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Volumetric Rock Quality Designation with Lognormally Distributed Intact Lengths

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ABSTRACT. Rock fragments due to different joint types are classified qualitatively into three categories as bars, plates and prisms. However in engineering evaluations their quantitative descriptions based on the field observations leading to reliable design values are of prime importance. Simple conceptual models of rock fragments coupled with the scanline measurements provide objective relationships between the rock quality designation *(RQD)*, volumetric, areal of linear (along scanline) joint counts (J_v) and block volumes *(V)*. The main purpose of this paper is to derive such relevant relationships for the logarithmically distributed intact lengths. Due to the complication of these relationships the results are presented in the form of various charts which are hoped to provide useful tools for any engineering geologist. The presented charts are for standard deviation equal to unity, however, charts for any desired value of standard deviation can be prepared from the relevant equations. The implementation of the methodology is performed for actual field data. A significant conclusion is that the negative exponential distribution provides a single volumetric *RQD* value which is different than the directional *RQD's*. However, the log-normal distribution gives almost the result within the practical limits both for directional and volumetric *RQD* values. This is a valid conclusion that the log-normal distribution represents the field data better than negative exponential.

Introduction

The quantification of joints in a rock mass for construction purposes such as dams, highways, tunnels,... etc. presents one of the most delicate problems in engineering geology domain. With his sound geological background, an engineering geologist

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might recognize the genesis of the joints but lack of quantitative evaluation techniques hinders him from a reliable decision concerning construction of engineering structures. Existance of joints in forms of faults, fractures, fissures, ...etc., render a rock mass into a collection of fragments of different sizes, shapes and stabilities. A first glance on the surface of a rock at an outcrop or at freshly cut locations, gives the invariable impression that the joints occur in a random fashion and so are the block shapes, sizes and positions. It is, therefore, necessary to use statistical techniques in their evaluations. Consequently, extensive field data are needed for the effective use of these techniques.

The early field measurements of joined rocks for engineering purposes are initiated by Deere (1963) who was interested in knowing the percentage of intact lengths greater than 10 cm along any direction. He referred to this percentage as the Rock Quality Designation *(RQD)* which became an intensive study area since then. His simple equation can be written as :

$$RQD = 100 \frac{L_s}{L} \tag{1}$$

where L is the total length and L_s is

$$L_s = \sum_{i=1}^{n} x_i \tag{2}$$

in which x_i is the i-th intact length greater than 10 cm; and n is the number of such intact lengths. In order to get a reliable *RQD* value, the scanline length must be rather long and practically, not less than 10 m. A useful chart depending on the average intact length has been developed by Şen and Kazi (1984, Figure 2) at different relative percentage errors.

Equation (1) gives different *RQD* values along different directions for the same rock mass. So the engineering geologist is confused as to which one of the values to adopt in quantitative evaluations. This point brings out various questions as (i) what is the probability distribution function *(PDF)* of intact lengths in a given rock mass?; (ii) what is the relationship of the *PDF* to the *RQD*; and (iii) which value of *RQD* should be adopted as a representative measure of the rock mass concerned ?

Pioneering studies concerning partial answers to the first and second questions are due to Priest and Hudson (1976, 1981), and Hudson and Priest (1979) who relied on the negative exponential *PDF* for the intact lengths. Their analytical studies lead to the expectation of *RQD* value within a rock mass as :

$$E(RQD) = 100 \; (1 + 0.1\,\lambda) \; e^{-0.1\,\lambda} \tag{3}$$

where λ is the average number of the fractures along a scanline and it is the only parameter of negative exponential distribution. Şen and Kazi (1984) suggested modifications to equation (3) for finite and very short scanlines. Goodman and Smith (1980) made extensive computer simulation for appreciation of *RQD* distribution again on the basis of negative exponential *PDF*. However, nobody so far succeded in obtaining *RQD* distribution. In fact, it is a potential research topic not for practical activities but rather for academic interest and achievements.

A more general framework concerning intact length *PDF* and *RQD* relationship is presented by Şen (1984) who considered not only the negative exponential distribution but additionally, uniform, normal (Gauss), logarithmic normal and Gamma distributions. Scanline surveys have revealed on many occasions that it is not possible to attribute a unique value of *RQD* to either a rock mass or part of a rock mass since there appears more than one *RQD* value. Hence, there is always a risk associated with the chosen *RQD* value to be less than the value used in any design. The answer to the third question has been provided by Şen (1990) by defining new terminologies such as Rock Quality Percentage *(RQP)* and Rock Quality Risk *(RQR)*. Rock Quality Percentage is the relative frequency distribution of a certain type of rock quality description (as very good, good, fair, poor and very poor) to occur within the same rock mass. On the other hand, Rock Quality Risk is the probability of an *RQD* value being less than a measured *RQD* value. *RQR* acts as a quantitative measure of risk description and it is related to the cumulative *PDF* of *RQD*.

Unfortunately, non of the aforementioned equations or definitions are applicable to rock fragments in terms of volumes. However, Palmstrom (1982, 1985) proposed the volumetric joint count, J_v as a simple measure of the degree of jointing which is easily calculated from standard joint descriptions. Şen and Eissa (1990) have proven that his relationship is valid only for moderate values of *RQD* otherwise it gives unreliable results. Besides, all of the aforementioned studies were based on the negative exponential *PDF* of intact lengths whereby an implied assumption exists such that the average intact lengths is equal to their standard deviation value. Such an assumption cannot be valid for all of the natural occurrences of fractures, (Şen 1984). Therefore, there is a need to investigate the fracture behaviors based on intact length *PDF* apart from negative exponential distribution.

The main purpose of this paper is to derive analytical expressions relating J_v, *RQD* and block volumes of different shapes such as bars, plates or prisms. The results are presented in forms of charts which provide simple and practical tool for practicing earth scientists without any theoretical background.

Basic Definitions

Figure 1a shows a set of three dimensional orthogonal discontinuities within a rock mass. These discontinuities split the rock mass into blocks of different volumes, shapes and sizes all of which depend basically on the intact lengths between successive discontinuities along any direction. In this study, the *PDF* of the intact lengths in all directions will be assumed as the logarithmic normal *PDF*.

In practical studies, if intact length measurements are taken along more or less orthogonal three directions, namely, *X*, *Y* and *Z* then the average number of discontinuities along each direction will be denoted as λ_x, λ_y and λ_z. However, irrespective of *PDF* there is only one unique relationship between these parameters and the average intact lengths, $\bar{x}$, $\bar{y}$ and $\bar{z}$ as :

$$\bar{x} = 1/\lambda_x \;,\; \bar{y} = 1/\lambda_y \;\text{ and }\; \bar{z} = 1/\lambda_z \qquad (4)$$

Depending on the relative values of average discontinuity numbers of average intact lengths along each direction the fractured rock mass may be regarded as either homogeneous or heterogeneous. The fractured rock mass can be idealized either as collection of prismatic blocks or as plates or as bars according the significance of relative dimensions.

(i) Prismatic Blocks

The three dimensions of these blocks are individually significant in their definitions, (see Fig. 1b). Practically, none of the dimensions can be ignored and the relative error between any combination of the two dimensions is greater than 5 percent.

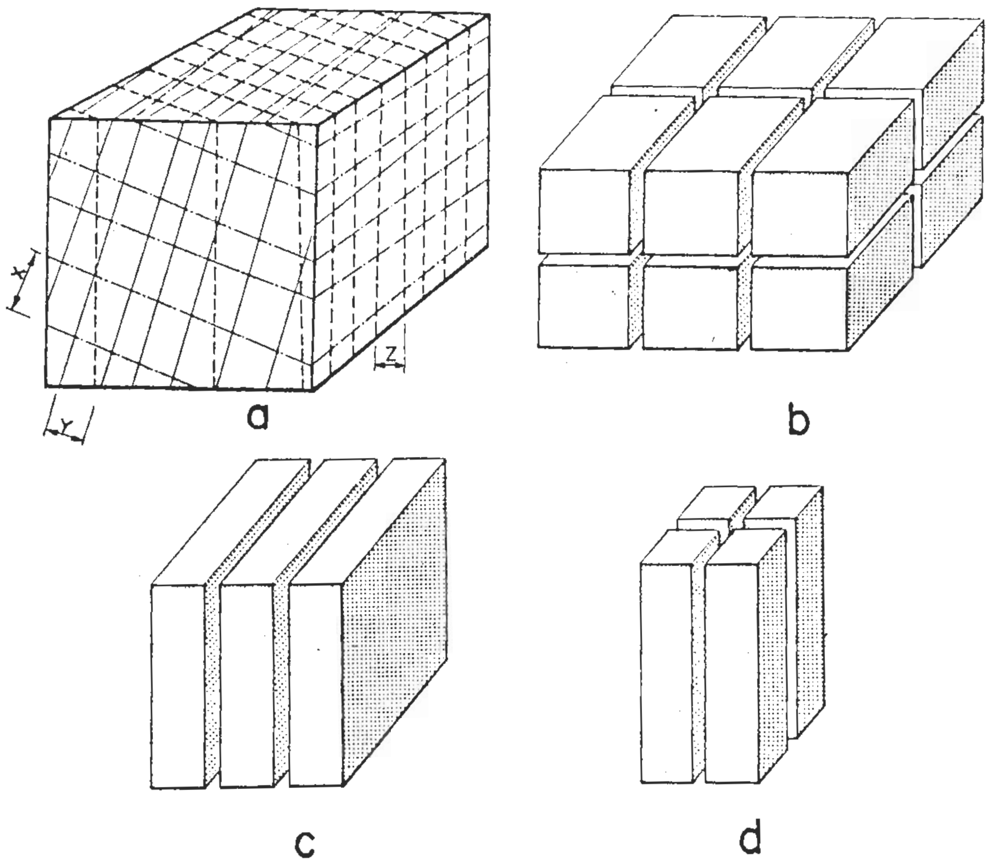

FIG. 1. (a) Block diagram with 3 orthogonal joint sets; (b) Prismatic blocks; (c) plate blocks; (d) bar blocks.

(ii) Plate Blocks

These are similar to slabs where two of the three dimensions are relatively larger than the third dimension, (see Fig. 1c). In the following sequel with no loss of generality the thickness of plate blocks will be assumed as unity.

(iii) Bar Blocks

Only on dimension is significant than any other dimension, (see Fig. 1d). The classical scanline measurements treat the rock mass along the measuring tapes as composed of the bar blocks. The importance is attached to a single dimension only whereas the other two dimensions are not taken into consideration or they are treated as fixed units, for instances, 1cm × 1cm or 1m × 1m, ... etc.

It is logical that the block number increases with the increase of joints (discontinuities) within the volume of rock mass. Besides, the block dimensions are limited by the intact lengths. Therefore, intuitively there appears relationships between the volume of the rock mass, number of discontinuities, intact lengths distribution, i.e. its statistical parameters such as the mean and standard deviation, *RQD* and volumetric joint count. To the best of authors knowledge there appear no analytical relationships in the literature concerning these variables. Hence, the following section includes the derivation of meaningful quantitative relationships which will help the engineers to base their design decisions concerning fractured or faulted rock behaviour prior to any engineering activity.

Analytical Derivations

Figure 1a indicates block diagram with three discontinuity sets having intact lengths x, y and z and correspondingly average number of discontinuities as λ_x, λ_y and λ_z. The number of discontinuities intersecting unit volume of rock mass is defined as the volumetric count, J_v (Palmstrom 1982),

$$J_v = \lambda_x + \lambda_y + \lambda_z \tag{5}$$

or by considering Eq. 4 one can write that

$$J_v = \frac{l}{\bar{x}} + \frac{1}{\bar{y}} + \frac{1}{\bar{z}} \tag{6}$$

In fact, J_v takes into consideration the degree of jointing and all the occuring joints in the rock mass. Eq. 6 can be written with a common denominator as :

$$J_v = \frac{A_{xy} + A_{yz} + A_{zx}}{V} \tag{7}$$

in which A_{xy}, A_{yz} and A_{zx} are the lateral surfaces of rock block and V is the volume of the block. Notice that J_v has the dimension 1/[L]. Furthermore, Eq. 6 can be written in terms of average discontinuity numbers by using Eq. 4 as :

$$J_v = \frac{1}{V} \left(\frac{1}{\lambda_x \lambda_y} + \frac{1}{\lambda_y \lambda_z} + \frac{1}{\lambda_z \lambda_x} \right) \tag{8}$$

This is the general expression which provides relationship between the volumetric joint count, average number of discontinuities and the block volume. It is interesting to notice at this stage that Eq. 8 does not depend on any *PDF*.

$RQD - J_v - V$ Relationships

These relationships prove useful in inferring the volumetric properties such as the block sizes or J_v from a scanline measurement along one direction leading to *RQD* value. The basic expression for the derivation of such relationships can be obtained from Eq. 6 as :

$$J_v = \frac{\bar{x}\bar{y} + \bar{y}\bar{z} + \bar{z}\bar{x}}{\bar{x}\,\bar{y}\,\bar{z}} \tag{9}$$

The relationship between *RQD* and the statistical parameters of the intact lengths can be obtained only after identifying the *PDF* of intact lengths. Identification of this *PDF* has been a preliminary requirement in all the previous studies (Priest and Hudson, 1976, 1981; Hudson and Priest, 1979 and Şen 1984). For instance the expectation of *RQD* for the logarithmically distributed intact lengths is given by Şen (1984) as follows :

$$E(RQD) = 100 \left[1 - F \left[\frac{Ln\,(\lambda t)}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right] \tag{10}$$

In which [.] denotes the area under the standardized normal probability distribution function from $-\infty$ to the value within the brackets; σ_{Lnx} is the standard deviation of logarithmic intact lengths; t is the threshold value, and finally λ is the average number of discontinuity. The combination of Eqns. 9 and 10 leads to the desired relationships for different block types as follows :

(i) Bar Blocks

In this case $\bar{x} = \bar{y} = 1$ and therefore Eq. 9 yields

$$J_v = 2 + \lambda_z \tag{11}$$

which relates the volumetric discontinuity count to the average discontinuity number along one direction. Substitution of λ_z from Eq. 11 into Eq. 10 leads to

$$E(RQD) = 100 \left[1 - F \left[\frac{\text{Ln}\,[(J_v - 2)\,t]}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right] \tag{12}$$

Furthermore, if $t = 0.1$m is used as a threshold value then practically Eq. 12 becomes

$$E(RQD) = 100 \left[1 - F \left[\frac{\text{Ln}\,[0.1\,(J_v - 2)]}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right] \tag{13}$$

which shows that there is a nonlinear correlation between *RQD* and J_v, contrary to what was proposed by Palmstrom (1982) as a theoretical correlation

$$RQD = 115 - 3.3\,J_v \tag{14}$$

In addition, at times Eq. 14 yields *RQD* values more than 100 which is not plausible. For instance, if $J_v = 3$ then Eq. 14 gives $RQD = 105$. However, for the same J_v value Eq. 13 yields results for any σ_{Lnx} value which are within the feasible *RQD* range. Fig. 2 shows the graphical variation of *RQD* with J_v. For the sake of comparison

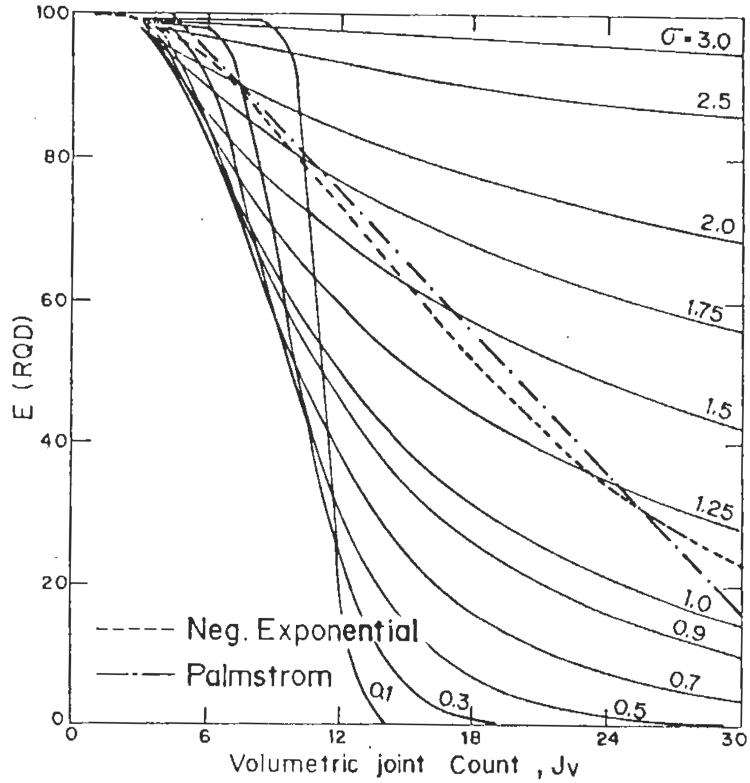

FIG. 2. Bar block RQD-J_v charts, (t = 0.10 m).

Palmstrom straight line and negative exponential *PDF* curve from Şen and Eissa (1990) are shown on the same graph. It is obvious that for only very small J_v values the logarithmic and negative exponential *PDF*s yield rather close *RQD* values. Otherwise, moderate and big J_v values show significant differences especially for large standard deviation values. On the other hand, as expected the bigger is the standard deviation the better is the rock quality. Especially, irrespective of standard deviation value, the Palmstrom straight line does not represent *RQD* deterioration is faster for small standard deviations, (practically less than 1.5). In order to appreciate the effect of threshold value on the rock quality description definition, Fig. 3 and 4 are provided with $t = 0.05$ and $t = 0.20$, respectively. Comparison of Figs. 2-4 indicates that smaller threshold values give rise to better rock quality descriptions for any intact length distribution. However, reduction in the rock quality is quicker for negative exponential distribution than the logarithmic normal distribution. Notice that

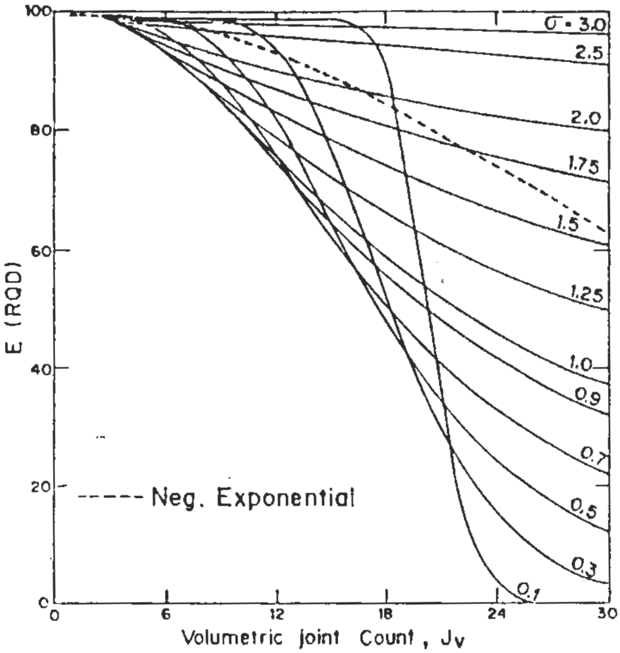

FIG. 3. Bar block RQD-J_v charts. (t = 0.05 m).

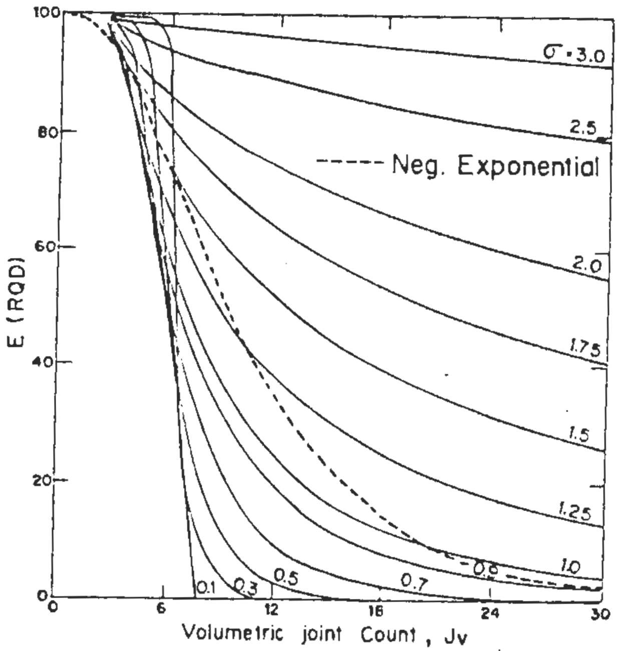

FIG. 4. Bar block RQD-J_v charts. (t = 0.20 m).

big standard deviation intact length rock quality is not affected by threshold value as for smaller standard deviations. Although Deere (1963) has adopted the threshold value as 10 cm, dependant on the significance of the engineering structure it might be bigger or smaller than this value. Although in coarsly fractured rocks the choice of threshold value as 0.05, 0.10 or 0.20 m does not make any change in *RQD* value, the effect of such choice is very much pronounced if the intact lengths concentrate around these figures. For instance, in a scanline measurement where the shortest intact length is above 20 cm the choice of threshold value is immaterial. However, if the intact lengths have smaller values than the choice matters.

On the other hand, the triple relationship between λ_z, J_v and V can be obtained from Eq. 9 after the necessary substitution for the bar blocks

$$J_v = (1 + \frac{2}{\lambda_z}) \frac{1}{V} \tag{15}$$

from which the substitution of λ_z into Eq. 10 yields in general

$$E(RQD) = 100 \{ 1 - F [\frac{\mathrm{Ln} (\frac{2t}{VJ_v - 1})}{\sigma_{Lnx}} - \sigma_{Lnx} + 1] \} \tag{16}$$

or specifically for $t = 0.1$ one can rewrite this expression as

$$E(RQD) = 100 \{ 1 - F [\frac{\mathrm{Ln} (\frac{0.2}{VJ_v - 1})}{\sigma_{Lnx}} - \sigma_{Lnx} + 1] \} \tag{17}$$

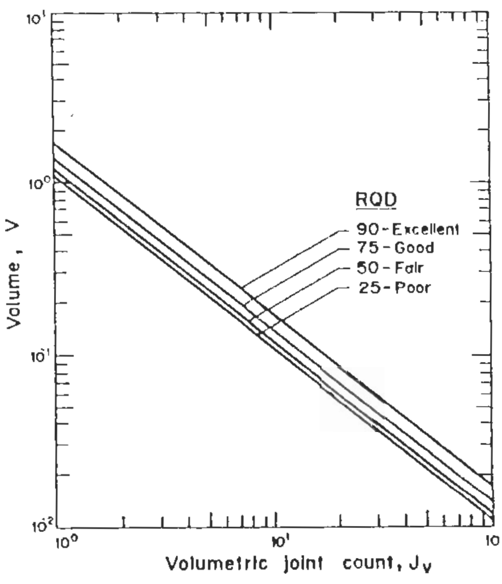

FIG. 5. Bar block *RQD*-J_v-*V* charts.

J_v cannot be selected independently from V hence the application of this equation is conditioned on Eq. 15. For practical purposes the necessary chart is presented in Fig. 5. It is to be noted that this figure is for $\sigma_{Lnx} = 1.0$. However, different charts may be obtained similarly for different standard deviations.

(ii) Plate Blocks

By considering a unit dimension along Z axis ($\bar{z} = 1$) and the properties of plate blocks as mentioned in the previous section, Eq. 9 yields

$$J_v = 1 + (1 + \alpha)\lambda \tag{18}$$

in which λ corresponds to the biggest value of λ_x and λ_y. The substitution of λ from this expression into Eq. 10 leads to

$$E(RQD) = 100 \left\{ 1 - F\left[\frac{\mathrm{Ln}\left[\left(\frac{J_v - 1}{1 + \alpha}\right) t\right]}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right\} \tag{19}$$

or for $t = 0.1$

$$E(RQD) = 100 \left\{ 1 - F\left[\frac{\mathrm{Ln}\left[\left(\frac{J_v - 1}{1 + \alpha}\right) 0.1\right]}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right\} \tag{20}$$

Figures 6, 7 and 8 present the relationship between RQD and J_v for different stan-

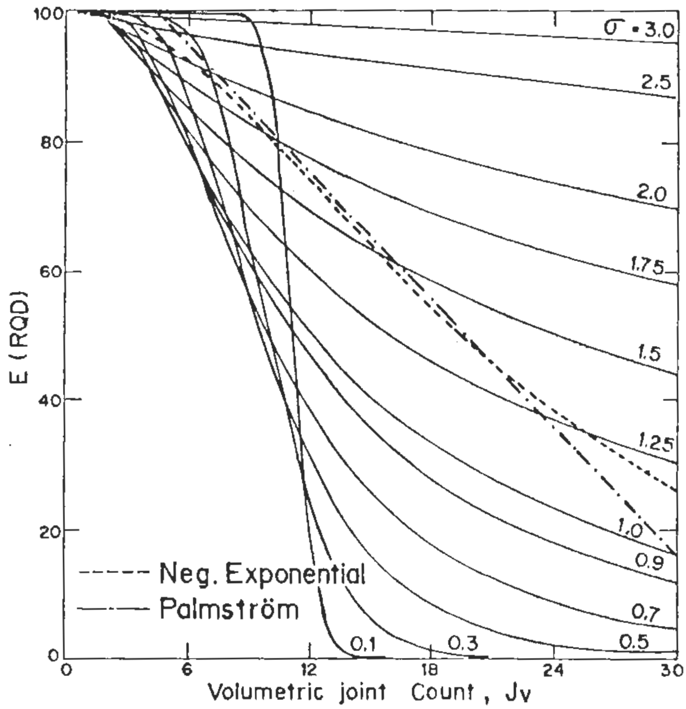

FIG. 6. Plate block RQD-J_v charts, ($\alpha = 0.1$, $t = 0.10$m).

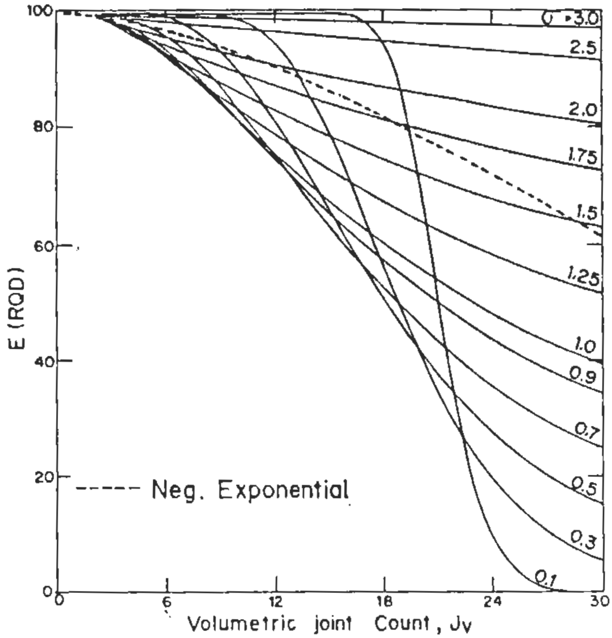

FIG. 7. Plate block RQD-J_v charts, (α = 0.1, t = 0.05m).

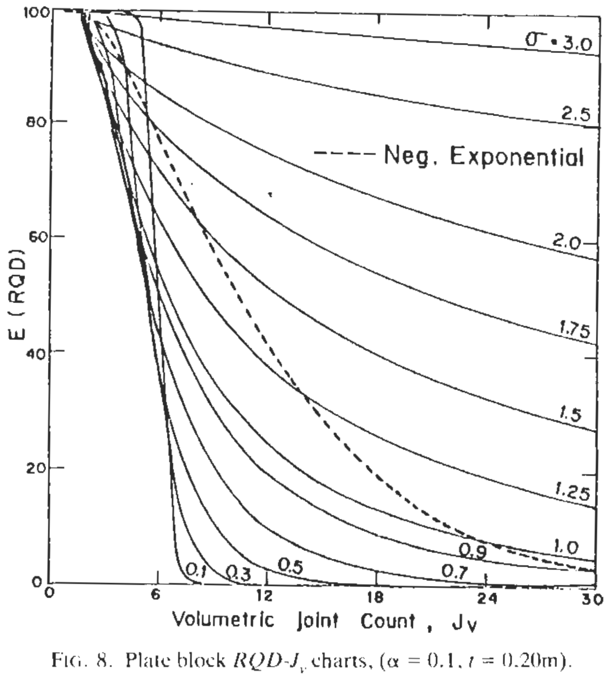

FIG. 8. Plate block RQD-J_v charts, (α = 0.1, t = 0.20m).

dard deviation and threshold values in the case of plate blocks. Again increase in the standard deviation value implies better rock qualities. On the contrary decrease in the threshold value gives rise to increase in the *RQD* value. The Palmstrom's straight line well represents the *RQD* values for plate blocks for moderate volumetric joint count especially when $5<J_v<20$. Such a representation is valid for the negative exponential distribution only as obvious from Fig. 6. However, this straight line approximation does not represent at all any RQD-J_v relationships if the intact lengths originate from logarithmic normal distribution. As was in the bar block case Fig. 7 and 8 indicate that *RQD* deteriorates with increasing threshold value for negative exponential distribution and for small standard deviation logarithmic normal distribution. Finally Fig. 9 and 10 provide RQD-J_v relationships for $\alpha = 0.5$ and $\alpha = 0.9$ respectively. Comparison of Fig. 6, 9 and 10 which are valid for $t = 0.1$ but different α

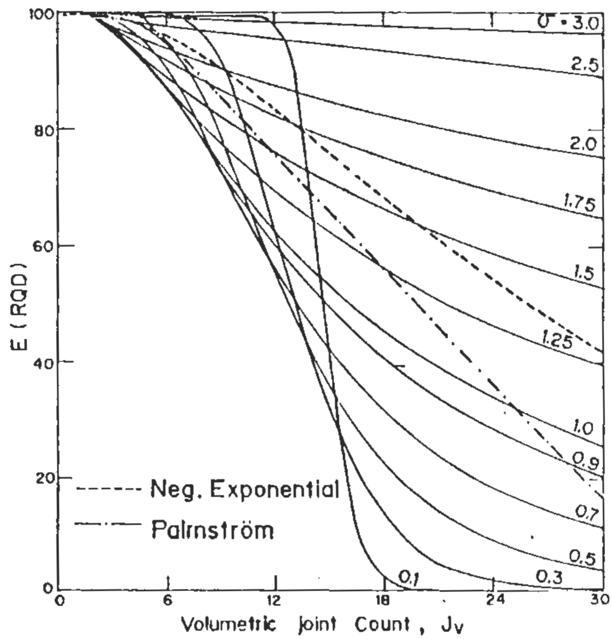

FIG. 9. Plate block RQD-J_v charts. ($\alpha = 0.5$, $t = 0.10$m).

values shows that the Palmstrom straight line deviates from negative exponential distribution even for moderate volumetric joint counts. Hence, one can conclude that Palmstrom's equation is very limited in practical and theoretical studies of rock quality assesments and it should be used with great care.

However, the triple relationships between the basic variables for this case can be obtained from Eq. 9 as

$$J_v = 1 + \frac{1 + \alpha}{\alpha \lambda V} \tag{21}$$

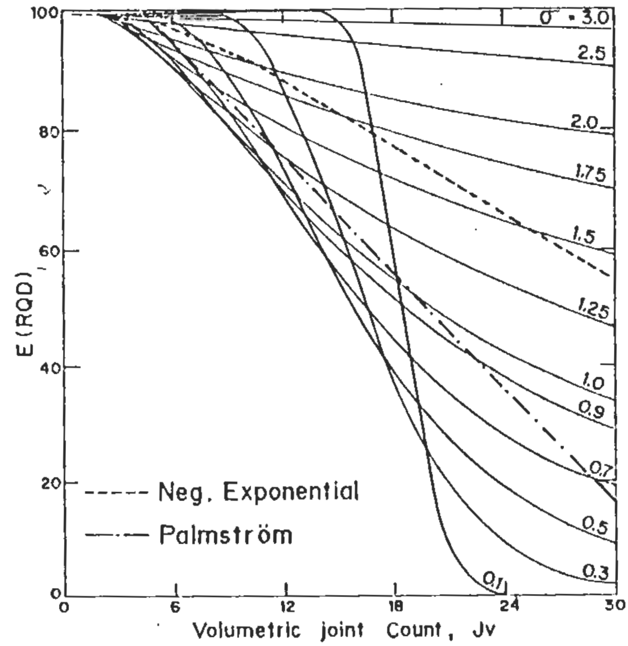

FIG. 10. Plate block RQD-J_v charts, ($\alpha = 0.9$, $t = 0.10$m).

The substitution of λ from this expression into Eq. (10) leads to a general relationship

$$E(RQD) = 100 \left\{ 1 - F \left[\frac{\mathrm{Ln}\left[\dfrac{(1+\alpha)\, t}{\alpha\, V\,(J_v - 1)} \right]}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right\} \qquad (22)$$

or for $t = 0.1$m

$$E(RQD) = 100 \left\{ 1 - F \left[\frac{\mathrm{Ln}\left[\dfrac{0.1\,(1+\alpha)}{\alpha\, V\,(J_v - 1)} \right]}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right\} \qquad (23)$$

The graphical form of Eq. 23 is presented in Fig. 11, 12, and 13 for $\alpha = 0.1$, 0.5 and 0.9, respectively.

(iii) Prismatic Blocks

In nature most often the discontinuities within a rock mass give rise to prismatic blocks of random sizes. With the aforementioned geometric properties in the previous section Eq. 9 combines the volumetric discontinuity count, heterogeneity coefficients and the average number of discontinuities as

$$J_v = (1 + \alpha + \beta)\, \lambda \qquad (24)$$

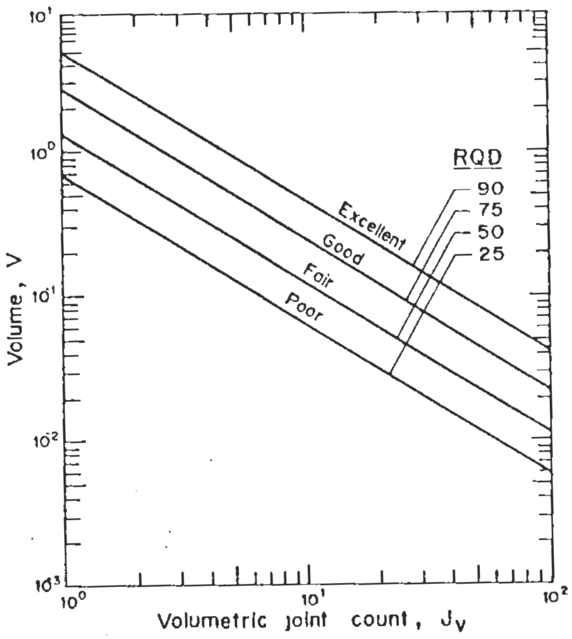

FIG. 11. Plate block RQD-J_v-V charts, (α = 0.1).

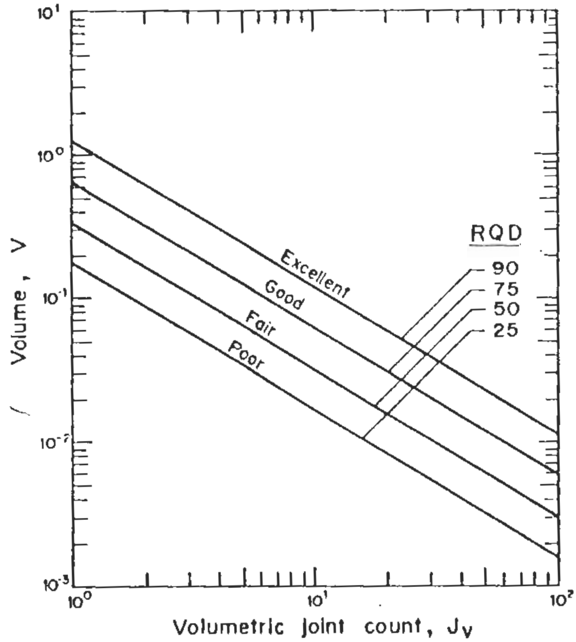

FIG. 12. Plate block RQD-J_v-V charts, (α = 0.5).

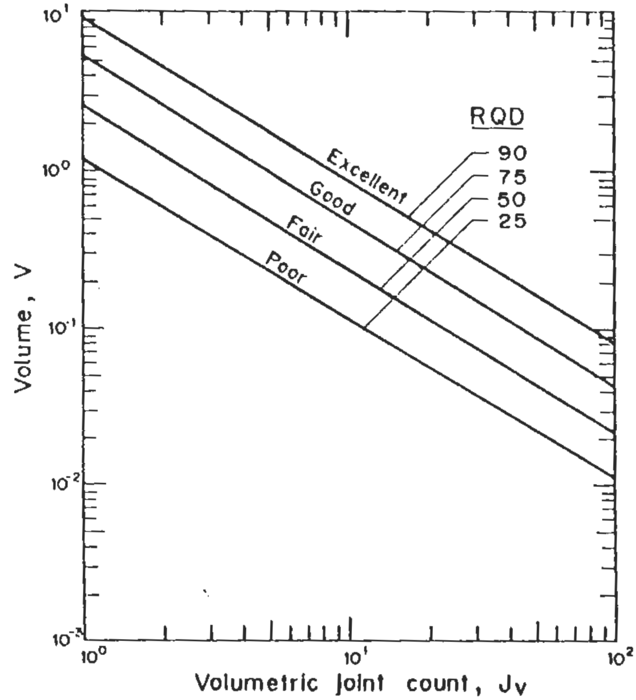

FIG. 13. Plate block RQD-J_v-V charts. ($\alpha = 0.9$).

Herein, λ implies the biggest among λ_x, λ_y and λ_z. Therefore, the substitution of λ into Eq. 10 leads to

$$E(RQD) = 100 \{ 1 - F[\frac{\mathrm{Ln} (\frac{J_v\, t}{1 + \alpha + \beta})}{\sigma_{Lnx}} \sigma_{Lnx} + 1] \} \quad (25)$$

with the practically used form of

$$E(RQD) = 100 \{ 1 - F[\frac{\mathrm{Ln} (\frac{0.1\, J_v}{1 + \alpha + \beta})}{\sigma_{Lnx}} \sigma_{Lnx} + 1] \} \quad (26)$$

Figures 14, 15 and 16 show a sample of relevant charts of prismatic blocks, for $\alpha = 0.1$, $\beta = 0.5$ but threshold value 0.10, 0.05 and 0.20 m, respectively. It is obvious from these figures that for prismatic blocks Palmstrom's straight line is representative neither for the negative exponential nor the logarithmic normal distributions. In order to see the effect of different heterogeneity coefficients on the *RQD* value Fig. 17 and 18 are also supplemented with $t = 0.1$. Comparison of these figures together with Figure 14 leeds to the conclusion that the non-representativeness of Palmstrom equation increases with increasing heterogeneity coefficient α.

However, the triple relationship appears as a complicated one

$$J_v = \frac{1 + \alpha + \beta}{\alpha\beta} \frac{1}{\lambda^2 V} \quad (27)$$

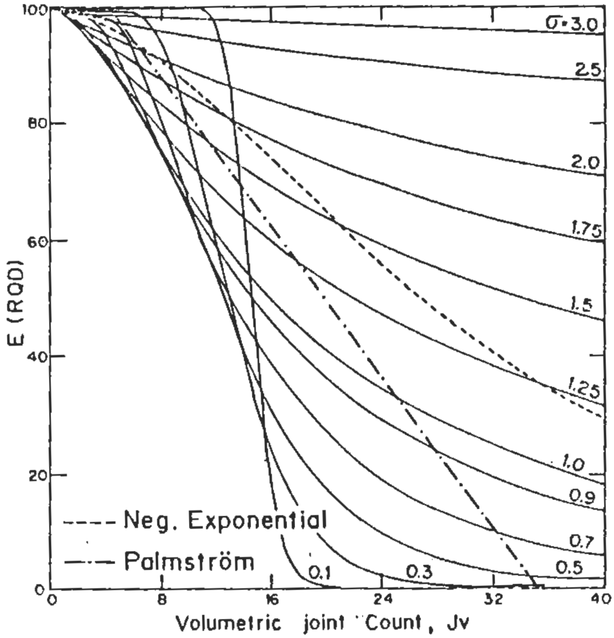

FIG. 14. Prismatic block RQD-J_v charts, ($\alpha = 0.1$, $\beta = 0.5$, $t = 0.10$ m).

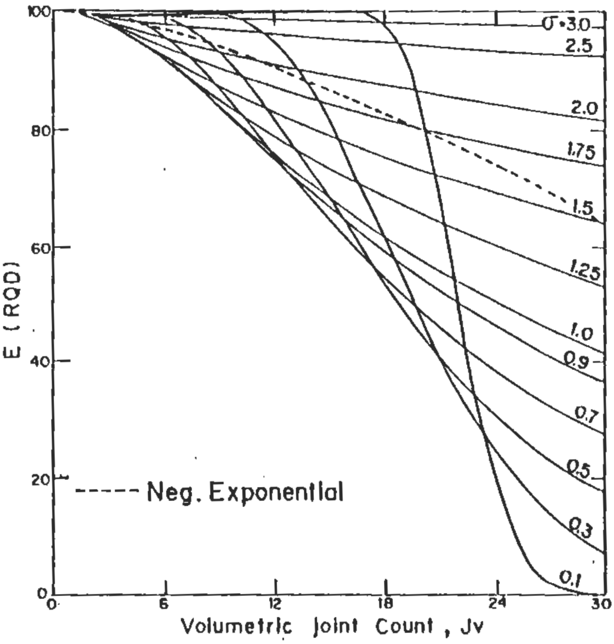

FIG. 15. Prismatic block RQD-J_v charts, ($\alpha = 0.1$, $\beta = 0.5$, $t = 0.05$ m).

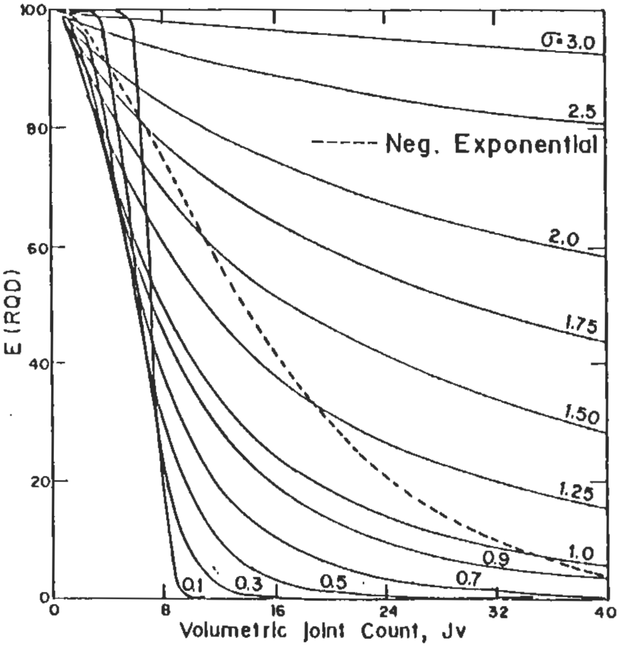

FIG. 16. Prismatic block *RQD-J_v* charts, (α = 0.1, β = 0.5, t = 0.20 m).

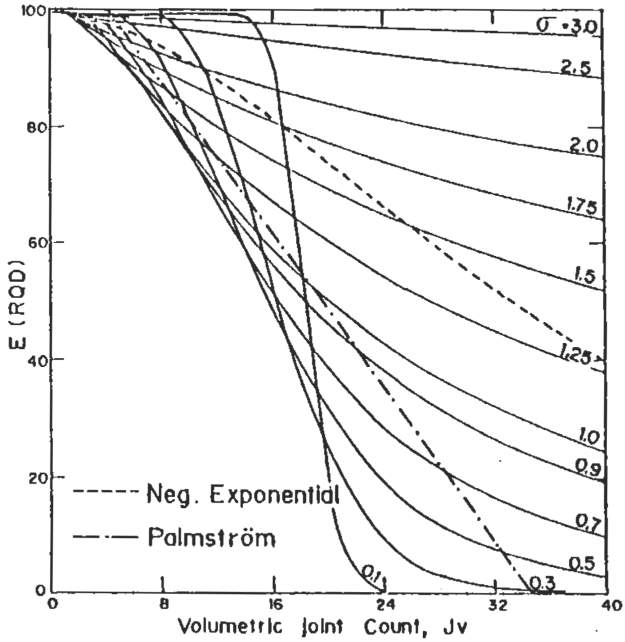

FIG. 17. Prismatic block *RQD-J_v* charts, (α = 0.5, β = 0.5, t = 0.10 m).

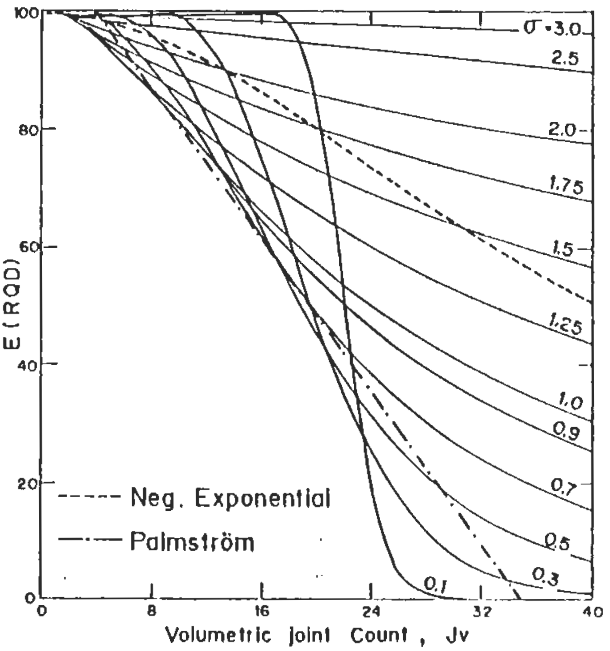

FIG. 18. Prismatic block RQD-J_v charts, ($\alpha = 0.9$, $\beta = 0.5$, $t = 0.10$ m).

Finally, combination of this expression with Eq. 10 gives the general equation as

$$E(RQD) = 100 \left\{ 1 - F\left[\frac{\mathrm{Ln}\left(\sqrt{\dfrac{1+\alpha+\beta}{\alpha\beta V J_v}}\, t \right)}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right\} \qquad (28)$$

or more specifically

$$E(RQD) = 100 \left\{ 1 - F\left[\frac{\mathrm{Ln}\left(\sqrt{\dfrac{1+\alpha+\beta}{\alpha\beta V J_v}}\, 0.1 \right)}{\sigma_{Lnx}} - \sigma_{Lnx} + 1 \right] \right\} \qquad (29)$$

The necessary charts for prismatic blocks are presented in Fig. 19, 20 and 21 for $\beta = 0.5$ but $\alpha = 0.1$, 0.5 and 0.9 values, respectively.

Field Application

The application of methodology developed in this paper is carried out for the field data measured along the exposed outcrop surfaces of granitic rocks in the western part of the Kingdom of Saudi Arabia. The study area is approximately 80 km north-east of the city of Jeddah. This area was selected since it has a good combination of well-exposed bedrock and relatively simple fracture geometry. Three sets of fracture orientations can be distinctively seen in the area. Each one of the fracture set is mea-

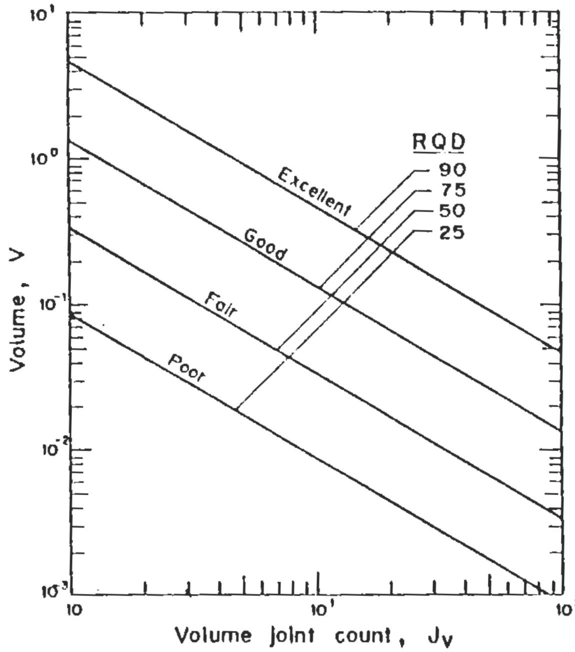

FIG. 19. Prismatic block RQD-J_v-V charts, ($\alpha = 0.1$, $\beta = 0.5$, $t = 0.10$ m).

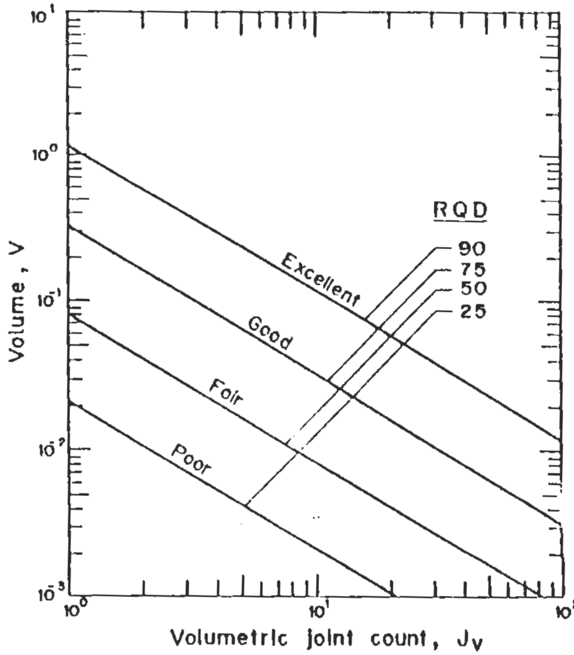

FIG. 20. Prismatic block RQD-J_v-V charts, ($\alpha = 0.5$, $\beta = 0.9$, $t = 0.10$ m).

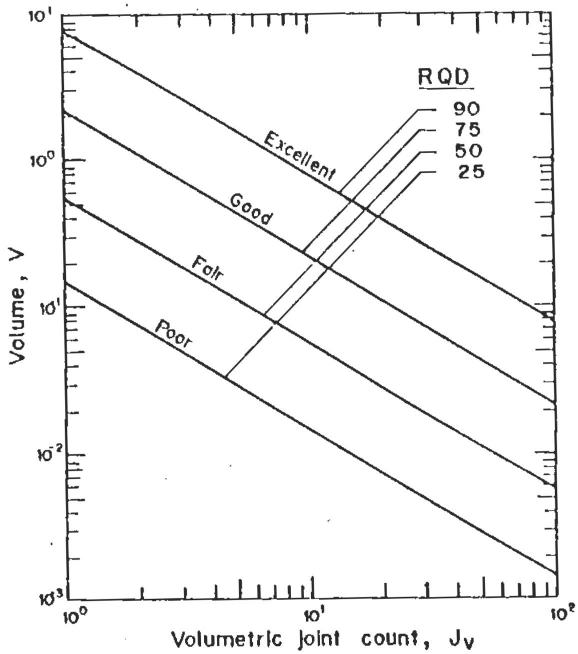

FIG. 21. Prismatic block RQD-J_v-V charts, (α = 0.9, β = 0.9, t = 0.10 m).

sured by the scanline perpendicular to the fracture traces. The fracture set measurements are carried out at three sites. These sites are selected such that they give rather random characterization of the fracture patterns, i.e., they are quite independent from each other. In Table 1 the basic scanline measurement statistics are given.

TABLE 1. Scanline measurement results.

Scanline	Site 1		Site 2		Site 3	
	Average (m)	λ (1/m)	Average (m)	λ (1/m)	Average (m)	λ (1/m)
x	0.64	1.56	0.36	2.75	0.56	1.78
y	0.38	2.65	0.55	1.83	0.55	1.80
z	0.96	1.04	0.50	1.98	0.64	1.56

The values in Table 1 enables the engineer to decide whether in each one of the site, blocks are either prisms, or plates or bars. In order to make such a decision as mentioned earlier in this paper it is necessary to calculate the relative errors, on the basis of average intact lengths. The relative error calculations indicate that it is less than 5% only at site 3 between $\bar{x}$ and $\bar{y}$, i.e., ε_{xy} = 100 (0.56-0.55)/0.56 = 1.78 < 5. Hence, blocks in sites 1 and 2 are of prismatic type whereas at site 3 they are of plate type.

In order to be able to apply the methodology developed herein the values in Table 1 are converted into the quantities that enable one to make use of the relevant charts. Table 2 presents block related quantities within the study area.

TABLE 2. Block characteristics.

Site	λ	α	β	J_v (l/m) Eq. 5	Type	V (m^3)	RQD %	Quality
1	2.65	0.59	0.39	5.25	prism	0.23	36	poor
2	2.75	0.66	0.72	6.56	prism	0.19	40	poor
3	1.80	0.99	0.87	5.14	plate	0.20	64	Fair

It is obvious from this table that the block volumes in the area are rather uniform especially sites 2 and 3 have almost the same block volume. However, they have different block types as prism and plate. In order to be able to decide whether the intact lengths are distributed in accordance with the logarithmic normal distribution it is necessary to know the averages and standard deviations after the logarithmic transformation. The relevant values are presented in Table 3. The average values are in cm and calculated from log values.

TABLE 3. Scanline statistics.

Scanline	Site 1		Site 2		Site 3	
	Average	σ_{Lnx}	Average	σ_{Lnx}	Average	σ_{Lnx}
x	3.90	0.79	3.41	0.69	3.62	0.87
y	3.35	0.78	3.79	0.70	3.88	0.54
z	4.31	0.73	3.63	0.74	4.09	0.40

Since, the average value of any scanline is not equal to the standard deviation. For the same scanline the intact lengths are not negative exponentially distributed. Hence, for RQD calculations charts developed in this paper becomes valid. Therefore, the RQD calculations for site 3 will be achieved from either the use of chart similar to Fig. 12 or from Eq. 17. Besides the RQD values for sites 1 and 2 can be read off from charts similar to Fig. 20 or from Eq. 29. For prismatic blocks and Eq. 23 for the plate blocks. The last two columns in Table 2 indicate that site 1 although has larger block sizes its rock quality is the worst among the others and it has poor rock quality. The same quality is valid for site 2. However, relatively better rock quality within the study area appears at site 3 which has fair quality of rocks.

Last but not least for the comparison of unidirectional and volumetric rock quality designations Table 4 is prepared with all the distinctive scanlines by using Eq. 10. The directional values both for negative (Şen and Eissa; 1990) and log-normal distributions are almost equal to each other, i.e., they are all of very good quality.

TABLE 4. Comparison of unidirectional and volumetric *RQD*

Scan-line	Site 1				Site 2				Site 3			
	λ 1/m	*RQD*			λ 1/m	*RQD*			λ 1/m	*RQD*		
		Directional	Volumetric			Directional	Volumetric			Directional	Volumetric	
			NEG	LOG			NEG	LOG			NEG	LOG
x	1.56	98		93	2.75	94		98	1.78	97		93
y	2.65	93	36	93	1.83	98	40	98	1.80	99	64	98
z	1.04	99		94	1.98	97		97	1.56	99		99

NEG = Negative Exponential.
LOG = Log-normal.

It is obvious from this table that directional and volumetric *RQD* values based on logarithmic normal distribution assumption yields almost the same results with practically insignificant relative error of less than 5%. The reason of obtaining different volumetric *RQD* values along each direction lies in the fact that the standard deviation is different along these directions. However, negative exponentical distribution leads to a single volumetric *RQD* value because as an underlying assumption the intact length average value is identical with the standard deviation. The good agreement between the directional and volumetric *RQD* values indicates the suitability of logarithmic distribution in describing the intact length behaviour.

Conclusion

The fractures within a rock mass cut it in various directions and delineate a block unit which is referred to as the blocks. Three different types of blocks, namely, bars, plates and prisms are defined in this paper. Each one of these blocks are separated from other in rock mass by at least three sets of fractures. Quantification of the fractures and therefore the blocks in engineering evaluations presents a delicate problem due to the random occurrence of these features. Consequently, statistical evaluation methods have been used in such evaluations so far in the literature. Most often the results are presented in the form of equations without any relationships between the basic fracture parameters. It has been the main purpose of this paper to relate these parameters to each other, and finally, to provide easily exploitable charts for design engineers.

The basic fracture parameters considered herein are the average number of fractures along one direction, volumetric joint count for all directions concerned, block volume and the rock quality designation, *(RQD)*. First of all charts are prepared for relating the average number of fractures, volumetric joint count and the volumes of various block types. Then combined with the *RQD* expression for logarithmic normal *PDF*, the volumetric joint count and block sizes are presented on separate charts with the delineation of different rock qualities on them. In general, most of the charts appeared as straight lines on double logarithmic papers except the ones that indicate the relationship between the *RQD* and J_v for different sets of standard deviation and heterogeneity coefficient values. One of the most significant conclusions is that the *RQD* is not related to J_v linearly as it stands in the literature but such a relationship is nonlinear. However, the existing linear relationship approximates the nonlinear relationship as found in this paper only for moderate volumetric joint count values. Comparison between the results indicates the following significant points:

(i) logarithmic-normal distribution represents the intact lengths better than negative exponential distribution.

(ii) negative exponential distribution based volumetric *RQD* values are underestimations of the real *RQD* value. In fact, they are more than 50% smaller than the logarithmic distribution.

(iii) depending on the standard deviation value more feasible region of *RQD* variation with J_v is covered than the negative exponential distribution.

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Notations

The following symbols are used in this paper;

A_{xy} = lateral surface area in x-y plane;
A_{yz} = lateral surface area in y-z plane;
A_{zx} = lateral surface area in z-x plane;
$E(.)$ = expectation of the argument;
$F[.]$ = area under *PDF*;
J_v = volumetric discontinuity count;
L = scanline length;
L_s = total intact lengths greater than t;
PDF = probability distribution function;
RQD = rock quality designation;

RQP	=	rock quality percentage;
RQR	=	rock quality risk;
t	=	threshold level;
V	=	block volume;
$\bar{x}$	=	sample average of intact length in x direction;
$\bar{y}$	=	sample average of intact length in y direction;
$\bar{z}$	=	sample average of intact length in z direction;
α	=	heterogeneity coefficient in x direction;
β	=	heterogeneity coefficient in y direction;
λ	=	average number of discontinuity in any direction;
λ_x	=	average number of discontinuity in x direction;
λ_y	=	average number of discontinuity in y direction;
λ_z	=	average number of discontinuity in z direction;
ε	=	relative error percentage; and
σ_{Lnx}	=	standard deviation of logarithmic intact lengths.

مَعْلَم جودة الصخور الحجمي مع مسافات الشقوق الموزعة لوغارتميا طبيعيا

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*قسم جيولوجيا المياه و **قسم الجيولوجيا الهندسية ، كلية علوم الأرض ، جامعة الملك عبد العزيز ،
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المستخلص . نتيجة تعدد أنواع الشقوق تقسم كسارات الصخور كيفيا إلى ثلاثة أقسام وهي أعمدة ، صفائح ومنشورات . إذ إن الوصف الكمي في التقييمات الهندسية المعتمدة على الملاحظات الحقلية يؤدي إلى قيم تصميم ملائمة هو موضوع غاية في الأهمية . والموديلات المفاهيمية البسيطة لكسارات الصخور مقترنة مع قراءات خط القياس تزودنا بعلاقات موضوعية بين مَعْلَم جودة الصخور (م ج ص) ، وعداد حجمي أو مساحي أو خطي (على طول خط القياس) وحجوم الكتل الصخرية . الغرض الرئيس من هذه الورقة هو استنتاج العلاقات المناسبة لتوزيع المسافات بين الشقوق لوغارتميا . ونتيجة لهذه العلاقات المعقدة فقد وُضعت النتائج على هيئة أشكال بيانية متنوعة لتكون أداة نافعة لاستخدام الجيولوجي الهندسي . الأشكال البيانية المقدمة هي لانحراف معياري يساوي واحد ، ولكن الأشكال البيانية لأي قيمة مطلوبة من الانحراف المعياري يمكن أن تحضر من المعادلات المتعلقة بها . هذه الطريقة طبقت على معلومات حقلية فعلية . الخلاصة هي أن توزيع الأس السلبي يعطي قيمة فردية لـ (م ج ص) الحجمي مختلف عن (م ج ص) الخطي . ولكن التوزيع الطبيعي اللوغارتمي يعطي تقريبًا نتائج تتراوح مابين الحدود العملية لكل من قيم الـ (م ج ص) الحجمية والخطية . وهذه الخلاصة تثبت أن التوزيع الطبيعي اللوغارتمي يمثل المعلومات الحقلية بشكل أفضل مقارنة بالأس السلبي .