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ROCK MASS MECHANICAL PROPERTY ESTIMATION STRATEGY FOR THE YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

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ABSTRACT

Rock mass mechanical properties are required in the design of repository drifts and ramps to asses the impact of thermal loads from the heat-generating wastes on excavation performance and long-term structural stability. The ramps, exploratory drifts and repository excavations will intersect both welded and nonwelded tuffs with varying abundances of fractures, degree of welding and lithophysal content. Rock mass mechanical properties are dependent on both intact rock properties and joint characteristics, and were derived from empirically based relationships of laboratory determined intact rock properties and rock mass quality indices (Q and RMR). Definition and verification of these empirical relationships is considered critical to the drift design methodology because planned thermomechanical testing in the Exploratory Studies Facility (ESF) is limited. Rock mass quality determinations may provide the only practical vehicle for assessment of the effects of variability in drift performance under thermal loads.

This paper presents a method of estimating the rock mass properties for the welded and nonwelded tuffs based on currently available information on intact rock and joint characteristics at the Yucca Mountain site. Variability of the expected ground conditions at the potential repository horizon (the TSw2 thermomechanical unit) and in the Calico Hills nonwelded tuffs is accommodated by defining five rock mass quality categories in each unit based upon assumed and observed distributions of the data.

INTRODUCTION

Sandia National Laboratories (SNL), a participant in the Yucca Mountain Site Characterization Project (YMP) for the U.S. Department of Energy (DOE), is currently investigating the feasibility of locating a high-level nuclear waste repository at Yucca Mountain, Nevada. The investigations include development of a project-wide data base of the thermal and mechanical properties of the rock mass to support pre- and post-closure design and performance assessment activities. Rock mass properties cannot be routinely measured, and therefore must be estimated by using a combination of field observations, laboratory and field testing data, and empirical and/or analytical models. In order to make estimates of rock mass mechanical properties, a review of the existing YMP data was initiated to determine the best available data in the professional judgement of the authors. This paper describes the procedures employed and results of the rock mass mechanical properties estimation. Full details and data sources are provided in Lin, et al (1992a, 1992b).

BACKGROUND

A methodology for estimating rock mass properties from laboratory and field geotechnical data was proposed by Hardy and Bauer (1991) for repository drift design. This methodology is adopted in this study. Two rock mass classifications, the Q system (Barton, et al 1974) and the RMR system (Bieniawski, 197[illegible], were adopted for estimating the rock mass properties because their widespread use has led to empirical correlations between rock mass properties and the rock mass classifications. These rock mass classification methods have been previously employed at Yucca Mountain (Langkopf and Gnirk, 1986) for ground support design.

Variability of rock quality and hence mechanical properties is indicated at the YMP from the core logging data (Lin, et al 1992a). The potential variation of rock mass quality was estimated based on the credible range of each parameter used to calculate the RMR and Q indices. The approach was used to calculate values for five rock mass categories representing the range from the poorest (category 1) to the best (category 5) expected. The rock mass quality categories 1 through 5 were defined so that in the total population of rock mass for a particular unit, the exceedance rate for individual parameters used to calculate RMR and Q would be 95%, 80%, 60%, 30%, or 10%. The parameter value for a particular exceedance rate was based on observed or assumed probability distributions.

Based on the range of expected conditions evident in cores from, and surface exposures near, the potential repository location, the rock models needed to describe the range of observed conditions include elastic, elastoplastic, compliant joint and distinct block models (Hardy and Bauer, 1991). The rock mass mechanical properties were derived for each of the above models. Figure 1 presents the models, the required rock mass mechanical property inputs, linkage of data inputs, and criteria and empirical relationships to develop the rock mass properties. Some properties are based solely on laboratory testing or field data. Others are developed from laboratory and/or field data, rock mass quality and empirical correlations.

ESTIMATED ROCK MASS QUALITY INDICES

Both the RMR and Q rock mass quality indices combine six parameters. The RMR parameters are: strength of the intact rock (C); Rock Quality Designation (RQD); joint spacing (JF); ground-water condition (JW); and rating adjustment for joint orientation (AJO). The six Q parameters are: RQD; joint set number (Jn); joint roughness number (Jr); joint alteration number (Ja); joint water reduction factor (Jw); and stress reduction factor (SRF). Details for assigning rating for each individual parameter are reported in Lin, et al (1992b). These parameters are briefly described herein in three groups: joint-related parameters, strength-related parameters, and groundwater-related parameters.

Joint-related parameters are RQD, JF, and AJO in the RMR system and RQD, Jn, Jr, and Ja in the Q system. RQD was estimated in Lin, et al (1992a) based on the exising raw data from U.S. Geological Survey open-file reports of core holes G1, G4, GU-3 and UE25A#1. Figure 2 presents the estimated RQD versus cumulative probability of occurrence for the Topopah Spring welded, lithophysae-poor unit (TSw2) and the Calico Hills and Lower Paintbrush nonwelded unit (CHn1). The RQD for five rock quality categories were selected so that the cumulative percentage of occurrence was less than 5%, 20%, 40%, 70% and 90% as shown in Figure 2, or alternatively, the RQD exceedance rate was 95%, 80%, 60%, 30%, and 10%. Joint geometric and physical characteristics reported in Lin, et al (1992a) provided the basis for the JF, Jn, Jr, Ja, and AJO parameters. The value of these parameters for the five rock mass quality categories, with the exception of RQD, were estimated assuming a uniform distribution over the parameter range. The probability of exceedance as listed above was used for each category.

One strength-related parameter is included in each of the RMR and Q systems: C and SRF, respectively. The mean value of uniaxial compressive strength laboratory data for each thermo-mechanical unit was used as the representative intact rock strength for all five rock mass quality categories (Lin, et al 1992b).

Both RMR and Q systems include a parameter to account for groundwater conditions. The groundwater condition is described as "dry" for the RMR and Q ratings for both TSw2 and CHn1 units because both units are above the water table in the unsaturated zone (Lin, et al 1992b).

The parameters and calculated RMR and Q indices for the TSw2 and CHn1 units are presented in Table 1 and 2 for each of the five rock mass quality categories. A design rock mass rating (DRMR) was developed to combine the Q and RMR ratings. An estimated RMR, called here RMR′ was calculated from a correlation proposed by Bieniawski (1976), linking Q and RMR:

$$RMR' = 9\ln Q + 44$$

The design rock mass rating (DRMR) listed in Tables 1 and 2 was calculated by averaging the original RMR value and RMR′. This DRMR was used as input in deriving the rock mass mechanical properties.

CALCULATION OF ROCK MASS MECHANICAL PROPERTIES

1. Rock Mass Strength Criteria

The rock mass strength criteria characterizes the strength-confining pressure relationships. The rock mass strength is widely recognized to be dependent on the intact rock strength, the rock mass quality and the scale considered. The empirical methods of Yudhbir, et al (1983) and Hoek and Brown (1988) are both considered credible methods for estimating rock mass strength because they are based on laboratory tests of fractured rocks and field experience. The Yudhbir, et al (1983) and Hoek and Brown (1988) criteria were therefore used to develop a relationship of strength versus confining pressure for the thermomechanical units. The general equation proposed by Yudhbir, et al (1983) was:

$$\sigma_s = A\sigma_c + B\sigma_c\left(\frac{\sigma_3}{\sigma_c}\right)^{\alpha}$$

where
σ_c = intact rock uniaxial compressive strength,

σ_s = the strength of the rock mass,

σ_3 = the confining stress (least principal stress),

A = a dimensionless parameter dependent on the RMR, and

α, B = dimensionless rock material constants dependent on rock type.

The values of A for the rock mass are obtainable from the RMR. The equation relating the RMR to A was developed by Yudhbir, et al (1983) from laboratory tests on fractured rock and is given below:

$$A = e^{0.0765(RMR)-7.65}$$

The material constants B and α are the constants related to the rock type and have to be determined by curve fitting of the triaxial compressive testing results.

The Hoek and Brown criteria was defined as:

$$\sigma_s = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2}$$

where m = a constant that depends on the properties of the intact rock and the rock mass quality for an undisturbed rock mass and is given by

$$m = m_i e^{(RMR - 100)/28} \text{ with}$$

m_i = a constant determined from triaxial strength tests on intact rock, and

s = a constant that depends on the rock mass quality and can be estimated for undisturbed rock from

$$s = e^{(RMR - 100)/9}$$

The relationship was developed by evaluating the Yudhbir and Hoek and Brown methods separately and then averaging the two predicted strengths at discrete confining pressures. With the existing laboratory intact rock compressive strength data and the derived DRMR values, the parameters in both criteria were obtained.

A power-law relationship of the form $\sigma_1 = A + B\sigma_3^C$ was then developed by fitting the resulting average strength versus confining pressure data to describe the strength-confinement response of the rock mass.

Figures 3 and 4 present the design rock mass strengths with confining stress of 0 to 3 MPa for TSw2 and CHn1 units. Rock mass strengths for all five rock quality categories and the curve fitting results for the parameters A, B, and C in the power law relationship are included in each figure. For comparison, the strengths of the TSw2 and Calico Hills intact laboratory-derived Hoek-Brown strength envelope is shown in each figure (Lin, et al 1992b).

2. Rock Mass Mechanical Properties for the Elastic and Elastoplastic Models

The assumption of an equivalent continuum in the elastic and elastoplastic models required an elastic modulus and Poisson's ratio for the rock mass and a Mohr-Coulomb strength criteria. The tensile strength and Mohr-Coulomb strength parameters are used to interpret the elastic analysis and in defining the onset of nonlinear deformation in the elastoplastic models. For the elastoplastic model, the dilation angle is also required as input data. Tables 3 and 4 present the mechanical property results for TSw2 and CHn1 units. Following is a brief discussion of each rock mass mechanical property:

Rock Mass Elastic Modulus: A correlation between the RMR and rock mass elastic modulus (E) was developed by Serafim and Periera (1983):

$$E = 10^{\frac{(RMR - 10)}{40}}$$

where E is in GPa.

The equation can predict elastic modulus values that exceed the values for intact samples when the rock mass quality is high. Therefore, the upper bound limit of the rock mass modulus is equal to the intact rock elastic modulus obtained from laboratory tests.

Rock Mass Poisson's Ratios: Empirical relationships to estimate Poisson's ratio from rock mass quality were not available. The Poisson's ratios obtained from laboratory tests on intact rock samples were therefore adopted as the rock mass Poisson's ratios for all five rock mass quality categories.

Rock Mass Tensile Strengths: Empirical relationships to estimate rock mass tensile strength based on rock mass quality were not available. Since joint strength and persistence are expected to be factors for limiting rock mass tensile strength, Hardy and Bauer (1991) recommended that the rock mass tensile strength be set at the value of one-half the rock mass joint cohesion, predicted using the joint persistence criteria derived for the CJM model. The tensile strength values were calculated based on the estimated continuity averaged cohesion of the weaker joint set discussed in the Joint Frictional Strength section below.

Rock Mass Mohr-Coulomb Strength Parameters and Dilation Angles: The power law rock mass strength criteria were used to obtain the cohesion and angle of internal friction of the Mohr-Coulomb strength parameters. The best-fit was performed over the range of confining pressures from 0 to 3 MPa, which is representative of the projected range in minimum principal stresses near the boundary of the repository excavations. The nonassociated flow rule, of Michelis and Brown (1986), which uses a dilation angle equal to half the internal friction angle, was used.

3. Rock Mass Mechanical Properties for the Compliant Joint and Distinct Block Models

Both the CJM and DBM require definition of the geometry of the joint sets, the mechanical properties of the joints, and the mechanical properties of the intact blocks of rock between joints. Lin, et al (1992b), concluded that the jointed models would not be appropriate for CHn1 unit due to the small number of joints observed in the core log and in excavations in other unwelded tuffs. Table 5 presents the mechanical property estimates for the five rock mass quality categories for the TSw2 unit. Brief discussions for each property are given in the following:

Joint Spacings: Joint spacings were estimated from the RQD for each rock mass quality category based on the relationship proposed by Hudson and Priest (1979). This relationship assumes joints are the primary factor in determining RQD:

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

where λ = total joint frequency (units per meter).

The logs of fracture dips suggest that the majority of fractures are near vertical (60 to 90° dip) with a minor population near horizontal (0 to 30° dip). The percentages of occurrences of joints with high-angle (60-90°) or low-angle (0-30°) dips recognized from the core logs were used to derive the vertical and horizontal joint sets frequencies by taking the calculated total frequencies and multiplying them by the percentage of occurrence for each set.

Joint Frictional Strength: The Mohr-Coulomb strength parameters (cohesion and angle of friction) are used to described the joint strength. In practice, many joints are discontinuous, requiring both failure of intact material at the termination of joints and slip along existing joints for large-scale displacement to occur. A simple method to approximate the strength of a discontinuous joint, proposed by Brown (1971) is to develop effective strength parameters for the joint that are equal to the length-weighted averages of the joint and intact material. The continuities of joints for the Yucca Mountain site were estimated based on traces of joints in photographs of excavated surface pits in the Topopah Spring Member. Experimental data on both the joint and intact rock strengths were summarized by Lin, et al (1992b). The continuity weighted strength parameters were then calculated using the joint and intact rock strength parameters and joint continuities.

Joint Stiffness: Joint deformation in the CJM are described by a hyperbolic normal stress closure relationship and a bilinear shear stiffness expression. Two parameters--the half-closure stress (An) and the maximum closure of the joint (u_{max})--are used to characterize the normal stiffness relationship (Thomas, 1982). Shear stiffness is described using a bilinear model with an elastic stiffness (Gs) until the joint failure is reached, and with a linear, hardening stiffness (Gs'), after the critical shear stress. The joint stiffness values for the five rock mass quality categories were generated from the joint mechanical properties test data from YMP tuff samples and generic-size and stress-dependent studies of shear stiffness by Bandis, et al (1983). The hardening shear stiffness was assumed to be zero or equivalent to perfectly plastic behavior for this study. The joint deformation in the DBM has both the normal and shear stiffness as either a constant value or a function of the normal stress. These values were determined from straight line fits to the joint deformation curves defined for the CJM.

Intact Block Elastic Properties: Elastic modulus and Poisson's ratio for the intact blocks between joints were assumed to be equal to laboratory test values.

Compressive Strength of Intact Blocks: The effect of size on the intact rock strength for the welded tuff in the Topopah Spring Member as determined by Price (1986) was adopted to estimate the strength of the blocks of intact rock between joints. A power law best-fit result was reported as

$$\sigma_c = 1944D^{(-0.846)} + 69.5$$

where σ_c = uniaxial compressive strength (MPa)

D = sample diameter (mm)

The spacing between vertical joints was used as the size of the intact blocks.

CONCLUSIONS

The rock mass mechanical properties for various rock mass quality categories in two thermomechanical units, where most of the site characterization excavations will occur, have been calculated and presented. Existing data from the four coreholes used to evaluate rock mass quality at the YMP site indicates considerable vertical and lateral variability in all thermomechanical units. This variability has been used as the basis for evaluating credible ranges in rock mass mechanical properties. The resulting estimated range in rock mass mechanical properties is large. For example, the rock mass modulus estimates range between 5.5 and 32.7 MPa for the TSw2 unit.

The large range in estimated properties may be due in part to several factors, including the limited data on which the estimates are based, the conservative assumptions that have been made in lumping all adverse or worst case parameters together for the poorest rock mass categories, and the inaccuracies or inadequacies of the empirical correlations on which some of the properties are based.

An approach for estimating the rock mass mechanical properties is considered of equal or greater importance than the current estimates of the properties themselves. Strategies for field testing to verify and/or measure the rock mass properties are based on very limited testing. Extrapolations of these limited results to repository designs that accommodate thermal loads in particular will be based, to a large degree, on quantification of the variability of rock mass quality indices and subsequent estimates of how that variability will impact rock mass mechanical properties. Projections of excavation response to thermal loads, and the ground support necessary to maintain the excavation for the retrievability period, will be based upon modeling studies using the rock mass properties. Hence it is important that the ESF testing strategies recognize how data developed at one site can be utilized and extrapolated to sites with differing rock quality.

ACKNOWLEDGEMENTS

Data utilized to estimate the rock mass properties for input to the various constitutive models is based upon numerous technical studies conducted in the Yucca Mountain Project. This paper cites only the background literature that provides the basis for the technical approach to estimating the rock mass properties. The specific data references are too numerous to cite in this article and the reader is directed to Nimick and Schwartz (1987), Price, et al (1984), and Olsson and Jones (1980) and to the reports by Lin, et al (1992a and 1992b) for the sources of specific data.

REFERENCES

Bandis, S. C., A. C. Lumsden and N. R. Barton, 1983. "Fundamentals of Rock Joint Deformation," International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 20(6):249-268, Pergamon Press Ltd., Great Britain.

Barton, N. R., R. Lien and J. Lunde, 1974. "Engineering Classification of Rock Masses for the Design of Tunnel Support," Rock Mechanics, 6:189-236, Springer Verlag.

Bieniawski, Z. T., 1976. "Rock Mass Classification in Rock Engineering," Proceedings, Symposium on Exploration for Rock Engineering, Johannesburg, South Africa, pp. 97-106, A. A. Balkema, Rotterdam.

Bieniawski, Z. T., 1979. "The Geomechanics Classification in Rock Engineering Applications," Proceedings, 4th International Congress on Rock Mechanics, Montreaux, Switzerland, 2:41-48, A. A. Balkema, Rotterdam.

Brown, E. T., 1971. "Strength of Models of Rock with Intermittent Joints," Journal of the Soil Mechanics and Foundation Division, 96(SM6):1935-1949.

Hardy, M. P. and S. J. Bauer, 1991. "Drift Design Methodology and Preliminary Application for the Yucca Mountain Site Characterization Project," SAND89-0837, Sandia National Laboratories, Albuquerque, NM.

Hoek, E. and E. T. Brown, 1988. "The Hoek-Brown Failure Criterion - A 1988 Update," Canadian Rock Mechanics Symposium, np.

Hudson, J. A. and S. D. Priest, 1979. "Discontinuities and Rock Mass Geometry," International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 16(6):339-362, Pergamon Press.

Langkopf, B. S. and P. R. Gnirk, 1986. "Rock-Mass Classification of Candidate Repository Units at Yucca Mountain, Nye County, Nevada," SAND82-2034, Albuquerque, NM.

Lin, M., M. P. Hardy and S. J. Bauer, 1992a. "Fracture Analysis and Rock Quality Designation Estimation for the Yucca Mountain Site Characterization Project," SAND92-0449, Sandia National Laboratories, Albuquerque, NM.

Lin, M., M. P. Hardy and S. J. Bauer, 1992b. "Rock Mass Mechanical Property Estimations for the Yucca Mountain Site Characterization Project," SAND92-0450, Sandia National Laboratories, Albuquerque, NM.

Michelis, P. and E. T. Brown, 1986. "A Yield Equation for Rock," Canadian Geotechnical Journal, 23:9-17, np.

Nimick, F. B. and B. M. Schwartz, 1987. "Bulk, Thermal, and Mechanical Properties of the Topopah Spring Member of the Paintbrush Tuff, Yucca Mountain, Nevada," SAND85-0762, Sandia National Laboratories, Albuquerque, NM.

Olsson, W. A. and A. K. Jones, 1980. "Rock Mechanics Properties of Volcanic Tuffs from the Nevada Test Site," SAND80-1453, Sandia National Laboratories, Albuquerque, NM.

Price, R. H., 1986. "Effects of Sample Size on the Mechanical Behavior of Topopah Spring Tuff," SAND85-0709, Sandia National Laboratories, Albuquerque, NM.

Price, R. H., S. J. Spence and A. K. Jones, 1982. "Uniaxial Compression Test Series on Topopah Spring Tuff from USW GU-3, Yucca Mountain, Southern Nevada," SAND83-1646, Sandia National Laboratories, Albuquerque, NM.

Serafim, J. L. and J. P. Periera, 1983. "Consideration of the Geomechanical Classification of Bieniawski," Proceedings, International Symposium on Engineering Geology and Underground Construction, pp. 1133-1144, np.

Thomas, R. K., 1982. "A Continuum Description for Jointed Media," SAND81-2615, Sandia National Laboratories, Albuquerque, NM.

Yudhbir, W. Lemonza and F. Prinzl, 1983. "An Empirical Failure Criterion for Rock Masses," 5th International Congress on Rock Mechanics, pp. B1-B8, ISRM, Melbourne, Australia.

TABLE 1 RMR and Q Parameter Estimated Values for Each Rock Mass Quality Category, TSw2 Unit

Parameter		Rock Mass Quality Category				
		1	2	3	4	5
RMR	C	12	12	12	12	12
	RQD	3	8	8	13	17
	JF	5	6	7	9	10
	JC	25	26	27	29	30
	JW	15	15	15	15	15
	AJO	-11	-10	-7	-4	-1
	RMR	49	57	62	73	82
Q	RQD	16.0	26.0	41.0	62.0	84.0
	Jn	8.7	7.6	6.2	4.1	2.7
	Jr	2.1	2.4	2.8	3.4	3.8
	Ja	3.9	3.4	2.8	1.9	1.3
	Jw	1.0	1.0	1.0	1.0	1.0
	SRF	4.8	4.2	3.4	2.2	1.4
	Q	0.21	0.57	1.94	12.30	64.96
DRMR		40	48	56	70	82

TABLE 2 RMR and Q Parameter Estimated Values for Each Rock Mass Quality Category, CHn1 Unit

Parameter		Rock Mass Quality Category				
		1	2	3	4	5
RMR	C	4	4	4	4	4
	RQD	3	13	17	20	20
	JF	11	12	14	17	19
	JC	20	20	20	20	20
	JW	15	15	15	15	15
	AJO	-11	-10	-7	-4	-1
	RMR	41	54	63	72	77
Q	RQD	22.0	58.0	77.0	91.0	94.0
	Jn	1.0	0.9	0.8	0.7	0.6
	Jr	1.1	1.2	1.4	1.7	1.9
	Ja	3.9	3.4	2.8	1.9	1.3
	Jw	1.0	1.0	1.0	1.0	1.0
	SRF	10.0	10.0	10.0	10.0	10.0
	Q	0.61	2.27	4.81	12.53	24.98
DRMR		40	53	60	70	75

TABLE 3 Rock Mass Mechanical Properties for the Elastic and Elastoplastic Models for TSw2 Unit

Mechanical Property	Rock Mass Quality Category				
	1	2	3	4	5
Elastic Modulus (GPa)	5.47	9.02	14.04	31.61	32.7
Poisson's Ratios	0.22	0.22	0.22	0.22	0.22
Tensile Strength (MPa)	0.45	1.80	3.65	6.35	8.15
Rock Mass Cohesion (MPa)	1.1	1.5	2.2	4.7	9.9
Angle of Internal Friction (degrees)	48	49	49	49	48
Dilation Angle (degrees)	24	24	25	24	24

TABLE 4 Rock Mass Mechanical Properties for the Elastic and Elastoplastic Models for CHn1 Unit

Mechanical Property	Rock Mass Quality Category				
	1	2	3	4	5
Elastic Modulus (GPa)	5.74	6.00	6.00	6.00	6.00
Poisson's Ratios	0.23	0.23	0.23	0.23	0.23
Tensile Strength (MPa)	0.15	0.60	1.20	2.15	2.75
Rock Mass Cohesion (MPa)	0.3	0.5	0.8	1.4	1.9
Angle of Internal Friction (degrees)	19	20	20	20	20
Dilation Angle (degrees)	10	10	10	10	10

TABLE 5 Rock Mass Mechanical Properties for the Compliant Joint and Distinct Block Models for TSw2 Unit

Mechanical Property	Rock Mass Quality Category				
	1	2	3	4	5
Horizontal Joint Set Spacing (m)	0.61	0.76	1.00	1.51	2.81
Vertical Joint Set Spacing (m)	0.03	0.04	0.06	0.08	0.16
Horizontal Joint Cohesion (MPa)	18.9	21.6	25.2	30.6	34.2
Vertical Joint Cohesion (MPa)	0.9	3.6	7.3	12.7	16.3
Horizontal Joint Friction Angle (degrees)	41	42	43	43	42
Vertical Joint Friction Angle (degrees)	41	43	46	48	49
Half-closure Stress (MPa)	0.58	0.80	1.10	1.55	1.85
Maximum Closure of Joint (10^{-5} m)	3.44	2.94	2.28	1.29	0.63
Elastic Stiffness of Joint (10^{-5} MPa/m)	0.51	2.01	4.01	7.00	9.00
Intact Block Elastic Modulus (GPa)	32.7	32.7	32.7	32.7	32.7
Intact Block Poisson's Ratio	0.22	0.22	0.22	0.22	0.22
Intact Block Compressive Strength (MPa)	161	152	135	115	97

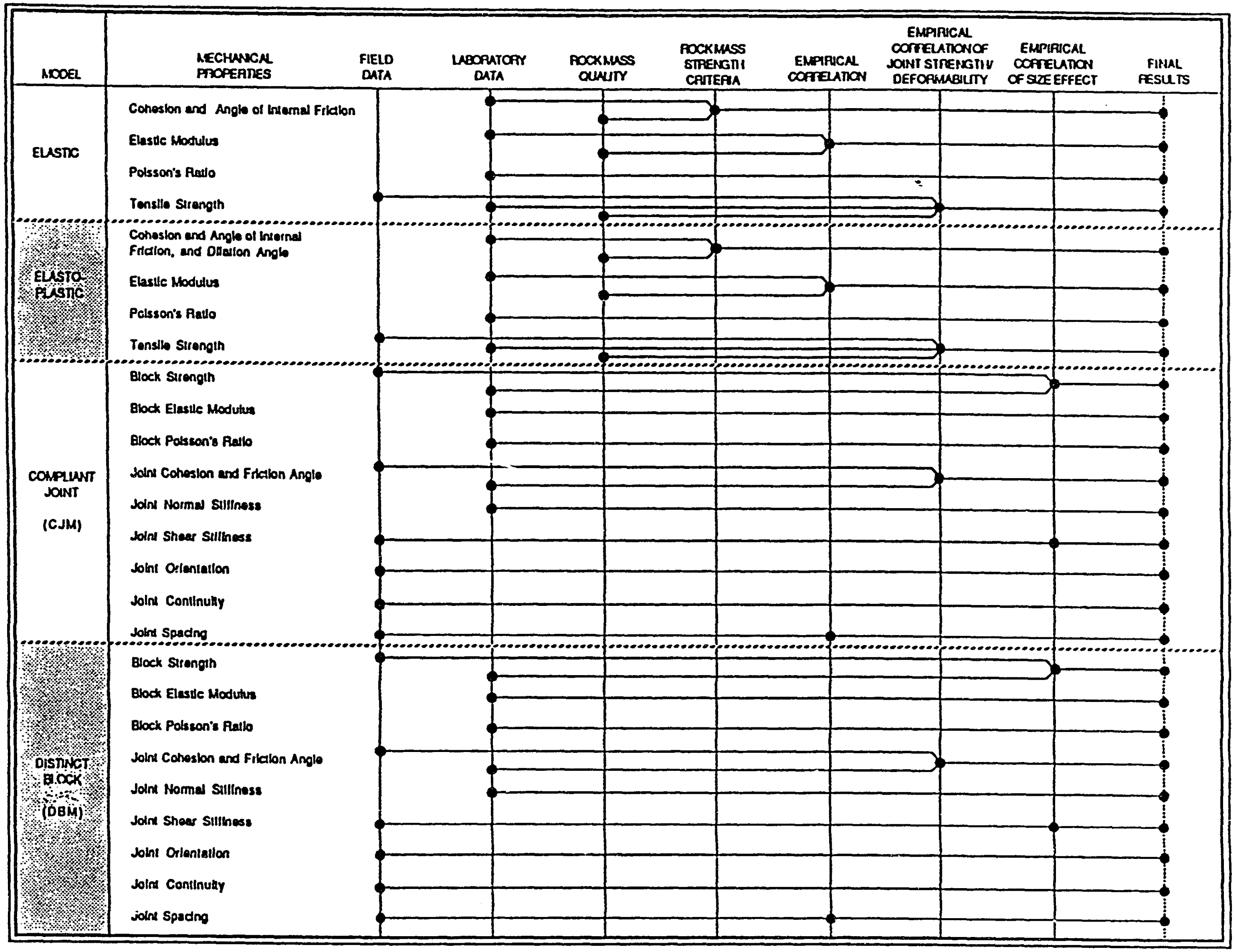

Figure 1. Paths for Derivation of Rock Mass Mechanical Properties

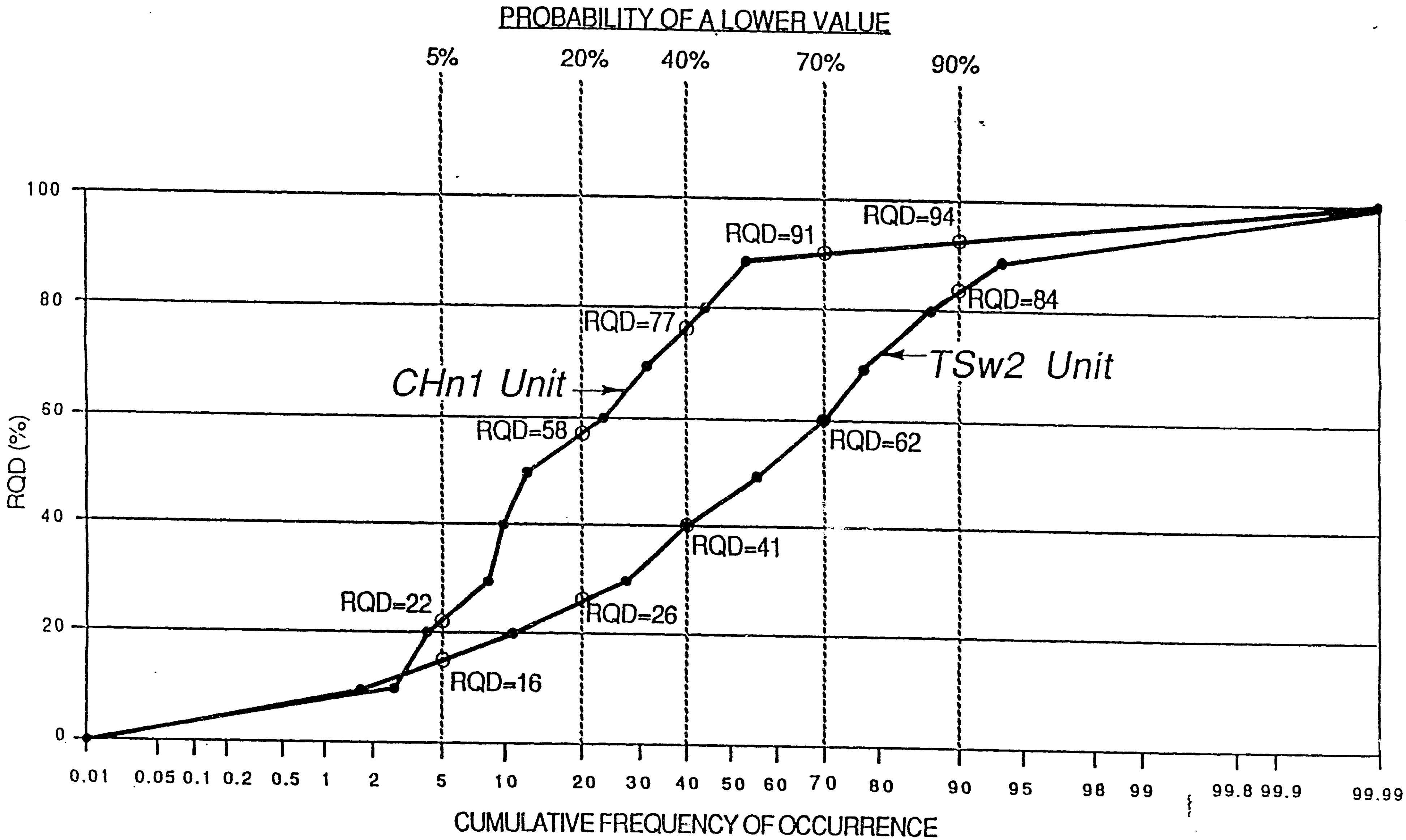

Figure 2. Rock Quality Designation Versus Cumulative Probability of Occurrence for TSw2 and CHn1 Units

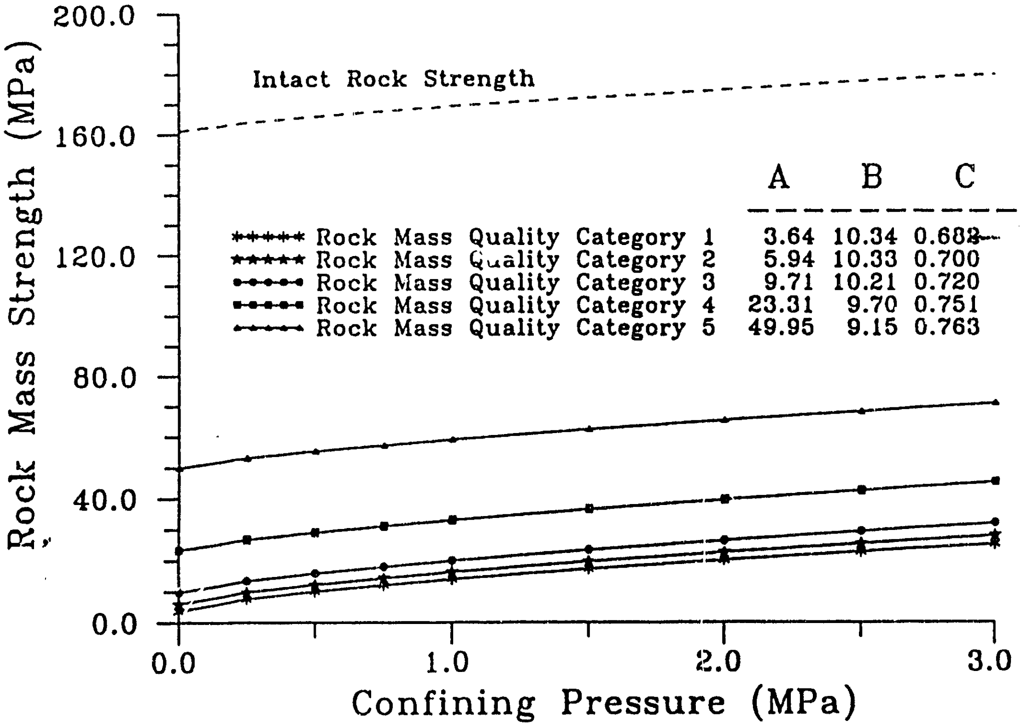

Figure 3. Rock Mass Strength Curves for TSw2 Unit

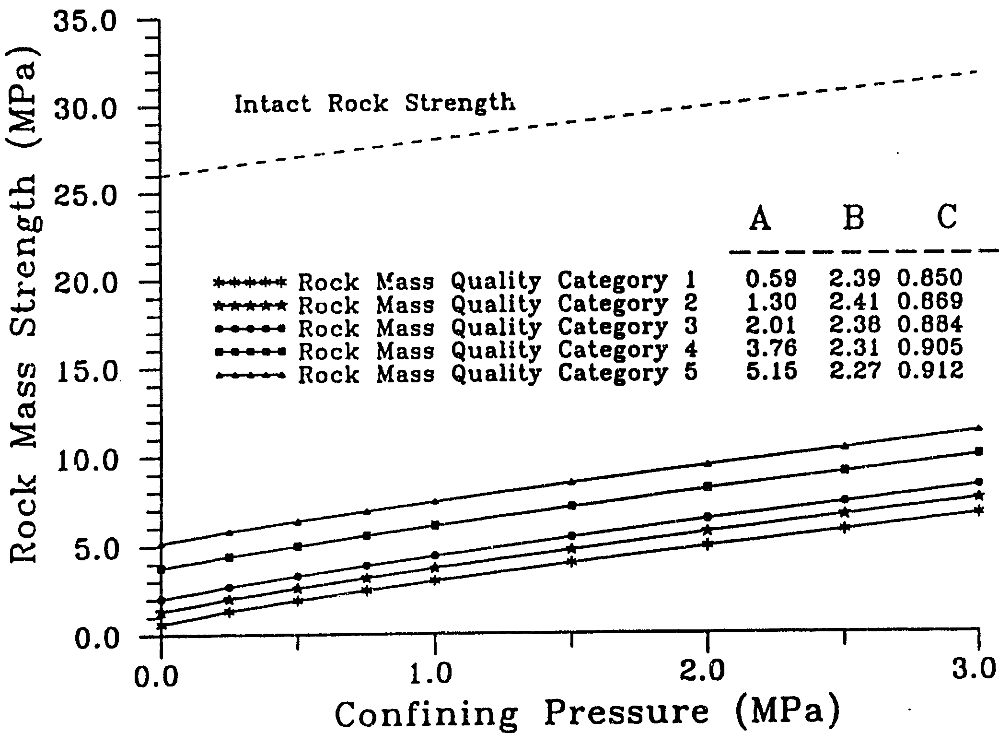

Figure 4. Rock Mass Strength Curves for CHn1 Unit

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