 (USAED, Jacksonville 1988a)) into constant 20-ft depth intervals.

b. Making a judgment as to the most prevalent rock type in each interval.

c. Determining an RMR value for each 20-ft interval using Schmidt Hammer, boring log and joint classification data (USAED, Jacksonville 1988a, 1996) and assigning this value to the rock interval above.

d. Assuming all groundwater conditions were moderate.

The primary departure of the current versus the initial RMR interpretation was to subdivide the available boring log information according to lithology and rock mass conditions rather than fixed intervals of depth. In addition, classification of strength parameters was generalized according

Table 2
Geomechanics Classification of Jointed Rock Masses (after Bieniawski 1973)

Classification Parameters and Ratings

Parameter			**Ranges of Values**						
1	Strength of intact rock material	Point-load strength index (Mpa)	> 10	4 - 10	2 - 4	1 - 2	For this low range, uniaxial compressive test is preferred		
		Uniaxial compressive strength (MPa)	> 250	100 - 250	50 - 100	25 - 50	5 - 25	1 - 5	< 1
		Uniaxial compressive strength (psi)[1]	> 36,250	14,500 - 36,250	7,250 - 14,500	3,625 - 7,250	725 - 3,625	145 - 725	> 145
	Rating		15	12	7	4	2	1	0
2	Drill core quality RQD (%)		90 - 100	75 - 90	50 - 75	25 - 50	< 25		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities OR		> 2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm		
	Fracture Frequency[2]		< 0.2 fx/ft	0.2 - 0.49 fx/ft	0.5 - 1.4 fx/ft	1.5 - 5 fx/ft	> 5 fx/ft		
	Rating		20	15	10	8	5		
4	Condition of discontinuities		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered wall	Slickensided surfaces or Gouge < 5 mm thick or Separation 1 - 5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Groundwater	Inflow per 10-m tunnel length (L/min)	None or	< 10 or	10 - 25 or	25 - 125 or	> 125 or		
		Joint Water Pressure. Major Principal Stress	0 or	< 0.1 or	-0.2 or	-0.5 or	> 0.5 or		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

[1] Conversion to English Units, included by authors.
[2] Inverse of spacing, included by authors.

to lithologies upon inspection of the available Schmidt Hammer results (described later in this report). Lastly, additional boring logs (mostly of weathered zones) were available for the current study which have not yet been published (USAED, Jacksonville 1998b).

RMR Calculation for Portugués Dam

The GCS requires the classification of the following parameters to calculate the RMR for a finite section of rock: unconfined compressive strength of the intact rock, RQD, joint condition, joint frequency, and groundwater condition. These data and methods used to classify these parameters are discussed below.

Initial strength ratings obtained from Schmidt Hammer tests were generalized into a single value for each lithology, by qualitative inspection of the Schmidt Hammer results. Values for RQD were taken directly from boring logs (DM22 (USAED, Jacksonville 1988a)) and an average was calculated for each designated interval. It is important to note that RQD did not vary much within a designated interval, because these intervals were chosen with respect to core runs with similar characteristics (rock type, RQD, and recovery). In other words, if a significant (nominal 10 percent) change in RQD was observed, a new interval would be designated, although the rock type may not have changed. In this way, sheared zones and weathered zones were distinguished because of their correlation to low RQD and low recovery. Joint conditions and frequencies were obtained from the joint classification logs (DM22), when available. Otherwise, these were interpreted from the boring logs. Finally, the groundwater condition was assumed as a moderate case rating (moist rock) for all intervals, as previously assumed by USAED, Jacksonville. Some specific details on the GCS ratings computed by ERDC are given below. Table 3 is an example worksheet used to calculate RMR.

Table 3 **Calculation Worksheet for GCS Rock Mass Rating**		
CORE BORING NO. EXAMPLE		DEPTH 416 408, ft
DATE ______	LOGGER ______	ELEV. 188 196, ft
1. STRENGTH OF INTACT ROCK ROCK GROUP meta-conglomerate RATING = 12		
2. RQD SUM OF RQD 105 ÷ NO. OF VALUES 3 = 35 RQD AVERAGE RATING = 8		
3. FRACTURES PER FOOT (INVERSE OF JOINT SPACING) NO. OF FRACTURES 75 ÷ TOTAL FOOTAGE 37 = 2.0 RATING = 8		
4. JOINT CONDITION – AVERAGE JUDGEMENT WEATHERING = SW ASPERITY = SR SEPARATION = T RATING = 23		
5. GROUNDWATER MOIST FOR ALL RATING = 7		
6. TOTAL RMR RMR = 58		
SW = Slightly Weathered, SR = Slightly rough, T = Tight		

Strength of intact rock

Based on observation of earlier District Schmidt Hammer results, the following ratings were assigned as constants:

a. Sound and firm dike – Rating = 15.

b. Sound and firm meta-sandstone – Rating = 12.

c. Sound and firm meta-conglomerate – Rating = 12.

d. Weathered material – Rating = 7.

e. Shear zone/gouge/mylonite – Rating = 4.

RQD

A single RQD was computed as an average of all RQDs (core runs) in a designated interval.

Joint spacing

The GCS uses metric units of joint spacing (e.g., m/unit fracture). This index was inverted into fracture frequency (fracture/unit ft) and into English units by ERDC for ease in calculating the rating. All logs in DM22 were documented using units of feet.

a. Less than 0.2 fracture/foot – Rating = 20.

b. 0.2 – 0.49 fracture/foot – Rating = 15.

c. 0.5 – 1.4 fracture/foot – Rating = 10.

d. 1.5 –5.0 fracture/foot – Rating = 8.

e. Greater than 5.0 fracture/foot – Rating = 5.

Joint condition

Joint condition was obtained from information stated in the joint classification and boring logs (DM22 (USAED, Jacksonville 1988a)).

Groundwater

A constant rating of seven was applied to each interval representing an average (moist) condition. This assumption was copied from earlier Jacksonville District interpretations.

Intact Rock Strength at Portugués Dam

ERDC used the following constant values (with respect to lithology) for the strength classification parameter during the derivation of RMR: 15 for dike material, 12 for meta-conglomerate and meta-sandstone, 7 for weathered material, and 4 for gouge material. These values were derived from a qualitative inspection of existing RMR worksheets (USAED, Jacksonville 1998b), that documented Schmidt Hammer tests performed by USAED, Jacksonville, at the site. After completion of the initial work, the District requested further evaluation of these constant ratings. Specifically, the District wanted to know if the variance in strength is great enough to change the strength parameter ratings within a rock group. To evaluate variance in strength, ERDC evaluated and compared the Schmidt Hammer results to the available unconfined compressive tests from DM22. This evaluation provided a means to determine the variance in the strength values and assess the validity of the qualitative ratings used. The results of the strength analysis are shown in Table 4.

Table 4
Schmidt Hammer and Unconfined Compressive Strength Test Results

Rock Type	ERDC Qualitative Strength Parameter Ratings	Statistical Function	Schmidt Hammer UC Strength, × 10^3 psi	Data Points	Schmidt Hammer, Average RMR Strength Parameter Rating	Laboratory UC Strength, × 10^3 psi	Data Points	Laboratory, Average RMR Strength Parameter Rating
MC	12	Avg	21.9	43	12	19.3	7	12
		Stdev	7.3			12.7		
D	15	Avg	24.2	15	12	12.6	4	7
		Stdev	6.2			8.0		
MS	12	Avg	21.7	78	12	20.2	25	12
		Stdev	6.7			12.3		

MC = meta-conglomerate, D = dike, MS = meta-sandstone, UC = unconfined compressive, avg = average, stdev = standard deviation.

Results from Schmidt Hammer tests were available for 25 of the 43 borings used in this RMR/modulus study, and these were used for the strength comparison. Laboratory data consisted of results from unconfined compressive strength tests conducted on specimens extracted from eight borings at the site of the underground uniaxial jacking tests (UJT), and six additional tests on cores from borings initiating from the surface. The average and standard deviation of these strength (laboratory) tests are provided in the seventh column of Table 4.

Comparison of the Schmidt Hammer strength parameter ratings to the laboratory ratings is favorable for the meta-conglomerate and meta-sandstone, suggesting that the Schmidt Hammer is an acceptable index method of estimating unconfined compressive strength at this site. Further, the Schmidt Hammer parameter ratings agree with the qualitative ratings ERDC used for the meta-conglomerate and the meta-sandstone, 12 and 12, respectively. In contrast, the correlation between Schmidt Hammer ratings and laboratory ratings for the dike material is poor and is discussed in the following paragraph.

The laboratory tests results for the dike material do not agree with the Schmidt Hammer tests or the qualitative field observations. The four laboratory tests, conducted on the dike material, suggest a lower strength than the 15 Schmidt Hammer tests. The Schmidt Hammer average strength (Table 4) for the dike material (24.2×10^3 psi) is twice the laboratory strength (12.6×10^3 psi). The significance of this comparison is decreased by the small number (4) of laboratory tests conducted. Considering the observations of the field geologists and the good correlation between the Schmidt Hammer and laboratory strengths of the other two rock groups (MC and MS), the Schmidt Hammer results for the dike material were accepted as reasonably accurate. The effect of the strength rating on rock mass modulus is evaluated below.

This comparison of Schmidt Hammer and unconfined compressive strength results corroborates the assumed ratings for the meta-conglomerate and meta-sandstone rock groups. However, there is uncertainty associated with the dike materials. Based on Schmidt Hammer results, the RMR value for these units should be 12 compared with the qualitative rating of 15 that was used. The possible error introduced to RMR by the qualitative assumption of the dike strength is discussed in the following text.

A change in modulus values due to a change in RMR is dependent upon the magnitude of RMR and not greatly dependent on any one classification parameter. For example, if RMR is between 51 and 78, (which is the range of RMR values for the dike material), a difference of three does not make a noticeable difference in the resulting modulus (Table 5). Therefore, the strength rating of 15 used for the dike material is assumed reasonable because: (a) the geologists' observations indicate that the dike material is qualitatively harder than the country rock, and (b) the variance in the strength parameter, from 12 to 15, produces a fairly small variation in computed deformation modulus. Further, the range-of-influence of a specific geologic unit's modulus within a specific cross section can be quantified through a FE sensitivity analysis.

Table 5
Effect of Small Changes in RMR on Rock Mass Modulus

Range for Dike Materials	RMR	Modulus × 10^6 psi	RMR Difference
Minimum	51	1.5	3
	54	1.8	
Maximum	78	7.3	3
	81	8.6	

Assignment of RMR Values to Section Lithology

The following section describes the process of assigning RMR values to the 14 cross sections from the boring data. This was a quantitative exercise, tempered with engineering judgment.

a. Each cross section (Figures 3 through 16) was evaluated individually and characterized using RMR and rock type data obtained from nearby borings. These data were plotted versus elevation on the cross sections (plots not shown in this report).

b. Trends in boring lithology were evaluated and compared to trends in cross section lithology. For example, meta-sandstone identified in the logs would be paired with all meta-sandstone identified in the cross section at the same approximate elevation. Dips are not usually available in boring logs. Therefore, lithologic orientation was not assessed while comparing borings to sections, only depth and relative location were used to project boring data onto cross sections.

c. Trends in RMR values (with respect to lithology and depth) were identified between proximate borings. If significant changes in RMR occurred consistently with depth in each boring, within a given rock unit, that unit was divided into smaller units of separate RMR values. This is illustrated by cross section L-12, where the meta-sandstone is divided into three units of RMR values increasing with depth. A significant change between neighboring RMR values was defined as an approximate change of plus or minus 10 percent.

d. In general, vertical borings within 5 to 10 ft (horizontally) of each other at the Portugués Dam site were observed to exhibit different rock types at a common depth because of the steeply dipping rock units and complex geology. Therefore, the District based the 14 cross sections primarily on the surface mapping, which defines the lateral extent and orientation of rock units. Further, because of the geologic structure, details of distribution of rock types in proximate borings 5 to 20 ft from the section line do not correlate directly to rock units represented in the cross sections with respect to depth. Hence, in a few cases, the boring data did not exhibit a particular lithology interpreted as present within its proximate cross section. For these cases, data for those units were obtained from the next closest boring and applied to that section.

e. If inconsistencies were noted between borings, the data from the boring closest to the section were given more importance over data from borings further removed from the section.

In some cases, selected boring intervals contained thin interbedded materials of differing rock types and/or thin shear or broken zones for which information was not sufficient to develop a separate RMR value. The physical attributes of those thin layers and zones (several inches to up to approximately 5 ft) were included in the overall classification of the RMR interval and were not distinguished from the major rock type of that interval. Thus, some shear zones illustrated by the geologic cross sections do not have separate RMR values, but were assigned the same value associated with their country rock. Similarly, at a few locations on the left abutment, large boring intervals (greater than 10 ft) were so highly weathered that data were insufficient to calculate RMR. For these few (6) cases, a low value of RMR (~20) was assigned to these intervals.

Computation of Deformation Moduli

After RMR values were assigned to lithologic units in the 14 sections, the modulus of deformation for each unit was computed. RMR was correlated to the rock mass deformation modulus with the following equation (after Serafim and Pereira 1983):

$$E_d = 1.45 \times 10^{(RMR\text{-}10)/40}$$
E_d = Rock Mass Modulus of Deformation, psi
RMR = Rock Mass Rating, integer (1)

This empirical correlation was determined by USAED, Jacksonville, personnel to correlate well with moduli calculated from uniaxial jacking tests conducted at the site (DM22 (USAED, Jacksonville 1988a)). Therefore, the correlation is assumed valid by the authors to estimate rock mass modulus at the Portugués Dam. The definition of "rock mass modulus" and the precision of calculating RMR are further discussed in Appendix A.

Results are shown in Figure 3 through Figure 16, illustrating the 14 cross sections. Each figure has a table that lists the following: lithologic units present in one cross section, unit RMR and modulus, and the boreholes used for the RMR interpretation. The results are presented to the District for use in an FE analysis to determine an equivalent deformation modulus representative of each cross section.

The modulus values on these sections are average values that were projected from nearby borings. They are not exact values but inferred from the available data. The most important observation of this analysis is the presence of weak materials adjacent to competent materials. The effect of this occurrence on structure integrity can be quantified through sensitivity analyses (parametric studies). Sensitivity analyses should be considered for individual cross sections and the range of possible moduli presented in the next section (Tables 6 and 7) should be addressed in the analysis.

Table 6
Left Abutment - Normalized Averages of Rock Mass Rating According to Lithology[1]

Lithologic Units, condition	Accumulated Vertical Footage, ft, out of 2,066 ft	RMR Normalized Average	E_d Normalized x 10^6 psi	RMR Max	E_d Max x 10^6 psi	RMR Min	E_d Min x 10^6 psi
Meta-sandstone (sound)	1,140	66	3.7	75	6.1	43	1.0
Meta-conglomerate (sound)	340	64	3.3	74	5.8	49	1.4
Meta-siltstone (sound)[2]	66	63	3.0	75	6.1	57	2.2
Dike (sound)	47	66	3.6	78	7.3	56	2.0
Meta-sandstone & meta-conglomerate (fractured or sheared)	60	52	1.6	60	2.6	41	0.9
All rock types (weathered)	344	33	0.5	63	3.1	19	0.2

[1] Averages calculated from partial database (43 borings).
[2] Not present on cross sections, but occurred in proximate borings.
Min = Minimum, Max = Maximum, Ed = Deformation Modulus (× 10^6 psi)

Table 7
Right Abutment - Normalized Averages of Rock Mass Rating According to Lithology[1]

Lithologic Units, condition	Accumulated Vertical Footage, ft, out of 2,227 ft	RMR Normalized Average	E_d Normalized × 10^6 psi	RMR Max	E_d Max × 10^6 psi	RMR Min	E_d Min × 10^6 psi
Meta-sandstone (sound)	1,096	64	3.2	76	6.5	45	1.1
Meta-conglomerate (sound)	646	64	3.2	74	5.8	50	1.5
Dike (sound)	223	65.3	3.5	75	6.1	51	1.5
Meta-sandstone & dike (fractured or sheared)	16	47	1.3	50	1.5	43	1.0
All rock types (weathered)	234	45	1.1	53	1.7	31	0.5

[1] Averages calculated from partial database (43 borings).
[2] Not present on cross sections, but occurred in proximate borings.
Min = Minimum, Max = Maximum, Ed = Deformation Modulus (× 10^6 psi)

Average RMR and Modulus Values

Tables 6 and 7 provide a generalized view of the rock properties at the Portugués Dam. These tables were derived using data from the 43 core borings examined during this analysis and not from the entire boring database available for the Portugués foundation. Analysis of the entire database (some 60 plus borings) was not included in this scope. However, these tables show the wide variation of RMR and modulus values within rock types and the relative difference of these properties between rock types. For summarizing, the foundation materials were grouped according to rock condition: sound/firm, sheared/fractured, and weathered units. Sound and firm units were separated by rock type, but the other two groups included all foundation materials.

The maximum and minimum moduli values Tables 6 and 7 show that a wide variation exists within rock groups, as mentioned previously. For example, the meta-sandstone in the right abutment has the largest range of moduli from 1.1×10^6 psi to 6.5×10^6 psi (a difference of 5.4×10^6 psi). The meta-sandstone range is followed in descending order on the right abutment by dike material, meta-conglomerate, meta-siltstone, weathered material, and finally sheared rock. As mentioned before, the range in moduli present within and among rock groups is an important result of this investigation. A parametric study should be conducted which addresses the range of possible displacements associated with this range of possible moduli for each rock group and the effect upon the structure.

To determine the average RMR (Tables 6 and 7), the vertical extent of each interval was calculated. This was necessary because some borings were angled at 45 deg and RMR intervals were of different lengths. The vertical extent was used as the basis for normalizing the RMR value of each interval (determining a weighted average of RMR with respect to vertical length of interval) and subsequently obtaining an average for each rock group. According to vertical extent, the most prevalent lithology delineated under the left abutment was meta-sandstone followed by weathered material, meta-conglomerate, meta-siltstone, fractured material, and dike material. Likewise for the right abutment, the most prevalent material was also meta-sandstone, followed in descending occurrence by meta-conglomerate, weathered material, dike, and finally sheared and fractured material.

The strongest material (highest modulus) in the foundation, as presented by these data, is the dike material followed by the meta-sandstone, meta-siltstone, meta-conglomerate, sheared rock, and finally, weathered material. The meta-sandstone, dike, and meta-conglomerate have similar average, maximum, and minimum moduli and, in some cross sections, are assigned the same properties (Figures 6 and 7).

These tables are useful to assess the variation in the rock mass properties. However, these averages should not be used for further analyses in general. Rather, data from nearby borings should be used to conduct local material analyses of the foundation because of the large variation in properties across the foundation.

3 Summary of Analysis

The purpose of this investigation was to assign rock mass moduli to cross section lithology at 14 locations. The results of this study will be used in structural analyses of the dam and foundation at these locations. The rock mass moduli were derived from the empirical correlation Equation 1 (Serafim and Pereira 1983) which is dependent on the RMR index property (Bieniawski 1973, 1990). Rock Mass Ratings were computed using data from borings near each cross section. Rock Mass Ratings were determined for core boring intervals distinguished according to rock type and condition and these values were projected to the appropriate cross section lithologies.

The range of moduli observed during the data analysis is the most important result of this investigation. The maximum and minimum values of RMR and modulus are summarized in Tables 6 and 7. They suggest the possibility of a low modulus material being juxtaposed to a high modulus material in this foundation. The influence of this scenario on the structure should be well examined using the maximum and minimum values presented in the modulus Tables 6 and 7 in this report. A parametric finite element study can now be conducted to estimate the magnitude of modulus differentiation that the structure can safely withstand, and an appropriate safety factor.

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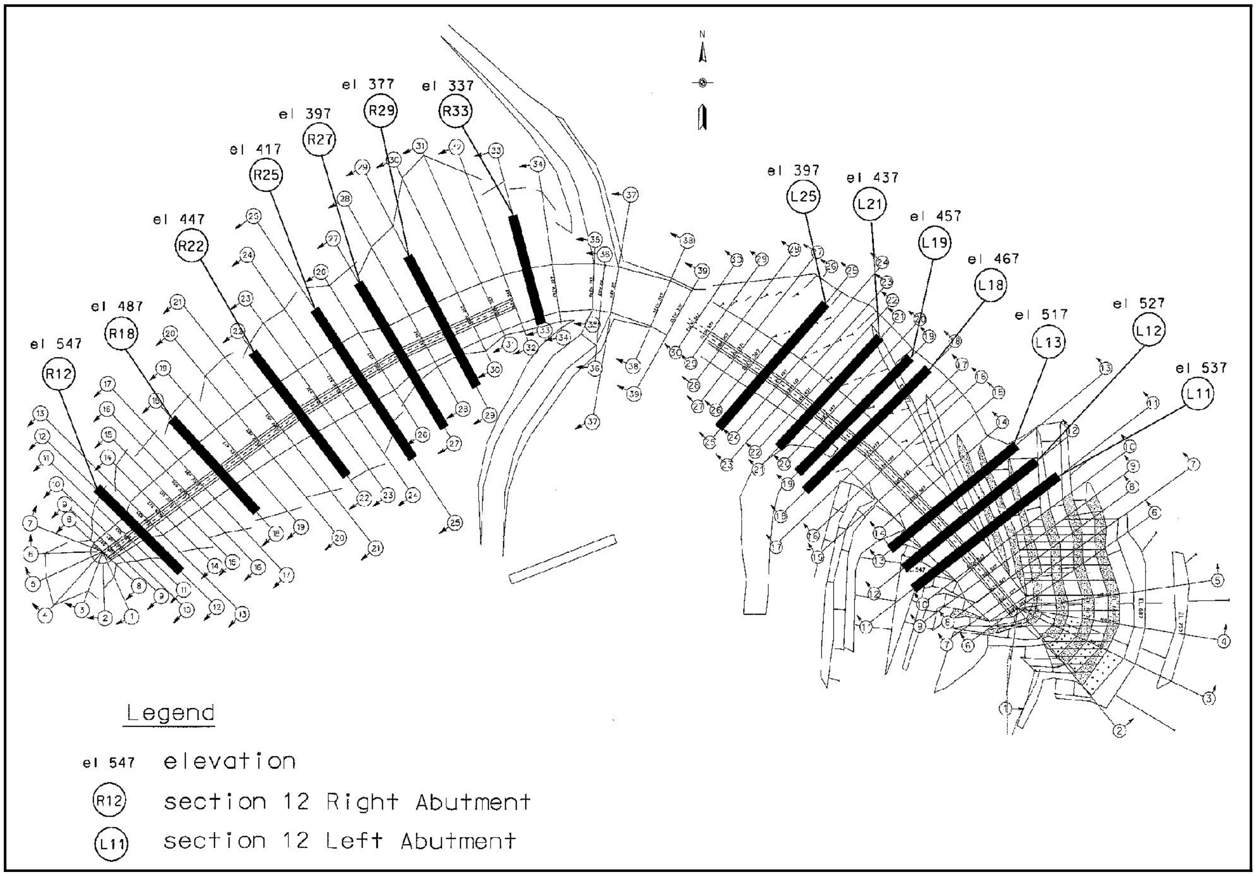


Figure 1. Plan view of the 69 radial cross sections (sections analyzed in this report shown in bold)

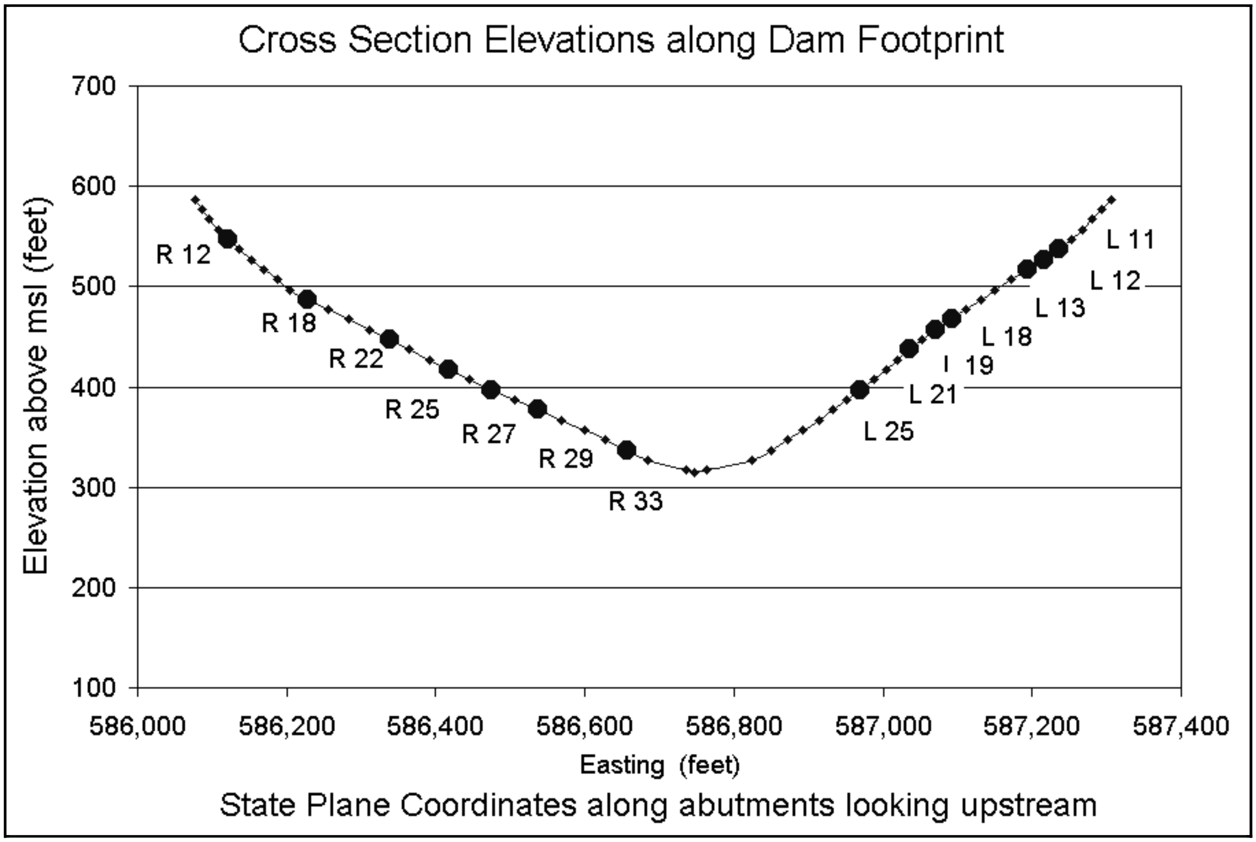
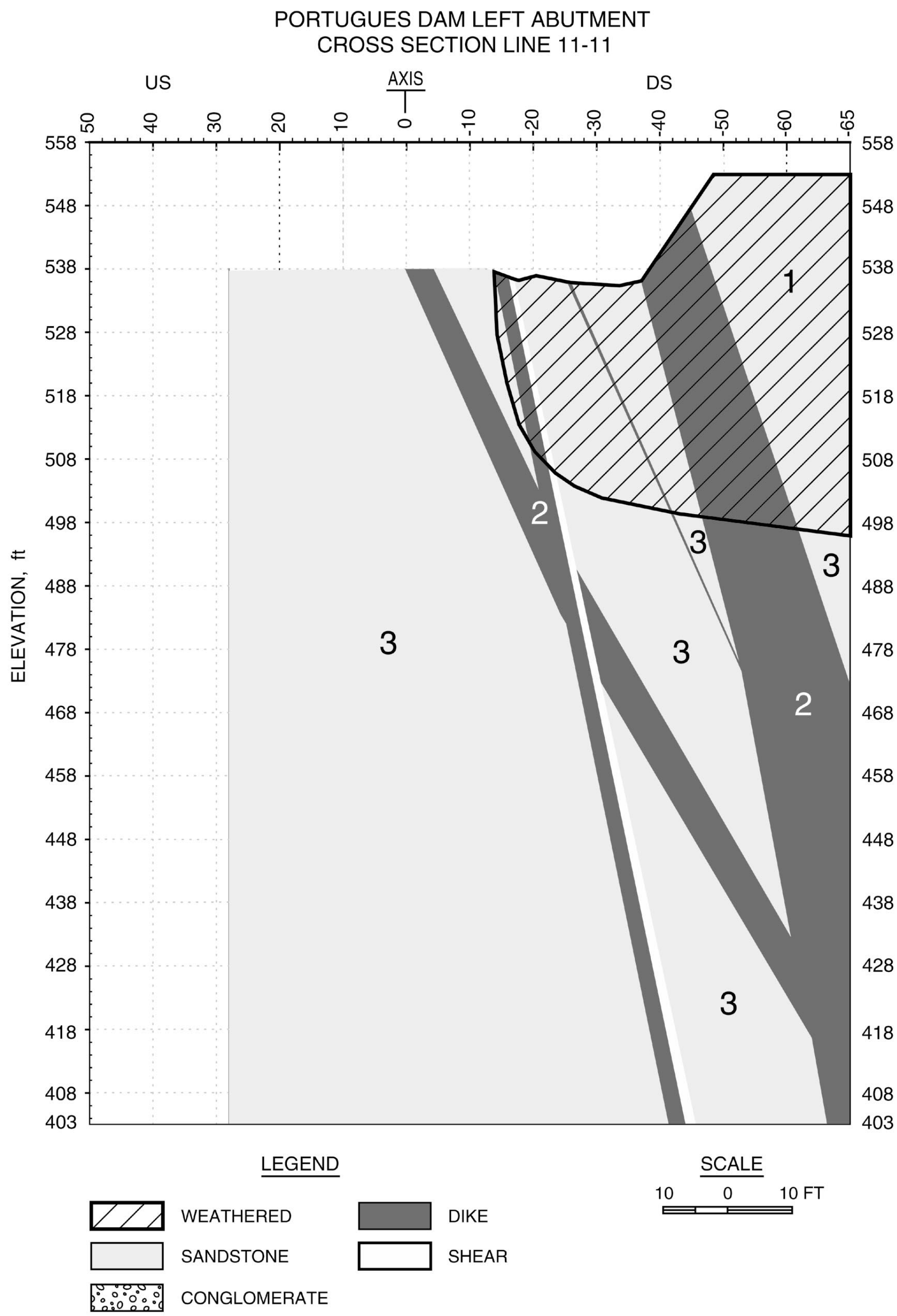
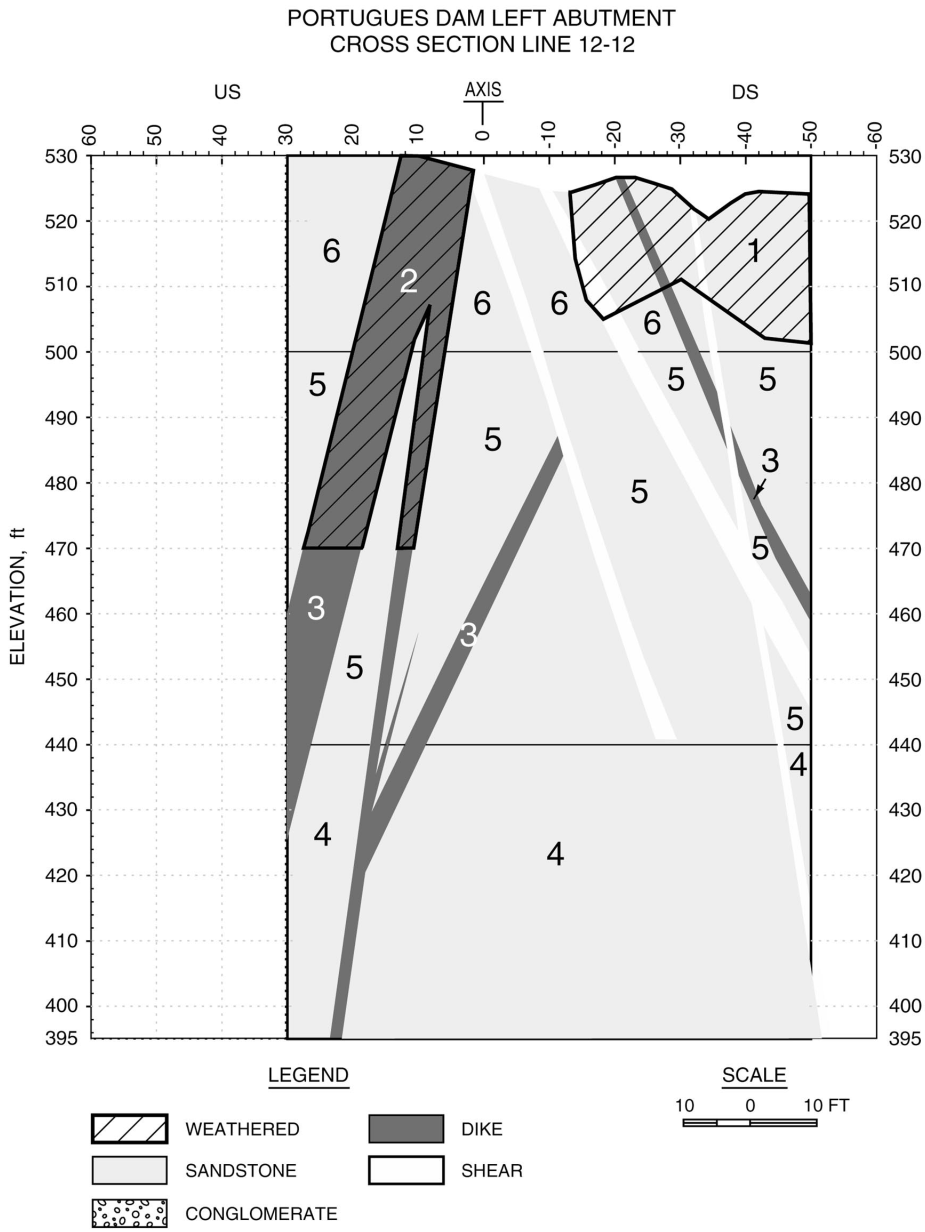


Figure 2. Vertical profile showing elevations of the 14 cross sections analyzed



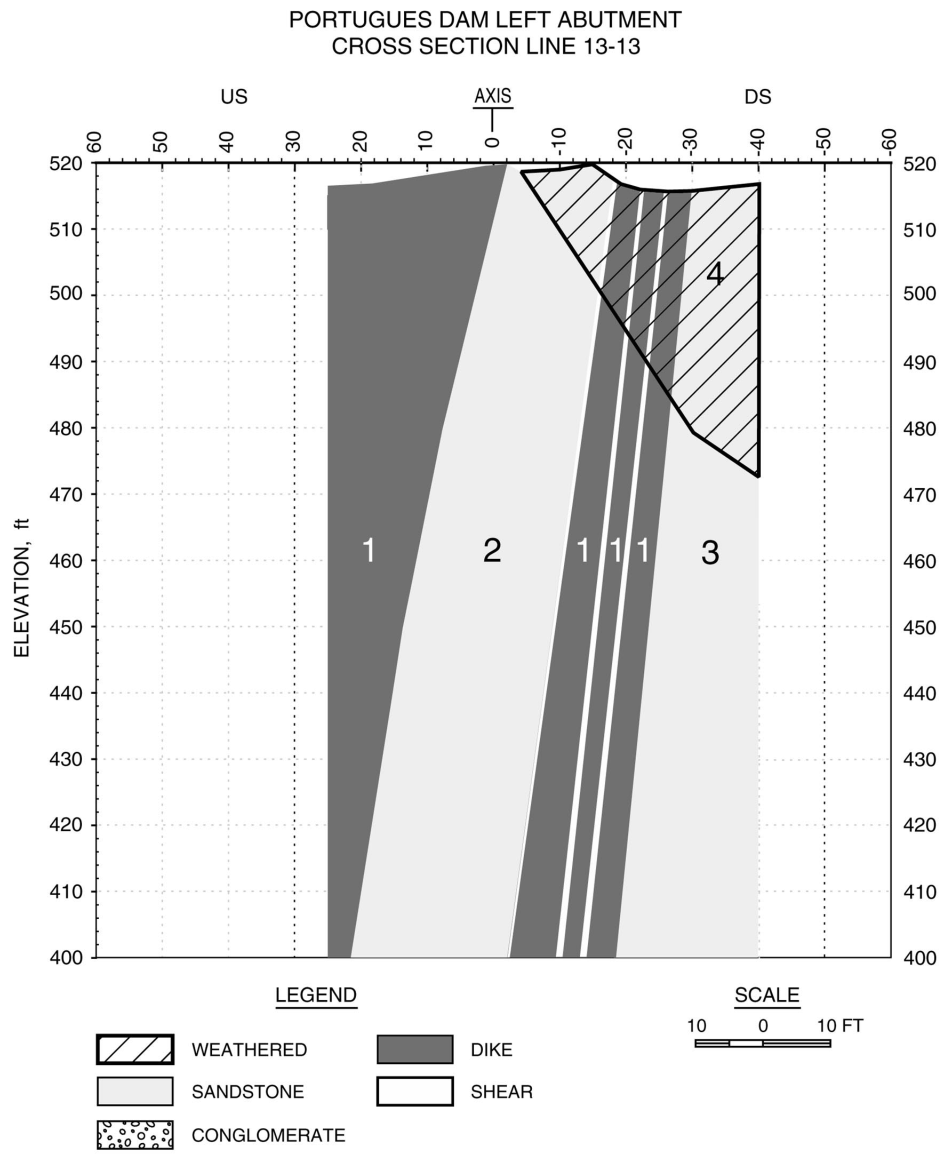
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Weathered	20	0.26	CB-PD-68 CB-PD-86, 87, 100, 103, 118
2	Dike	78	7.26	
3	Meta Sandstone	55	1.96	

Figure 3. Geologic cross section L-11



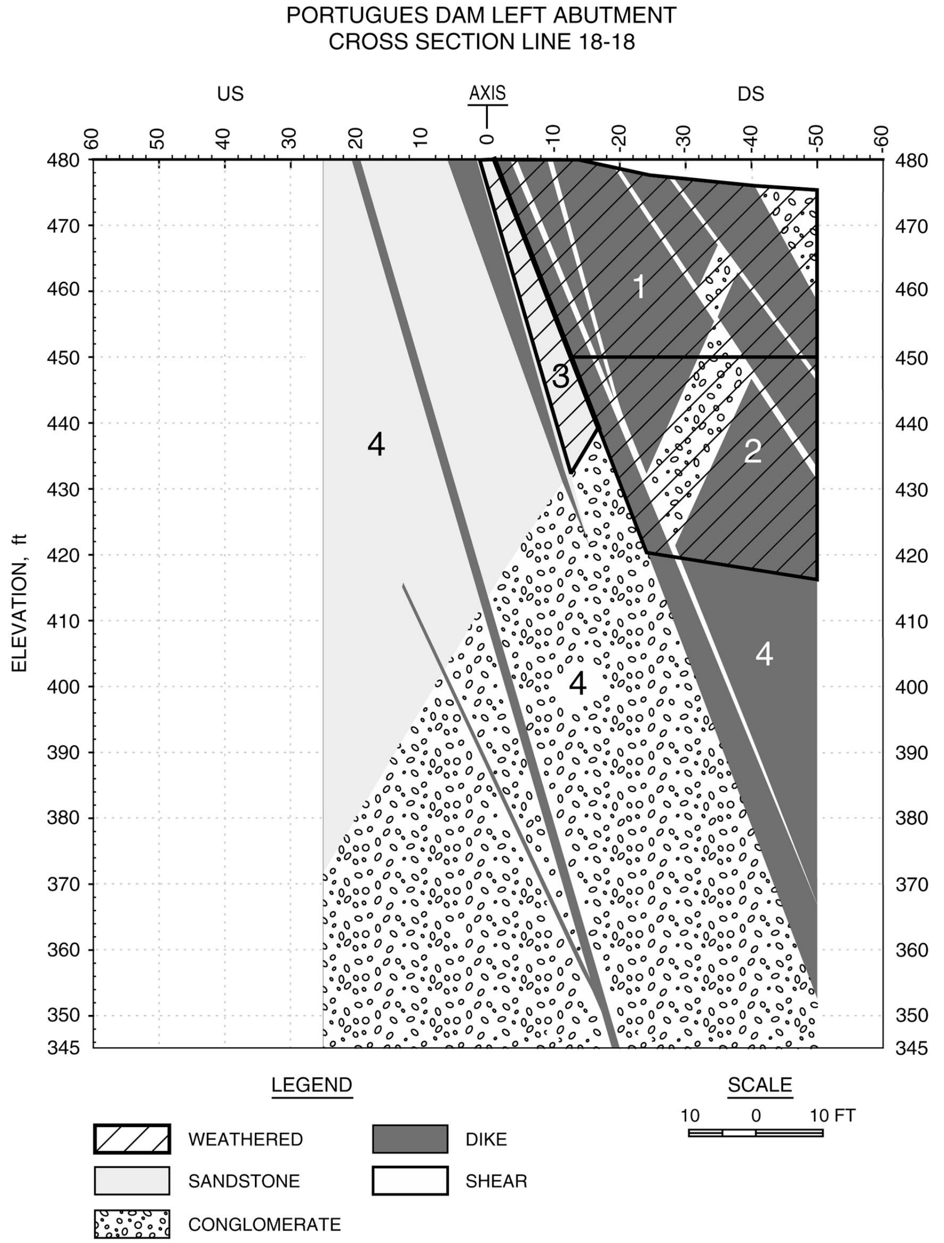
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Weathered 1	28	0.41	CB-PD-68 CB-PD-83 CP-PD-84
2	Weathered 2	20	0.26	
3	Dike	70	4.58	
4	Sandstone 1	75	6.12	
5	Sandstone 2	64	3.24	
6	Sandstone 3	49	1.37	

Figure 4. Geologic cross section L-12



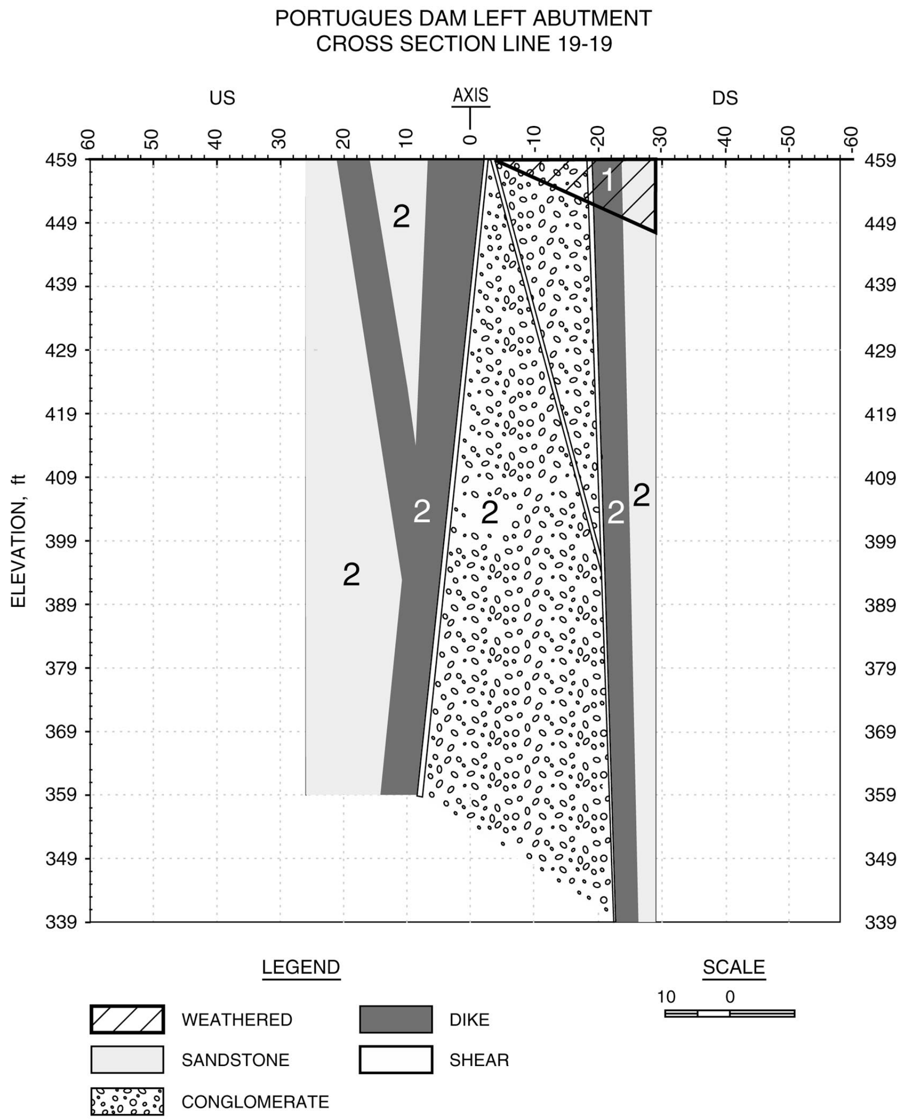
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Dike	68	4.08	CB-PD-68 CB-PT-05 CP-PD-82
2	Meta Sandstone 1	72	5.15	
3	Meta Sandstone 2	64	3.24	
4	Weathered	44	1.03	

Figure 5. Geologic cross section L-13



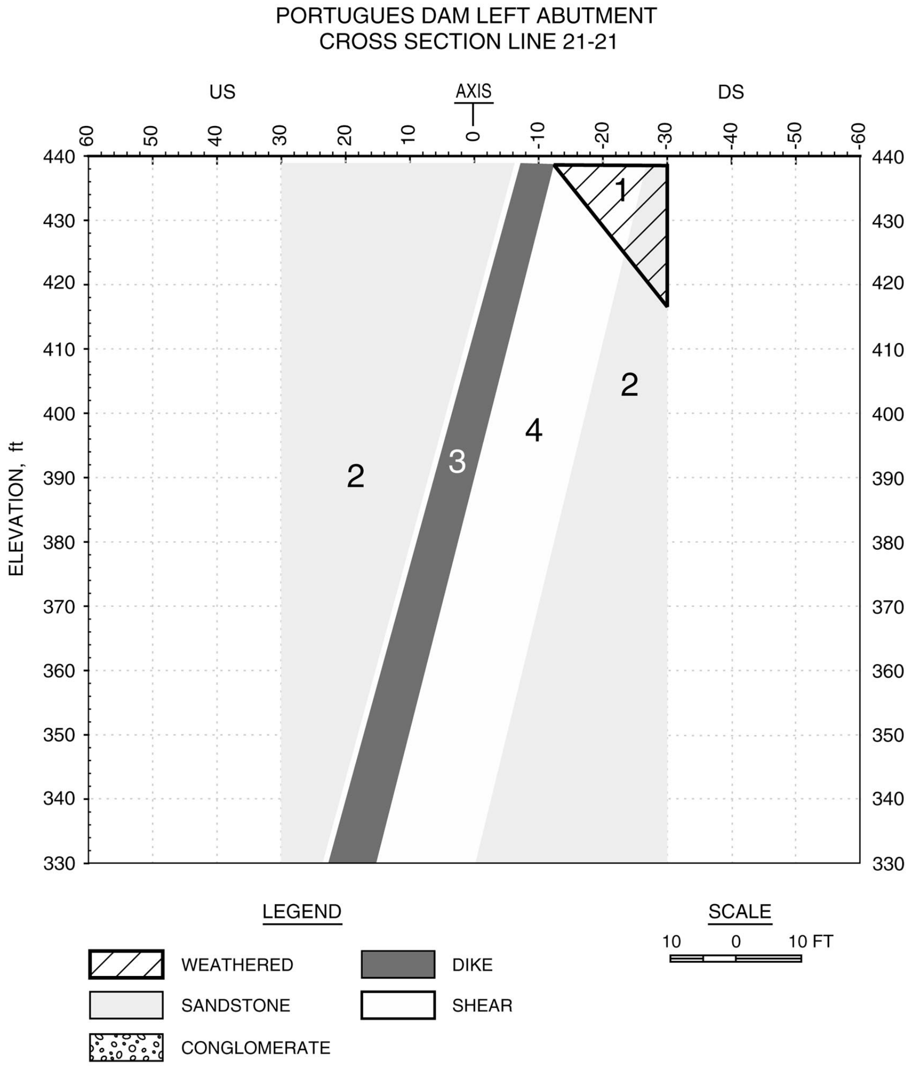
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Weathered 1	30	0.46	CB-PD-88, CB-PD-89 CP-PD-42
2	Weathered 2	53	1.72	
3	Weathered Sandstone	56	2.05	
4	Meta-Conglomerate Meta-Sandstone Dike	70	4.58	

Figure 6. Geologic cross section L-18



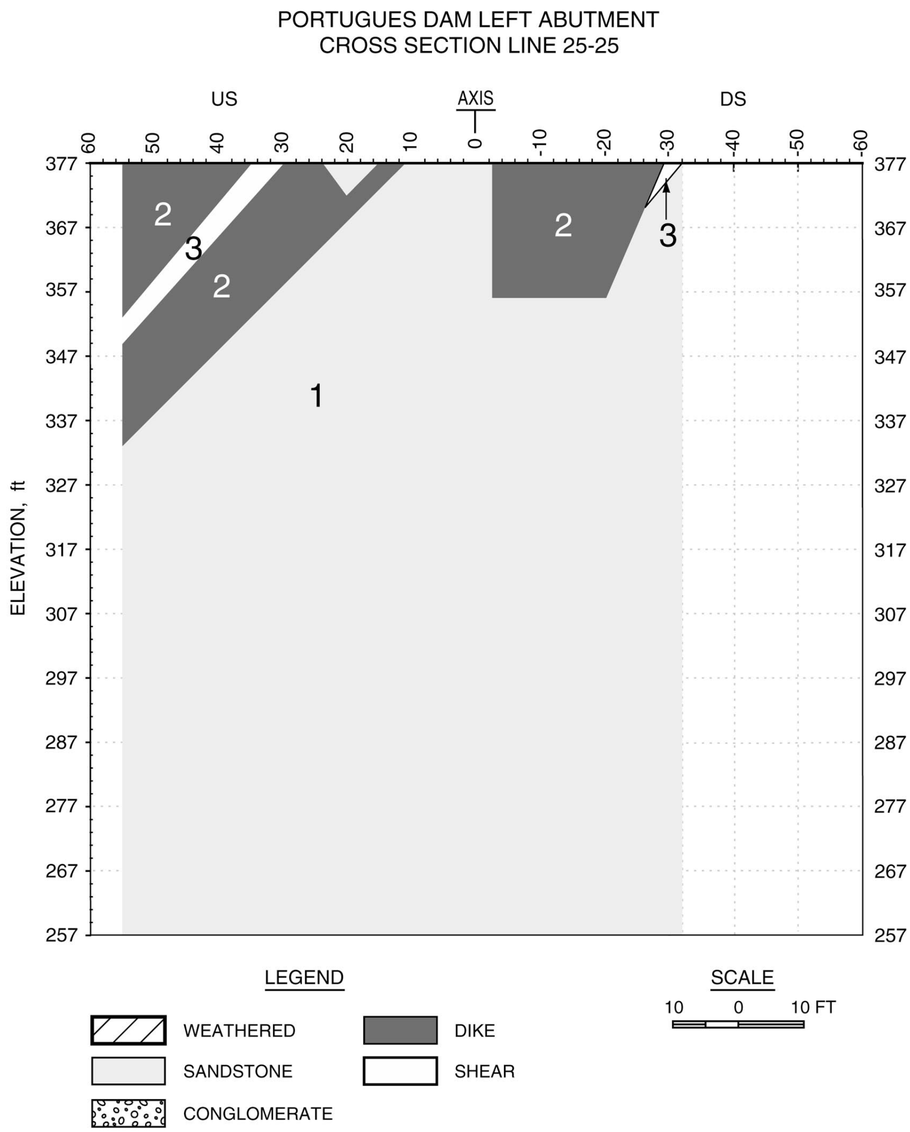
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Weathered	30	0.46	CB-PD-55
2	Meta-Sandstone, Meta-Conglomerate, Dike	63	3.06	

Figure 7. Geologic cross section L-19



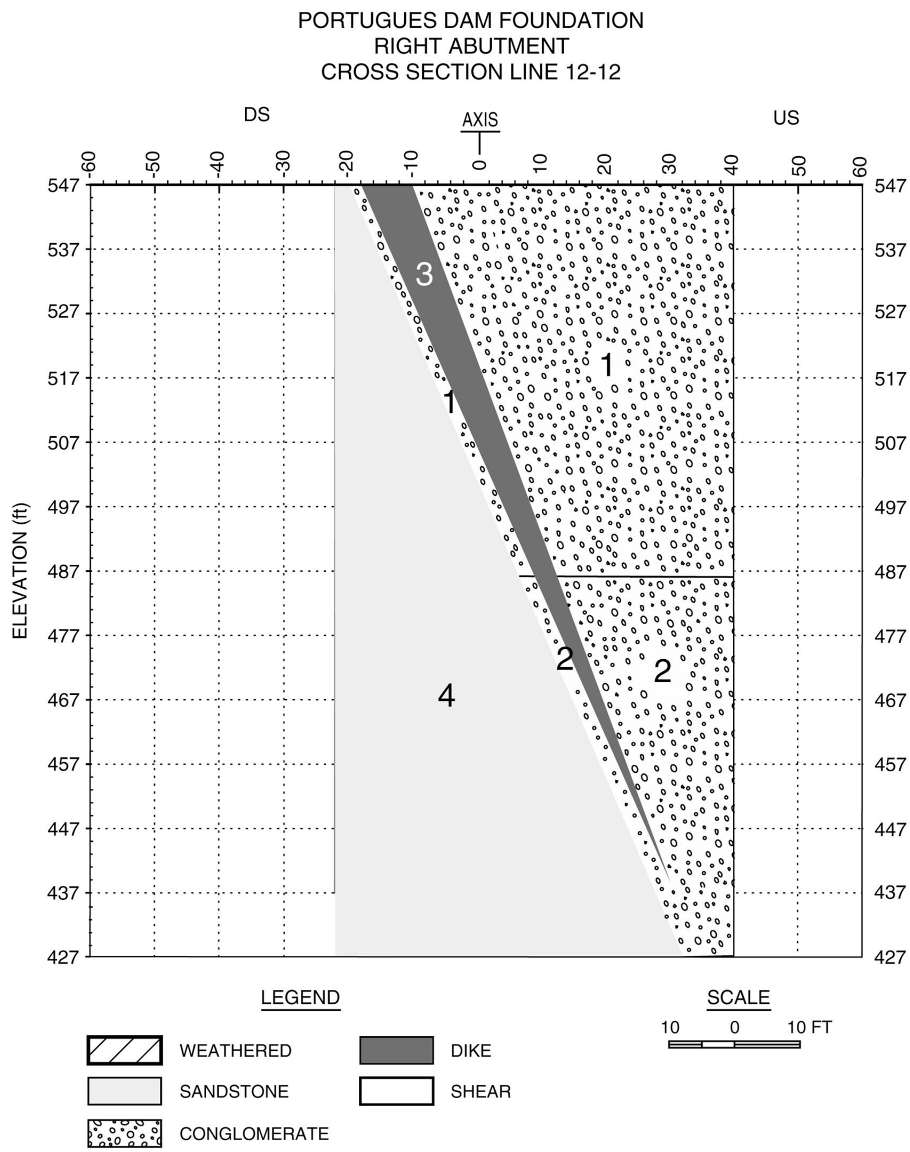
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Weathered	30	0.46	CB-PD-52
2	Meta-Sandstone	63	3.06	CB-PD-41, CB-PD-51, CB-PD-52 CP-PD-55
3	Dike	60	2.58	
4	Sheared Conglomerate	48	1.29	

Figure 8. Geologic cross section L-21



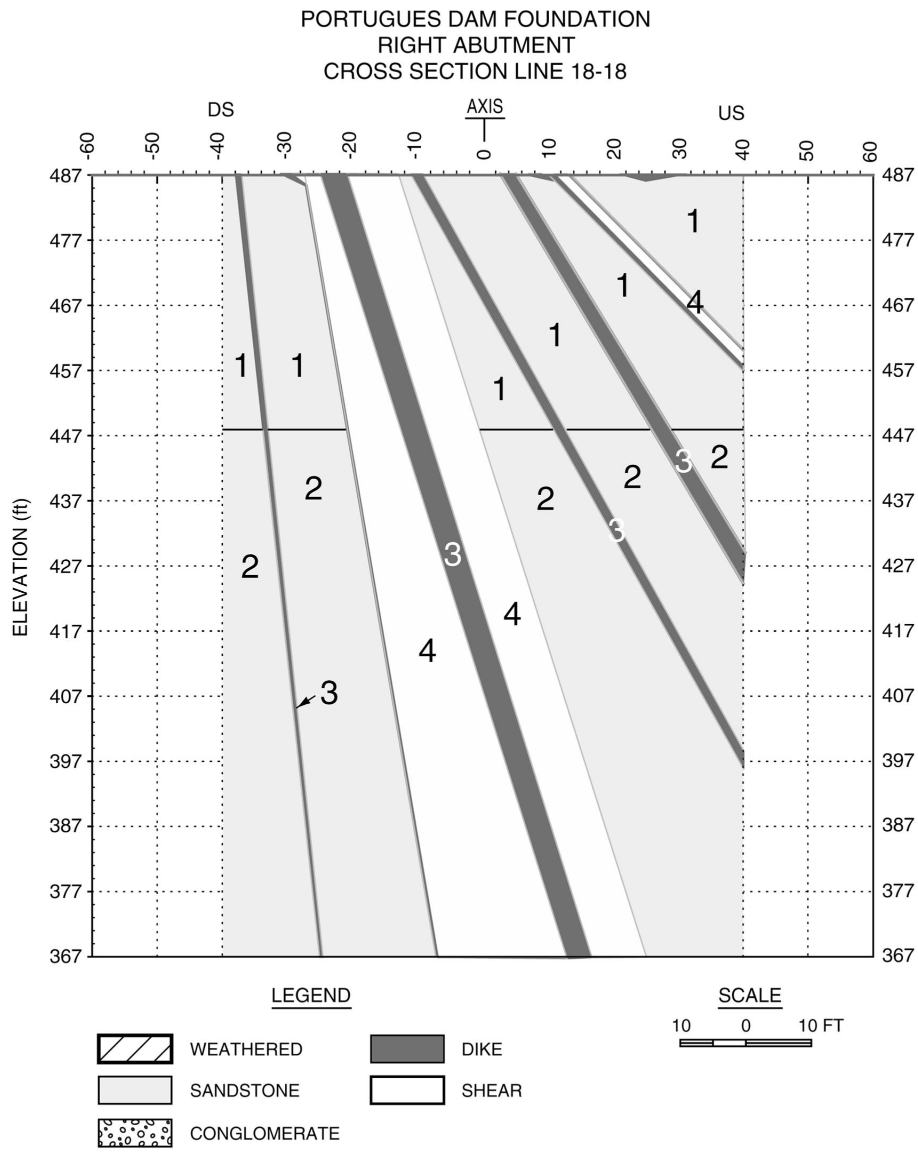
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Meta sandstone	68	4.09	CB-PD-51 CB-PD-70 CB-PD-41 CB-PD-42 CP-PD-53
2	Dike	66	3.64	
3	Shear Dike	56	2.05	

Figure 9. Geologic cross section L-25



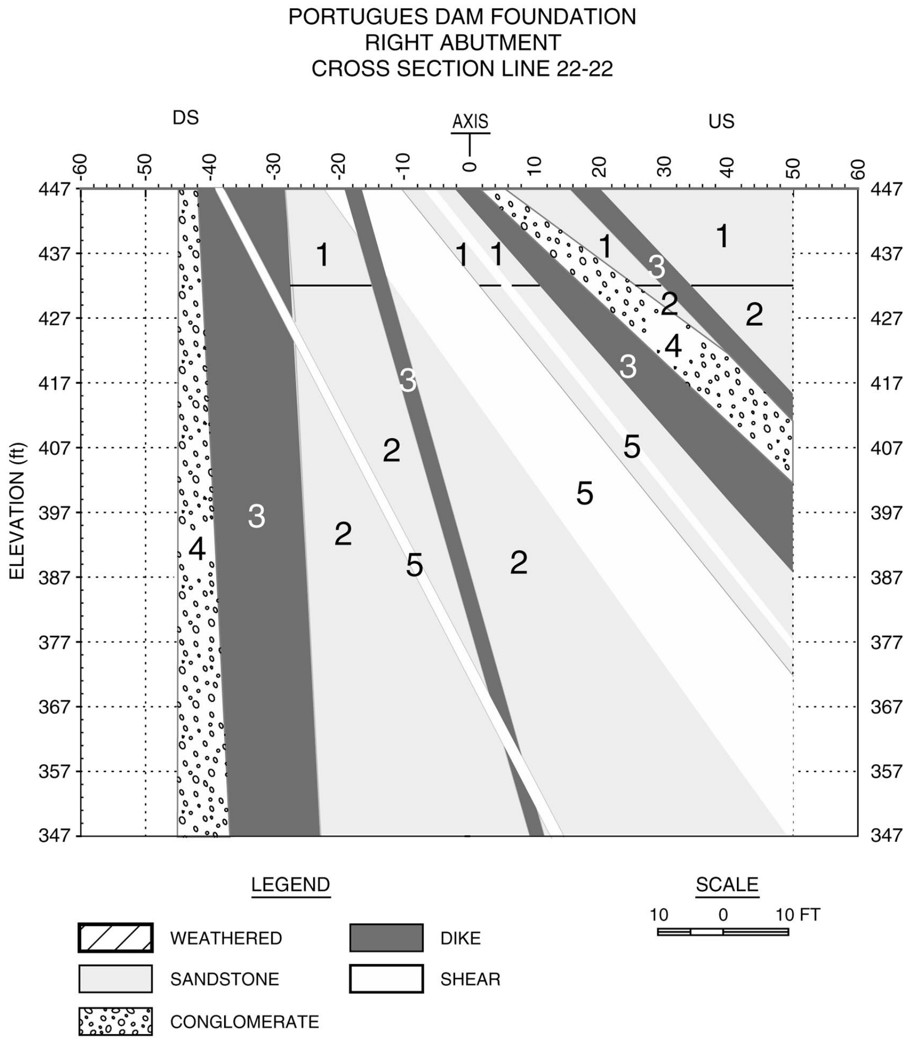
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Meta-conglomerate 1	55	1.93	CB-PD-26 CB-PD-65 CB-PD-66 CB-PD-67
2	Meta-conglomerate 2	65	3.44	
3	Dike	58	2.30	
4	Meta-sandstone	55	1.93	

Figure 10. Geologic cross section R-12



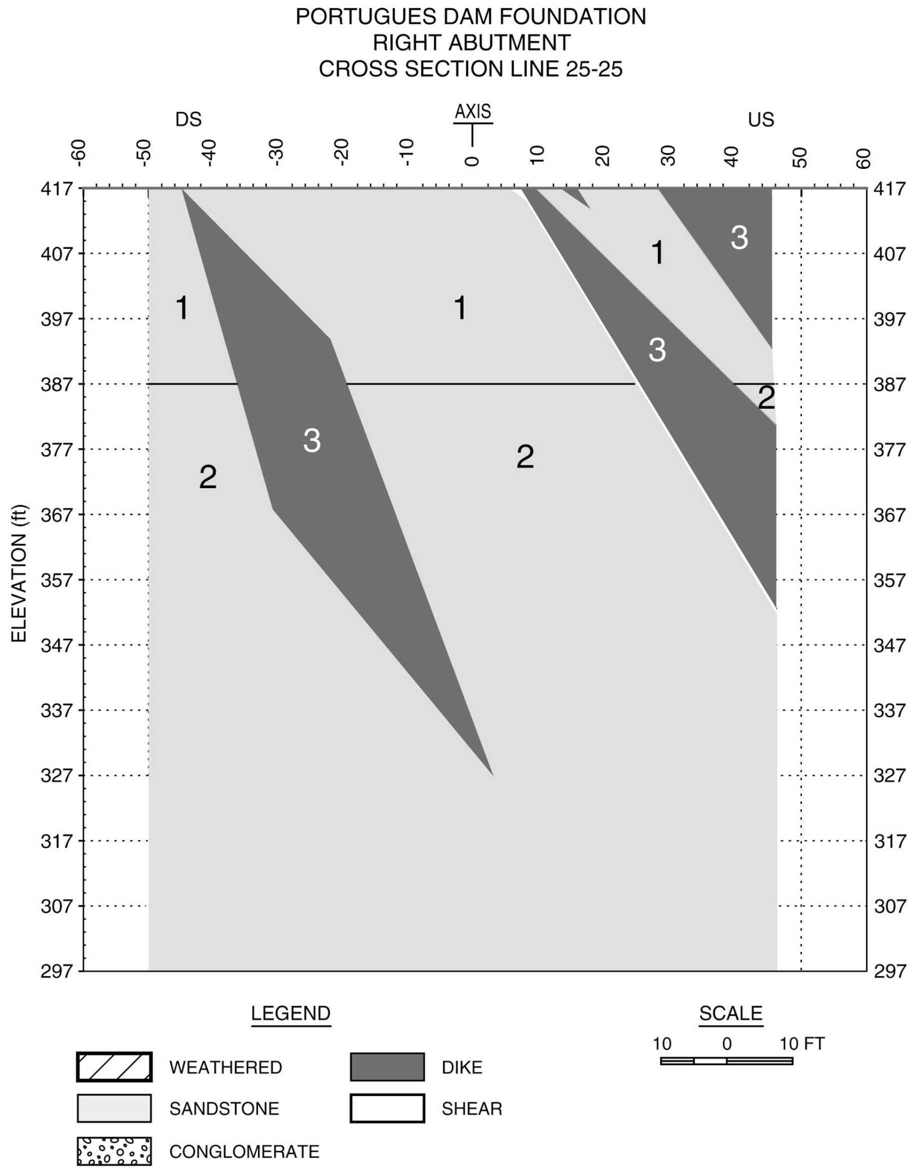
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Meta-sandstone 1	54	1.80	CB-PD-27 CB-PD-63
2	Meta-sandstone 2	65	3.44	
3	Dike	63	3.07	
4	Sheared Zone	43	0.97	

Figure 11. Geologic cross section R-18



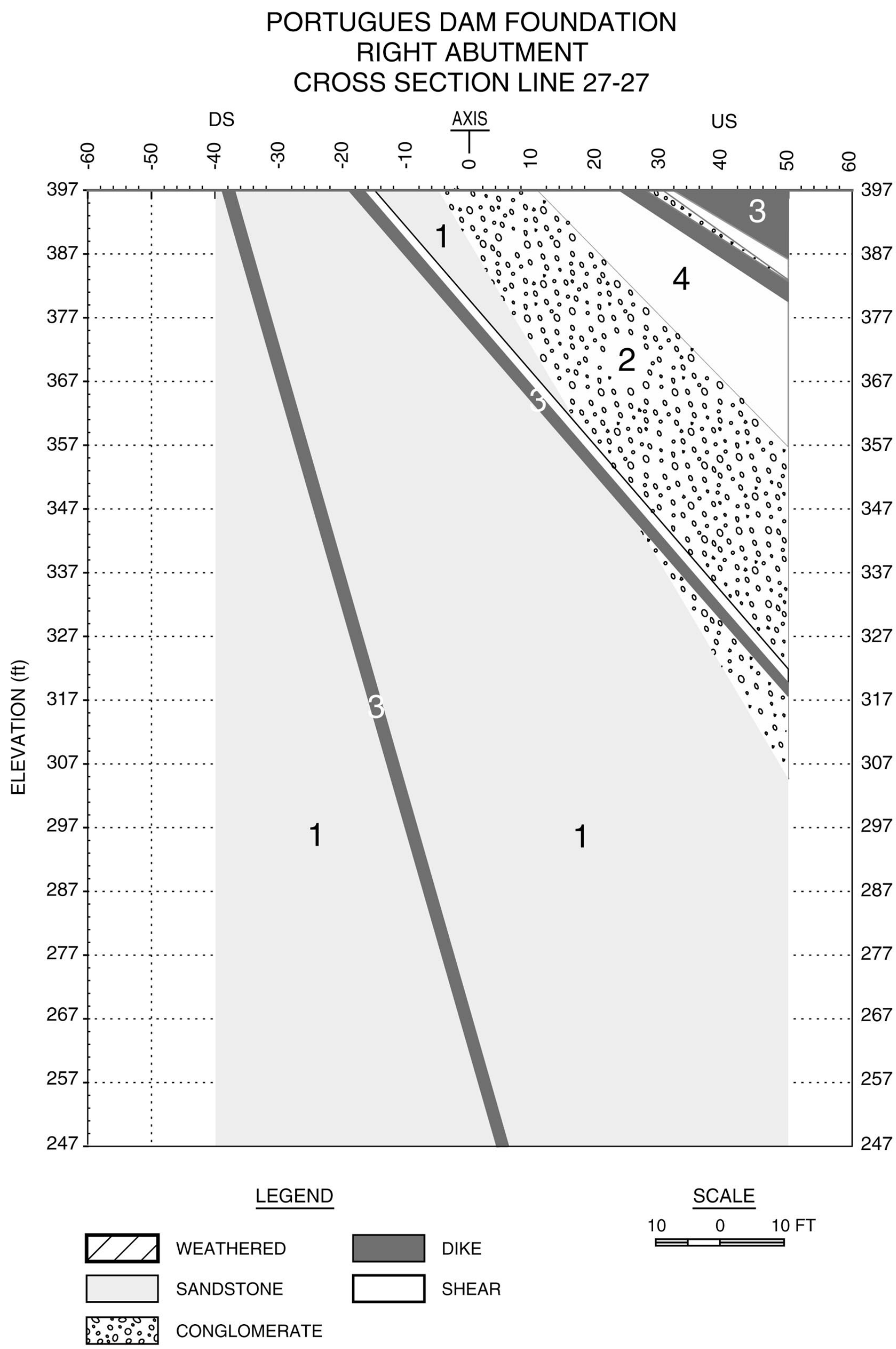
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	meta-sandstone 1	47	1.22	CB-PD-47 CB-PD-48 CB-PD-49
2	meta-sandstone 2	59	2.43	
3	Dike	70	4.59	
4	Meta-conglomerate	66	3.64	
5	Sheared Zone	38	0.73	

Figure 12. Geologic cross section R-22



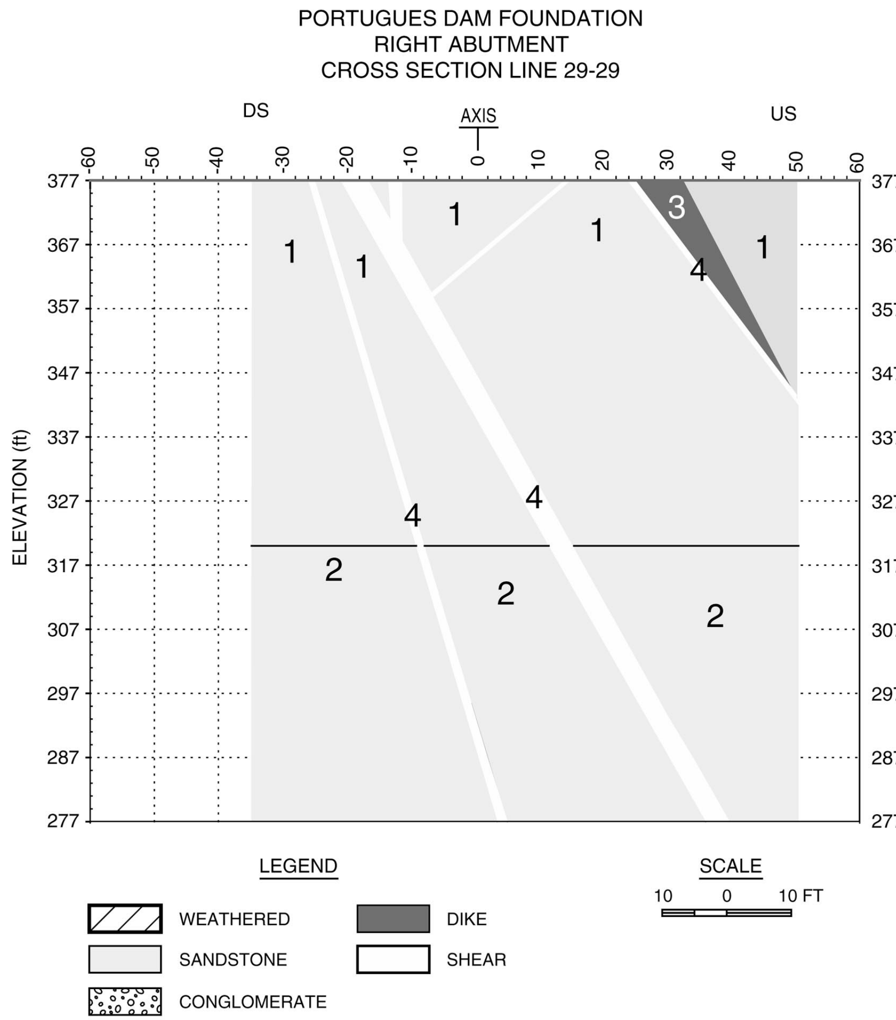
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	meta-sandstone 1	51	1.54	CB-PD-47 CB-PD-50
2	Meta-sandstone 2	64	3.25	
3	Dike	57	2.17	

Figure 13. Geologic cross section R-25



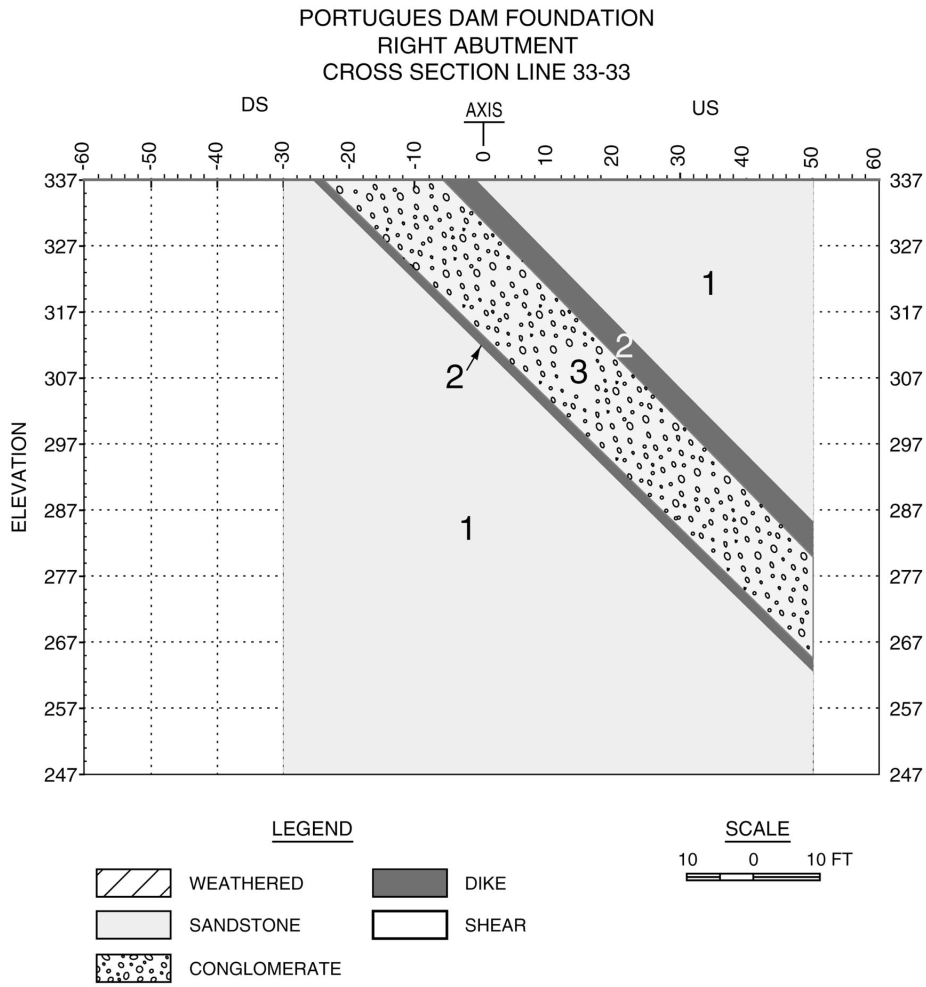
Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Meta-sandstone	62	2.89	CB-PD-43 CB-PD-59 CB-PD-61
2	Meta-conglomerate	68	4.09	
3	Dike	50	1.45	
4	Shear Zone	43	0.97	

Figure 14. Geologic cross section R-27



Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Meta-sandstone 1	60	2.58	CB-PD-43 CB-PD-61
2	Meta-sandstone 2	70	4.59	
3	Dike	65	3.44	
4	Sheared Zone	43	0.97	

Figure 15. Geologic cross section R-29



Material #	Description	RMR	Modulus of Deformation ($\times 10^6$ psi)	Borehole References
1	Meta-sandstone	65	3.44	CB-PD-60 CB-PD-62
2	Dike	75	6.12	
3	Meta-conglomerate	65	3.44	

Figure 16. Geologic cross section R-33

Appendix A
RMR Precision Issues

This appendix provides a brief overview on the definition of rock mass modulus and the empirical correlations commonly used to estimate it. Finally, the precision of the empirical methods are discussed and related to this study.

Definitions of In Situ Rock Mass Moduli

Modulus is a term for the strain response of a material to an applied stress. It is calculated as the slope of a selected portion of the graph of stress plotted versus strain. If a material under examination is linearly elastic, then the solution for the modulus (frequently referred to as the elastic or Young's modulus) is explicit and unique for that material. Because rock does not conform precisely to linear elastic principles, the modulus value depends upon the portion of the stress-strain response curve considered. Figure A1 shows the most common portions of the stress-strain curve used for determining in situ rock mass moduli.

The initial tangent modulus (line 1, Figure A1), determined from the initial concave upward section of the loading curve, reflects the effects of crack closure and stress damage phenomenon. Upon progressing further along the loading curve, the stress-strain response becomes essentially linear. The modulus of elasticity is derived from this linear or near linear portion of the curve (line 2, Figure A1). The final portion of the loading curve has no specific modulus term assigned. This portion of the curve can be either concave upward or downward. The concave downward characteristic generally indicates increased movement along the discontinuities with increasing pressures. A concave upward characteristic (as in Figure A1) indicates deformation behavior approaching that of intact rock.

The initial segment of the unloading curve (line 3, Figure A1) is termed the recovery modulus. The value of the recovery modulus is generally higher than any other moduli. The recovery modulus correlates closely

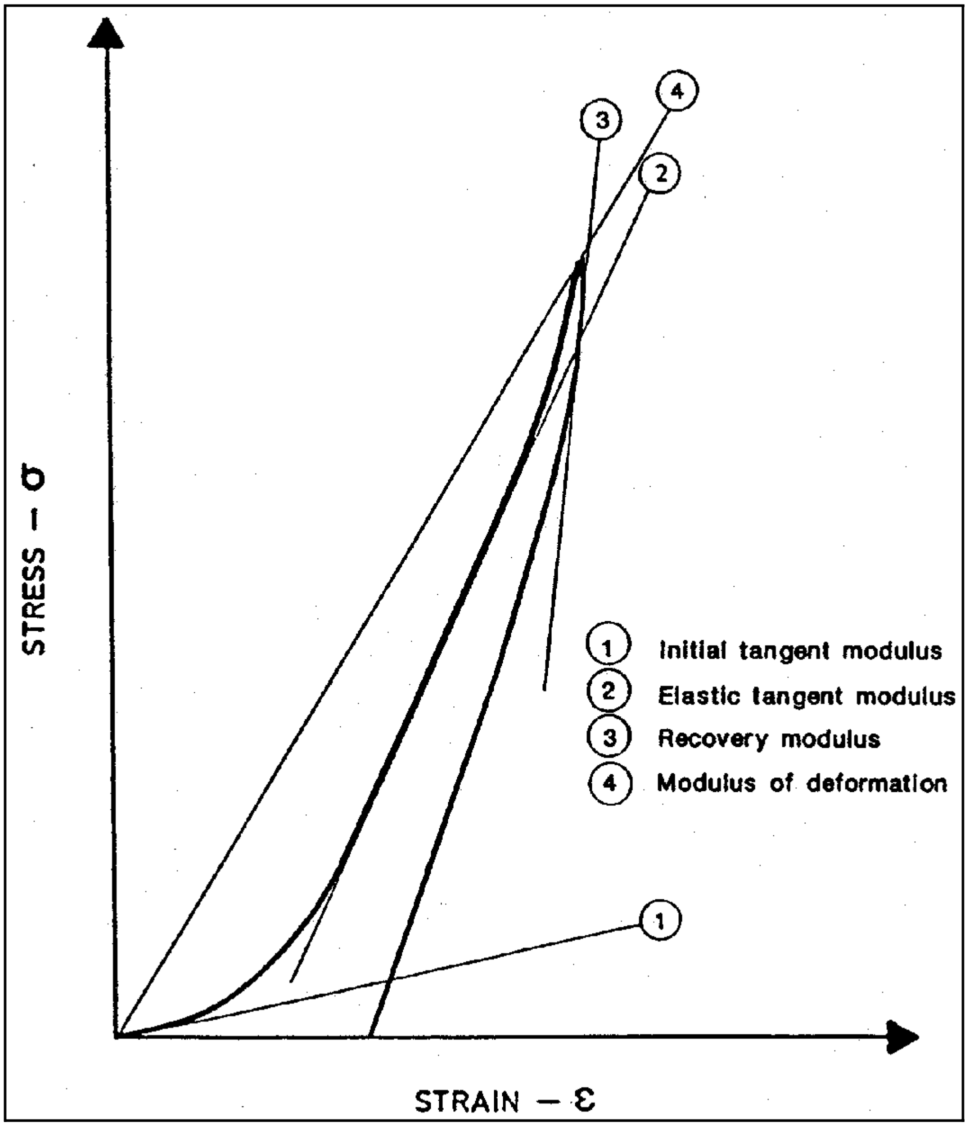


Figure A1. Definitions of rock mass moduli

with seismically assessed moduli. This modulus is thought to represent the rebound characteristics of the rock material devoid of cracks.

Although each of the previously mentioned moduli assesses deformability of the rock, these moduli are confined to specific regions of the load-deformation curve. For this reason, the modulus of deformation (E_d) is determined from the secant line (line 4, Figure A1), established between zero and peak load over the total deformation. The modulus of deformation incorporates all of the deformation behavior occurring under a load range. Presently, this modulus is perhaps the most commonly accepted parameter for describing deformability of rock mass under load. However, it must be recognized that a deformation modulus value is not unique but rather depends upon the peak load.

Empirical Correlations

Although expensive, the uniaxial jacking test is an acceptable and realistic method for obtaining rock mass modulus of deformation. Eight such tests were conducted at the Portugués Dam site. To adequately characterize the deformability along the total length of a major dam can require a prohibitively large number of in situ tests, particularly if the rock mass conditions are highly variable. For this reason, a number of investigators have attempted, with varying degrees of success, to empirically correlate in situ deformation moduli with easily obtained and inexpensive rock mass indices, as well as rock mass classification systems. The versatility of this approach is reflected by the fact that empirical correlations are probably the most widely used method for predicting deformation modulus in the United States.

Bieniawski (1978)[1] initially offered a successful correlation between the Geomechanics Classification System (GCS) (Bieniawski 1973) and the deformation modulus. However, no data points were available for Rock Mass Rating (RMR) values of less than approximately 50. Hence, Bieniawski's findings were restricted to RMR values greater than 50. Serafim and Pereira (1983) updated Bieniawski's findings to include a wider range of rock mass conditions, as shown in Figure A2. The correlation between RMR and the modulus test results at the Portugués site agreed with the curve in Figure A1. Therefore, the District assumed the Serafim and Pereira (1983) correlation as a valid prediction tool for the site (DM24) and used in the current study.

Precision Statements

Precision statements are of primary importance in evaluating how well the results of a particular test or procedure can be repeated and reproduced. Toward this end, the American Society for Testing and Materials (ASTM), ASTM E691 entitled "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method" (ASTM 1992a), provides guidance for measuring precision. As indicated above, precision statements primarily consist of repeatability and reproducibility statements. Repeatability (r) limit refers to the measure of variance within a participant (i.e., person or persons conducting a given test). Reproducibility (R) limit refers to the measure of variance between participants. The probability is approximately 95 percent that two or more test results obtained by the same participant on the same material will not differ by more than the repeatability limit r. Likewise, the probability is approximately 95 percent that two or more test results obtained by different participants on the same material will not differ by more than the reproducibility limit R.

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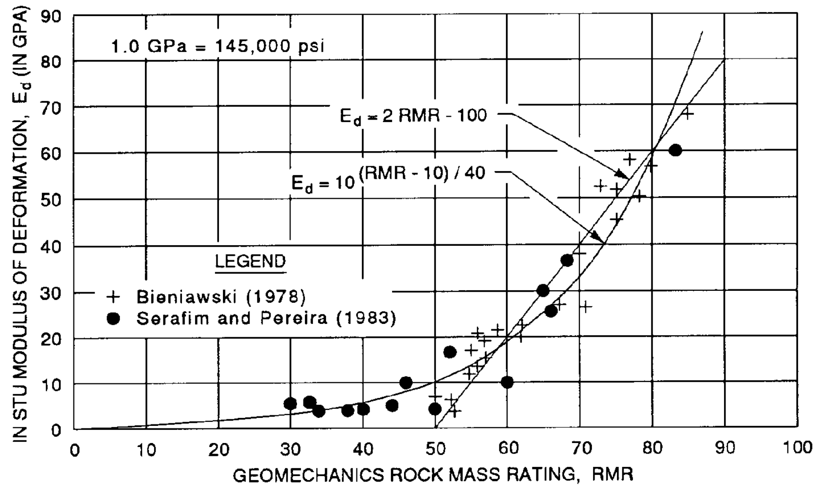
[1] Reference information is presented on page __ of main text.



V Very Poor Rock	IV Poor Rock	III Fair Rock	II Good Rock	I Very Good Rock
RMR 0 to 20	RMR 21 to 40	RMR 41 to 60	RMR 61 to 80	RMR 81 to 100
C < 100 Kpa	C = 100-200 KPa	C = 200-300 KPa	C = 300 to 400 KPa	C > 400 KPa
ϕ < 15	ϕ = 15 to 25	ϕ = 25 to 35	ϕ = 35 to 45	ϕ > 45
E < 1.8 Gpa	E = 1.8 to 5.6 GPa	E = 5.6 to 18 GPa	E = 18 to 56 GPa	E > 56 Gpa

Figure A2. Serafim and Pereira's correlation (1983)

Precision statements do not exist for the plate-load tests (uniaxial jacking tests) or the GCS. However, r and R values for several laboratory tests on intact rock are provided in the ASTM (1992b) document. In particular, this ASTM study found that r for uniaxial elastic modulus values for four different rock types varied from as little as plus or minus 6.5 percent to as much as plus or minus 14 percent about mean values. Similar trends were observed for **R** values. Laboratory modulus tests on intact specimens are relatively simple in comparison to uniaxial jacking tests. As a rule, **r** and **R** values tend to increase (i.e., more variance in test results) with increasing test complexity.

ASTM/ISR (1994) also provides precision statements for Rock Quality Designation (RQD) (Deere 1963, 1989) values. The RQD is one of the parameters that make up the RMR classification system (as described in the section Site Specific Data and the GCS of this report). The results of this ASTM/ISR study are summarized in Table A1. It is interesting to note that both r and R decrease with increasing values of RQD (i.e., variance decreases with increasing rock quality).

Table A1
Repeatability (r) and Reproducibility (R) Values for RQD Results on Four Materials (ASTM 1994)

Rock Type	RQD Mean	Repeatability, r, %	Reproducibility, R, %
B (Shale)	60	32	40
A (Anhydrite)	86	28	28
D (Anhydrite)	86	20	20
C (Limestone)	92	14	14

One would expect a greater variance for RMR than for RQD, since RMR determinations are more complex. Direct comparisons of R and r values between RQD and RMR are subject to speculation. However, one could expect (from Table A1) that both values would be on the order of at least ±15 percent for RMR values between 60 and 70. Hence, for an RMR mean value of 65 (typical of the Portugués Dam site) the variance between likely values would range between RMR = (0.85)(65) = 56 and RMR = (1.15)(65) = 75. One could expect the deformation modulus to range between 2.05×10^6 psi (RMR = 56) to 6.11×10^6 psi (RMR = 75) (Serafim and Pereira 1983), resulting in a possible difference factor of three (6.11/2.05).

An inspection of Tables 6 and 7 (main text) indicates a small variation in average RMR values for sound rock (nonweathered and nonfractured), between 63 and 66. As mentioned above, a value of RMR equal to 65 could result in a range of modulus from 2.05×10^6 psi to 6.11×10^6 psi. The sheared/fractured and weathered materials have RMR values ranging from 41 to 43 and 19 to 31, respectively. Thus, being consistent with the ASTM findings (Table A1), it is more difficult to determine the RMR values for these weaker materials. However, for materials with RMR lower than 50, the range of possible modulus values is small according to the Serafim and Pereira (1983) correlation. Therefore, even if the RMR is less precise for the weaker materials, the possible error in modulus is less significant than that for the sound rocks at the Portugués Dam.

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13. ABSTRACT ***(Maximum 200 words)***

This report describes the development of rock mass rating values for the purpose of estimating rock mass moduli for the Portugués Dam, Ponce, Puerto Rico. The Serafim and Pereira (1983) correlation of Rock Mass Rating to modulus was used in the analysis. Fourteen geologic cross sections were evaluated which were widely distributed along the foundation axis. Rock Mass Ratings were determined for each lithologic unit depicted in these cross sections by projecting rock mass characterization data from deep (~100- to 200-ft) borings. The purpose of this analysis was to provide rock mass moduli to District structural engineers for subsequent dam stability analyses.

14. SUBJECT TERMS

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Portugués Dam	Rock mass rating

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