From Palmström A.: RMi – a rock mass characterization system for rock engineering purposes.
PhD thesis, Oslo University, Norway, 1995, 400 p.

APPENDIX 4

AN INVESTIGATION OF THE QUALITY OF VARIOUS JOINTING MEASUREMENTS

> *"Present estimates of the intact block geometry and discontinuity properties can be better quantified."*
> D. Milne, P. Germain and Y. Potvin (1992)

A problem which arises when methods for measuring jointing density is investigated, is the variations in rock mass jointing and the associated difficulties in obtaining reliable information on the jointing distribution. This problem can be omitted by applying analysis where a known distribution of the joints is simulated in a computer. Lines, which represent boreholes, cut the simulated model of joints, and planes constitute outcrop surfaces in which the simulated number of joints can be found. In this way, results from different types of 'core logs' and 'surface observations' can be easily compared. The benefit in this method is that the block size, block type and shape are known; therefore, reasonable comparisons can be carried out between the accuracy of the various measurements of the degree of jointing.

1 LAYOUT OF THE INVESTIGATIONS PERFORMED

The simulation was carried out using a computer spreadsheet where the jointing was represented by three joint sets at right angles to each other. The spacing of the joint sets could be varied so that different types of blocks, such as compact (or cubical) blocks, long (or columnar) blocks, flat (or tabular) blocks, and long&flat (prismatic) blocks with varying shapes were included.

Lines representing boreholes with varying angles to the joint sets were used, and the length of the (core) pieces delineated by the joints calculated. From this a little more than 300 values of different "core logging" registrations were found. Similarly, for "observation planes" (outcrops) more than 500 values were used in the comparisons. The following variables were used:

- Angle between joint sets and borehole: 58^o, 30^o, 10^o; 24^o, 40^o, 42^o; 50^o, 40^o, 8^o; 10^o, 18^o, 70^o; 68^o, 11^o, 19^o; 5^o, 80^o, 8^o .
- Angle between joint sets and observation plane: 60^o, 32^o, 80^o; 22^o, 79^o, 71^o; 50^o, 40^o, 82^o; 80^o, 72^o, 20^o; 66^o, 48^o, 50^o; 85^o, 10^o, 82^o.
- Variation in the block shape factor: β = 27 - 1000 .
- Variation in the joint spacings which resulted in block volumes in the range of: Vb = 0.0001 - 10 m^3 .

The results shown in diagrams include the connection or relations between:
- the volumetric joint count (Jv), and other joint frequency measurements;
- the estimated and the known block shape factor (β); and
- the block volume (Vb) found from other jointing density measurements.

As the details of jointing are known, the correlations found can be compared directly.

2 BLOCK SHAPE MEASUREMENT

The block shape factor β is, according to eq. (A3-28) in Appendix 3, defined as

$$\beta = \frac{(\alpha 2 + \alpha 2 \times \alpha 3 + \alpha 3)^3}{(\alpha 2 \times \alpha 3)^2}$$

β can also be found from Fig. A3-31, provided that the block is delimited by 3 parallel pairs of faces or 3 joint sets intersecting at right angles. The error introduced by other intersecting angles between the joint sets is probably small as their influence on the volume, as shown in Section 3.2 in Appendix 3, is limited.

Eq. (A3-28) requires that all the (three) joint set spacings or the dimensions of the (six) block faces are known. As blocks may have more or less than six faces, it can be difficult to find β from this expression. Thus, a simplified measurement of β would be advantageous; therefore the following expression to estimate the block shape factor has been found by trial and error:

$$\beta = \beta_o + 7(\alpha 3 - 1) = 20 + 7\ \alpha 3 = 20 + 7\ a3/a1 \qquad \text{eq. (A4-1)}$$

where $\beta_o = 27$ is the lowest value of β, i.e. for a cubical block.

By this simplification β can roughly be estimated from the ratio between the longest and shortest side of the block, given as a3/a1 = α3. The quality of eq. (A4-1) has been investigated, and the results are given in Fig. A4-1.

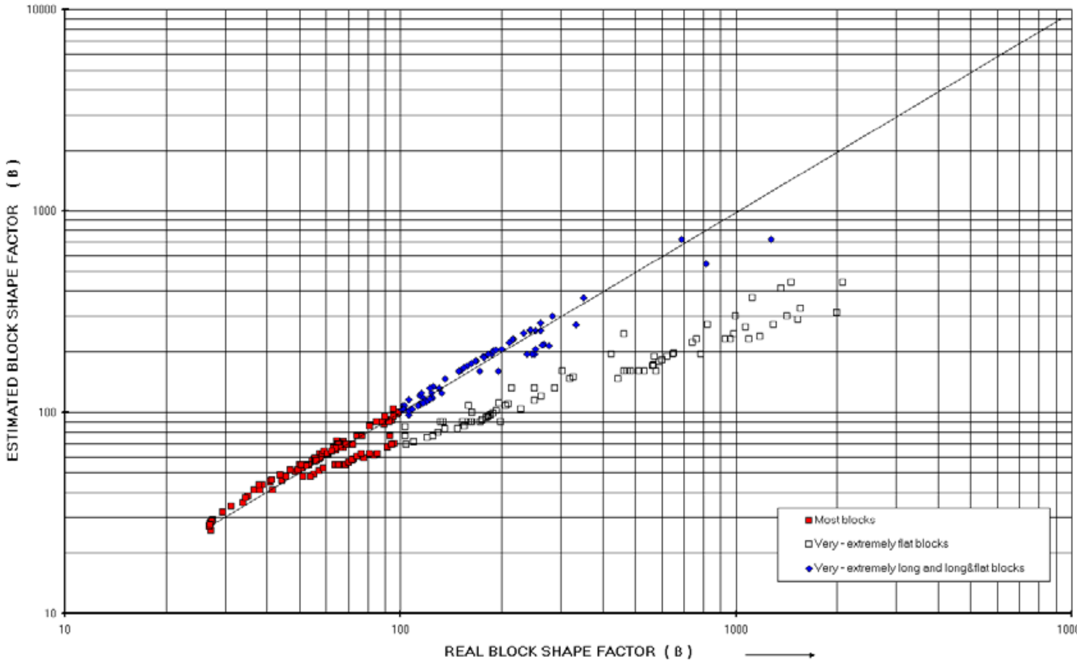

Fig. A4-1 The correlation between the real and estimated block shape factor (β) found from eq. (A4-1) for observation made on surfaces.

The figure shows that this simplified block shape factor β can be found with a reasonable accuracy (± 25%) for most types of blocks with β < 1000, except for very - extremely flat blocks. For the latter acceptable results are found for β < approx. 100. To also include very flat and very long blocks eq. (A4-1) can be adjusted by an exponent

$$\beta = 20 + 7\ a3/a1 = 20 + 7\ (a3/a1)^{(1 + 0.1 \log(a3/a1))} \qquad \text{eq. (A4-2)}$$

The effect of this exponent is significant only where a3/a1 > 10, so for most cases the simpler expression eq. (A4-1) is sufficient as shown in Fig. A4-2.

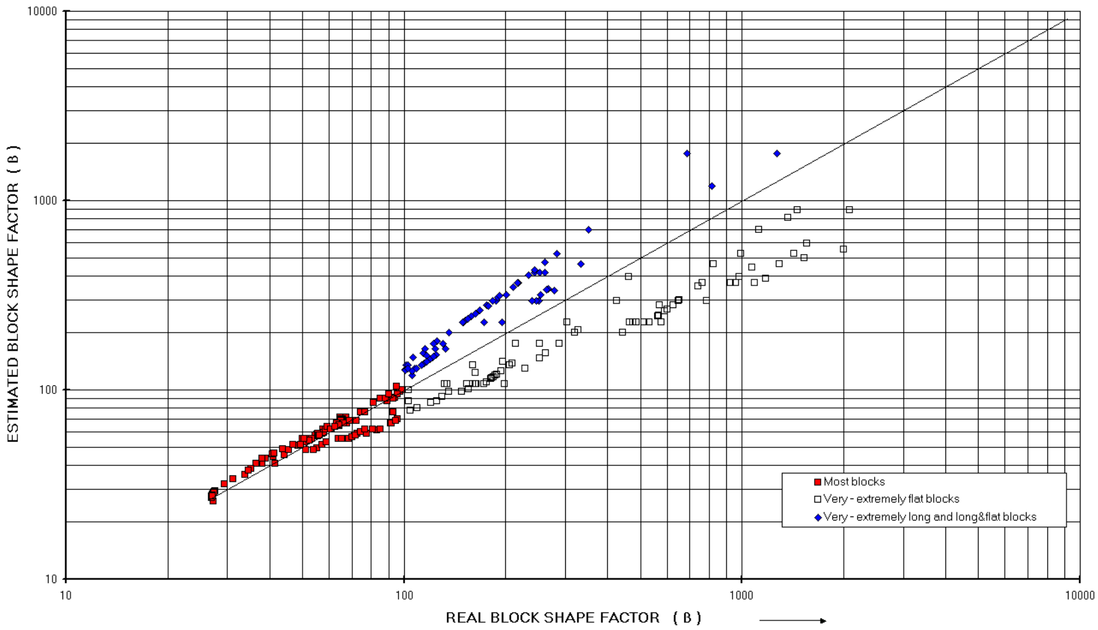

Fig. A4-2 The correlation between the real and estimated block shape factor (β) found from eq. (A4-2) for observation made on surfaces.

The application of this simplified expression for the block shape factor is further dealt with in Appendix 3, Section 3.

3 2-D AND 1-D JOINT FREQUENCY REGISTRATIONS

The joint frequency can be found from 1-D or 2-D registrations measured in boreholes or surfaces respectively. (From surface measurements it is also often possible to apply 3-D registrations in the form of volumetric joint count.

3.1 2-D frequency measurements

As mentioned in Appendix 3 it is seldom defined whether the frequency (or spacing) given in a report or paper is meant to represent the main joint set or if it represents the mean frequency for the joint sets in an area. In this thesis, the 2-D joint frequency is defined as the number of joints per unit length recorded in a surface. It can be found from the number of joints recorded within a known area, given as Na = n / $\sqrt{A}$ where n is the number of joints observed in the outcrop with an area, *A*.

The results from a simulation with
- variation in the density of joints (Jv) [or block volumes (Vb)],
- variation in block types and shapes (from variation in the joint spacings), and
- various angles between joints and the observation plane (i.e. outcrop)

is shown in Figs. A4-3 and A4-4.

As expected there is a rather poor correlation between the 'measured' 2-D joint frequency and the real 3-D density of jointing (given as the volumetric joint count (Jv)) or the real block volume. The Jv varies between 0.4Na and 1Na with an average value of

$$Jv \approx 1.5\ Na \qquad \text{eq. (A4-3)}$$

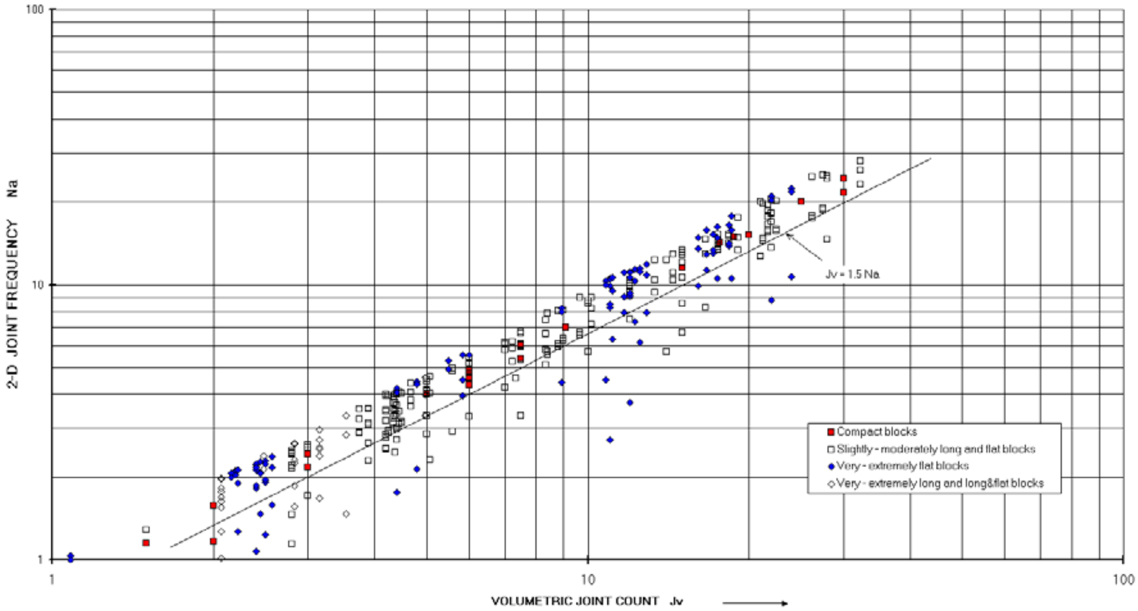

Fig. A4-3 The connection between measurement of 2-D frequency (Na) and volumetric joint count (Jv).

By applying eq. (A3-27) $Vb = \beta \times Jv^{-3}$, the block volume is found as

$Vb \approx 0.3\beta(Na)^{-3}$ eq. (A4-4)

(To obtain the best possible registration of the 2-D joint frequency the length of the joints should be included in the measurement as described in Appendix 3, Section 3.6.1.)

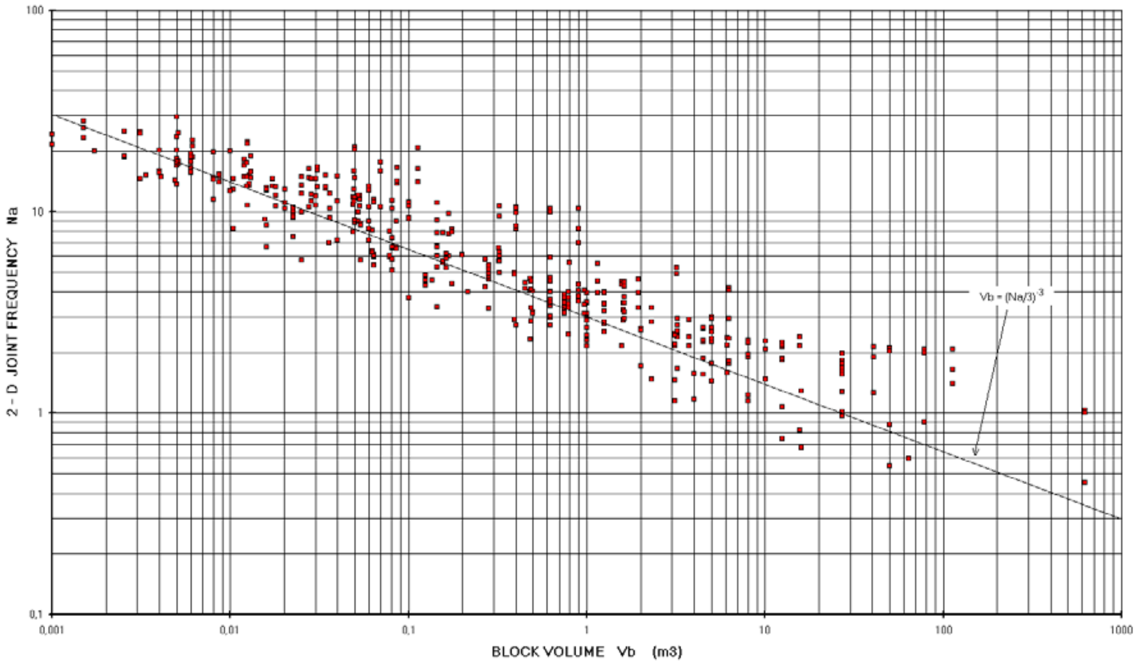

Fig. A4-4 The relation between 2-D joint frequency measurement (Na) and block volume (Vb).

Another very rough correlation is found from Fig. A4-3 given as

$Vb \approx (Na/3)^{3}$ eq. (A4-5)

The error in these registrations can vary between + 500% and -50%, especially in cases where very to extremely flat blocks occur.

3.2 1-D frequency measurements

Where the jointing frequency (or joint spacing) is recorded along a borehole or a scanline a sort of average frequency is found. From a simulation with the same procedure as for 2-D (surface) measurements the results in Fig. A4-5 and A4-6 show that the error in the jointing measured by this method is, as expected, larger than for surface observations.

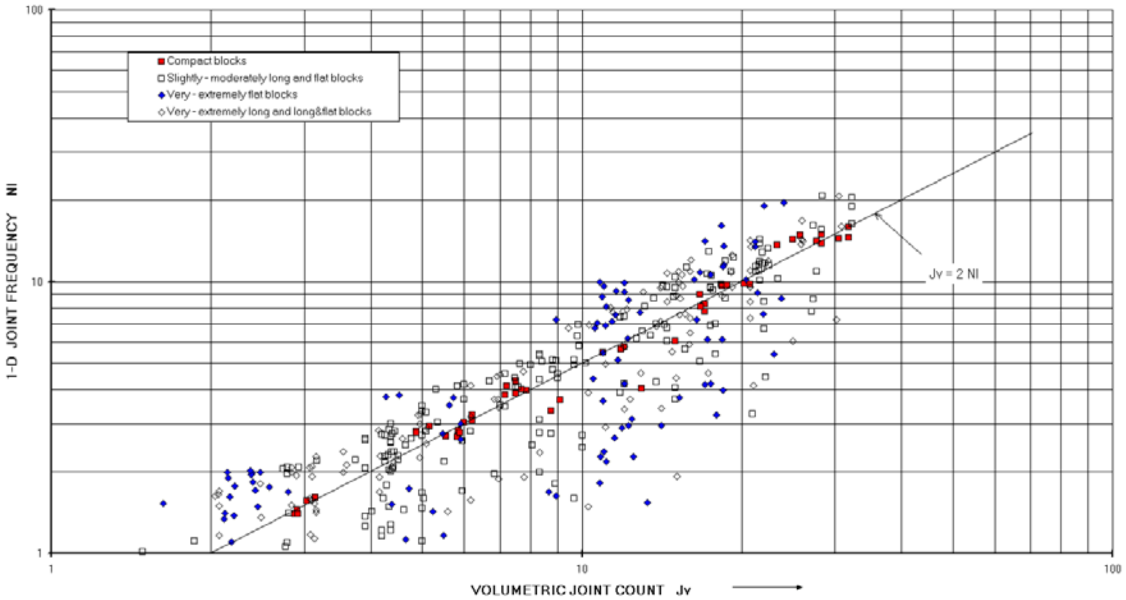

Fig. A4-5 The connection between 1-D joint frequency (Nl) and volumetric joint count (Jv).

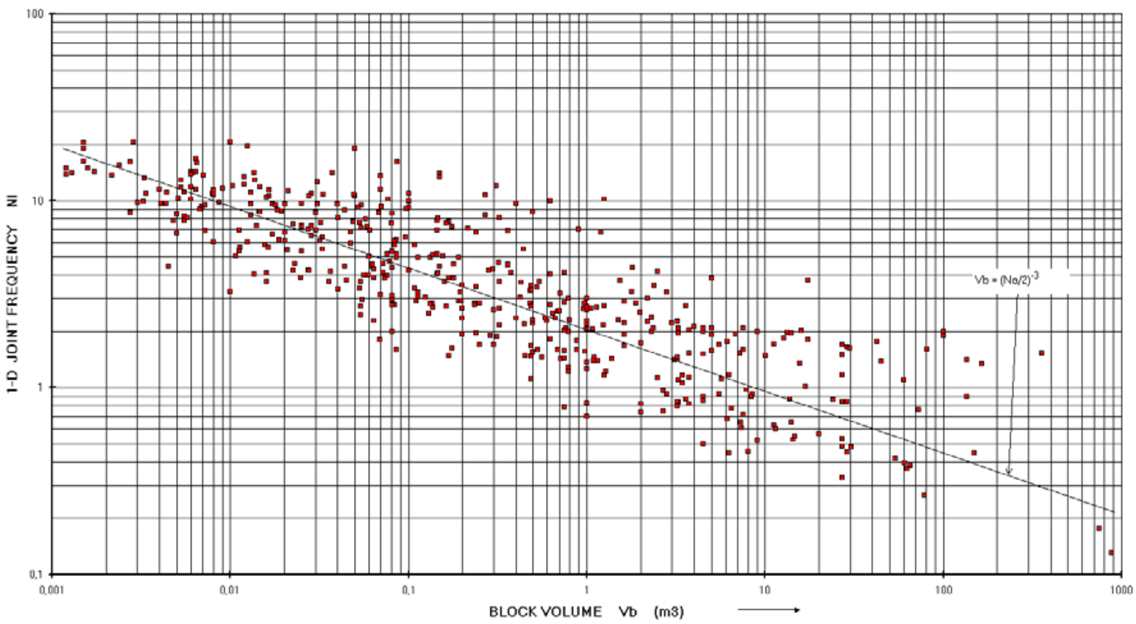

Fig. A4-6 The connection between 1-D joint frequency (Nl) and block volume (Vb).

A transition between 1-D frequencies and real block volume or volumetric joint count which depends on the block type and shape, will mainly vary between

$Jv = 2\ Nl$ and $Jv = (Nl/2)^3$ eq. (A4-6)

Consequently, the block volume will vary between

$Vb = \beta \times Jv^{-3}$ and $Vb = 0.13\beta(Nl)^{-3}$ eq. (A4-7)

As seen in Figs. A4-5 and A4-6 the error is significant, between +500% and -40%, when the block volume (Vb) or the volumetric joint count (Jv) is estimated from 1-D measurements.

4 WEIGHTED JOINT DENSITY MEASUREMENTS

The orientation of a joint compared to an observation surface or a borehole influences the number of joints observed (Franklin et al., 1971; Terzaghi, 1965). Joints perpendicular to the surface plane will be more frequently intersected and may bias the observations. This can to a large extent be corrected for by including the angle between the individual joint and the observation surface or borehole in the measurement, thus obtaining a registration of the 'weighted joint density' (or frequency, given as number of joints per volume unit). This is defined as

$$wJd = \Sigma(1/\sin\delta_i)/A \quad \text{for 2-D (surface) observations} \qquad \text{eq. (A4-8)}$$

and

$$wJd = \Sigma(1/\sin\delta_i)/L \quad \text{for 1-D (borehole) observations} \qquad \text{eq. (A4-9)}$$

Here δ_i is the angle between the observation plane (surface) and the individual joint,
A is the size of the actual area, and
L is the actual length of borehole.

The weighted joint frequency method for joint density registration has earlier been suggested by R. Terzaghi (1965) who suggested to take into account the orientation of the joints and the probability for them to be cut by the observation plane or the scan line (or drill hole).

Where accurate registrations have been performed both for the number of joints and the angles between joint and observation surface or borehole the wJd should be equal to the volumetric joint count (Jv = wJd).

For joints parallel or nearly parallel to the observation plane the factor ($1/\sin\delta$) will give high contribution to the joint count. A single joint may easily disturb the measurement. For this reason a common factor connected to an interval for the smallest angles should be applied.

Where many joints occur with different angles to the observation plane the weighted recording can be time-consuming. By grouping the angles into intervals with adjacent factor will make the registration considerably simpler and easier. A factor f_i representing $1/\sin\delta$ is introduced for the intervals in Table A4-1.

TABLE A4-1 INTERVALS OF THE ANGLE δ AND THE FACTOR f_i REPRESENTING $1/\sin\delta$

Angle between joint plane and surface/borehole δ	**Factor f_i**
> 60°	1
31 - 60°	1.5
16 - 30°	3.5
< 16°	6

In this *interval method* the wJd is found as the sum the actual value of (f_i) for each joint for its angle interval. The results from a simulation including various orientation of joints and with respect to observations planes and boreholes is given in Figs. A4-7 and A4-8 where wJd is compared to the volumetric joint count (Jv).

Variations in block size and shape as well as angles between the joints and the borehole or the observation plane were used in the simulation. A total of 640 registrations were made including:

- Block shape factor between 27 and 2000
- Block sizes between 0,001 m^3 and 1000 m^3
- Angles between plane and joints:
  10^o and 85^o for surface planes;
  5^o and 80^o for boreholes.

The same values of f_i were applied both for 1-D and 2-D registrations.

4.1 Surface observations

The "observations" were made on surface planes corresponding to 75 m^2, where the number of joints were recorded together with the angle between the plane and the joint. As seen in Fig. A4-7 there is a good correlation within approximately ± 30%, except for the lower values of Jv (i.e. large blocks). This is caused by the large spacing of joints and small angles between joint and observation plane, resulting that the joints in the actual set is not recorded. Therefore, the Jv will be lower and hence the block volume larger than the real.

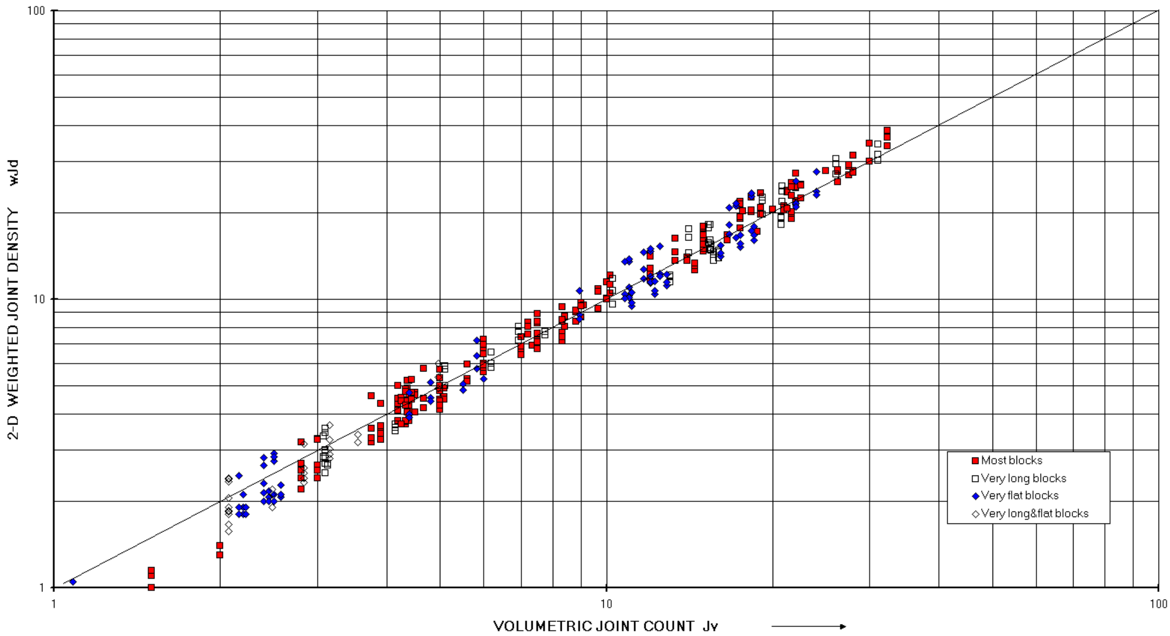

Fig. A4-7 Weighted 2-D joint density measurement (wJd) made in 'surfaces' compared to the (known value of the) volumetric joint count (Jv).

4.2 Borehole logging

In these simulations an observation length of 10 m was chosen. As expected, there is a poorer correlation for 1-D jointing measurements, - having an inaccuracy between approximately +35% and - 50% for Jv > 2 , - than for 2-D measurements. (See Fig. A4-8) Also here, the poorest correlation is for the lowest values of Jv (Jv < 2), and this can probably be explained from the fact that some of the joints were not encountered in the 10 m long measuring section in the 'boreholes'.

The interval method offers a relatively quick and simple way to measure jointing density as the intervals chosen for the angle between joint and borehole should be familiar to most people.

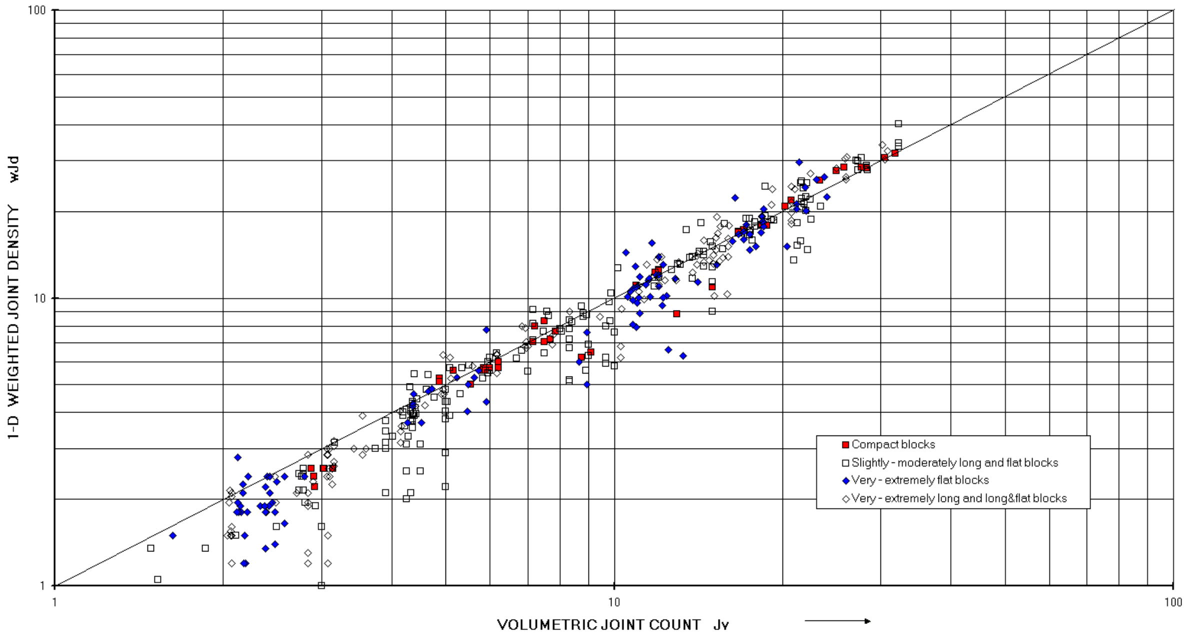

Fig. A4-8 Weighted 1-D jointing density measurement (wJd) made in 'boreholes' compared to the (known) volumetric joint count (Jv).

5 CALCULATIONS OF BLOCK VOLUME FROM SIMPLIFIED JOINTING MEASUREMENTS

Sections 3 and 5 show methods to measure the block shape factor (β) and the weighted jointing density. These measurements can be combined to estimate the block volume

$$Vb = \beta \times wJd^{-3} \quad \text{eq. (A4-10)}$$

From the simulations made in Section 4 the connection between the (known) block volume, and the estimated volume is shown in Figs. A4-9 and A4-10.

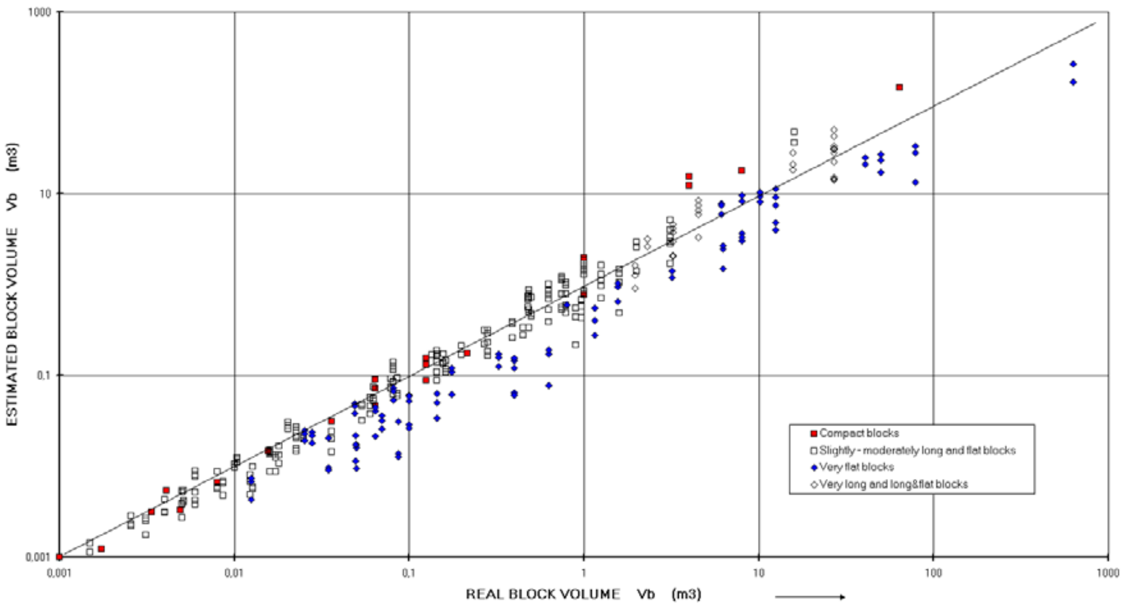

Fig. A4-9 Estimated block volume found from weighted 2-D measurements (in surfaces) compared to the known block volume.

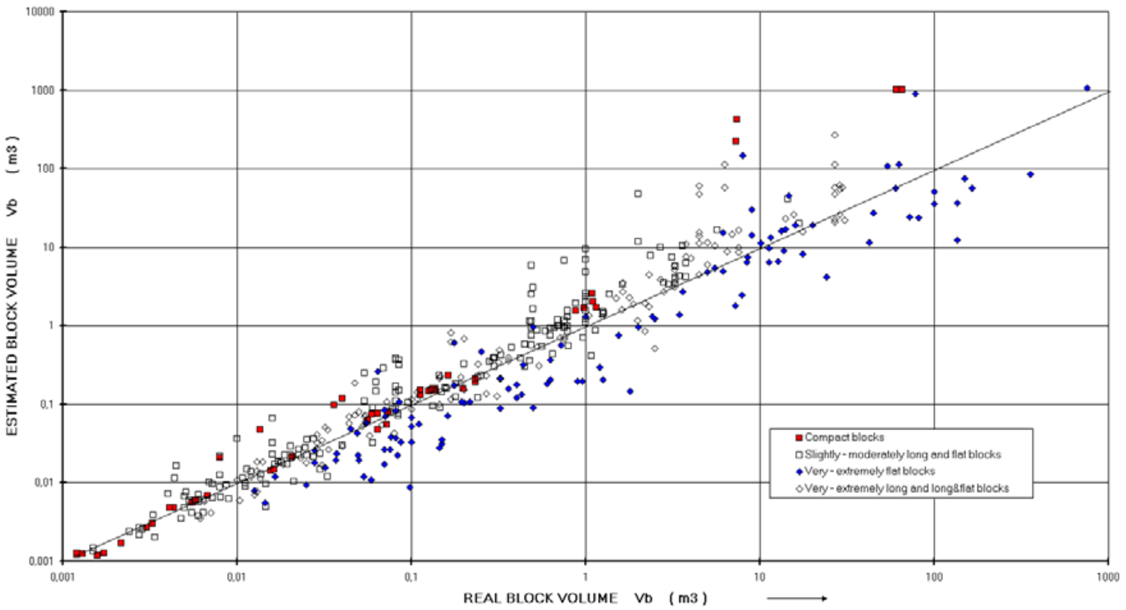

Fig. A4-10 Estimated block volume found from weighted 1-D measurements (in boreholes) compared to the known block volume.

For 2-D registrations the accuracy of the estimated block volume < 3 m^3 lies within +100% and -50%, except for very to extremely flat blocks (β > 100); for 1-D measurements the inaccuracy is much higher as shown in Tables A4-2 and A4-3.

TABLE A4-2 ACCURACY IN 2-D MEASUREMENTS, OBSERVATION AREA 75 m2

Vb	most blocks	very to extremely flat blocks
< 3 m^3	+100% to -60%	+50% to -8%
> 3 m^3	+300% to -50%	+50% to -15%

TABLE A4-3 ACCURACY IN 1-D MEASUREMENTS, OBSERVATION LENGTH 10 m

Vb	most blocks	very to extremely flat blocks
< 0,5 m3	+500% to -50%	+100% to -8%
> 0,5 m3	+2500% to -50%	+1000% to -8%

The relatively poor connections for the larger block sizes stem for a main part from the fact that some of the joints were not recorded along the observation length (or area) chosen. Also small angles between the observation plane or borehole and joints will highly bias the measurements. This is especially true for the 1-D registrations.

6 ROCK QUALITY DESIGNATION (RQD)

In the simulations made to compare RQD with other 1-D jointing density observations a total of 310 registrations were made for

- various block shape factors between 27^o and 58^o,
- various block volumes, and
- 9 different angles between borehole and joints varying between 8^o and 58^o.

All simulations used 3 joint sets at right angles to each other.

In these simulations, also the volumetric joint count (Jv), the weighted jointing density (wJd), and the estimated block shape factor (β) have been found in order to compare the results obtained by the measurements.

6.1 Connection between the RQD and the volumetric joint count (Jv)

Fig. A4-11 shows that for the same type of jointing (same block type and shape) the RQD can be both 0 and 100 for jointing within an interval of Jv = 13 - 22. A wide range of RQD values is also found for Jv = 22 - 40. Therefore, a general and reliable connection between RQD and Jv can hardly be found. According to Fig. A3-22 and eq. (A3-21) in Appendix 3 the general connection between RQD and Jv is RQD = 115 - 3.3 Jv (Palmström, 1974).

This expression is shown in Fig. A4-12 where it is seen that it gives lower RQD values than in the simulation. The expression

$$RQD = 140 - 4\ Jv \qquad \text{eq. (A4-11)}$$

seems to give a better connection. However, with values of RQD = 0 and 100 for a large span of jointing, it is uncertain to compare these two correlations. In practice, the jointing is less uniform and the threshold of t = 0.1 m often measured inaccurately because joints frequently intersect the core at acute angles. Thus, the 'original' expression eq. (A3-21) between RQD and Jv may give acceptable results.

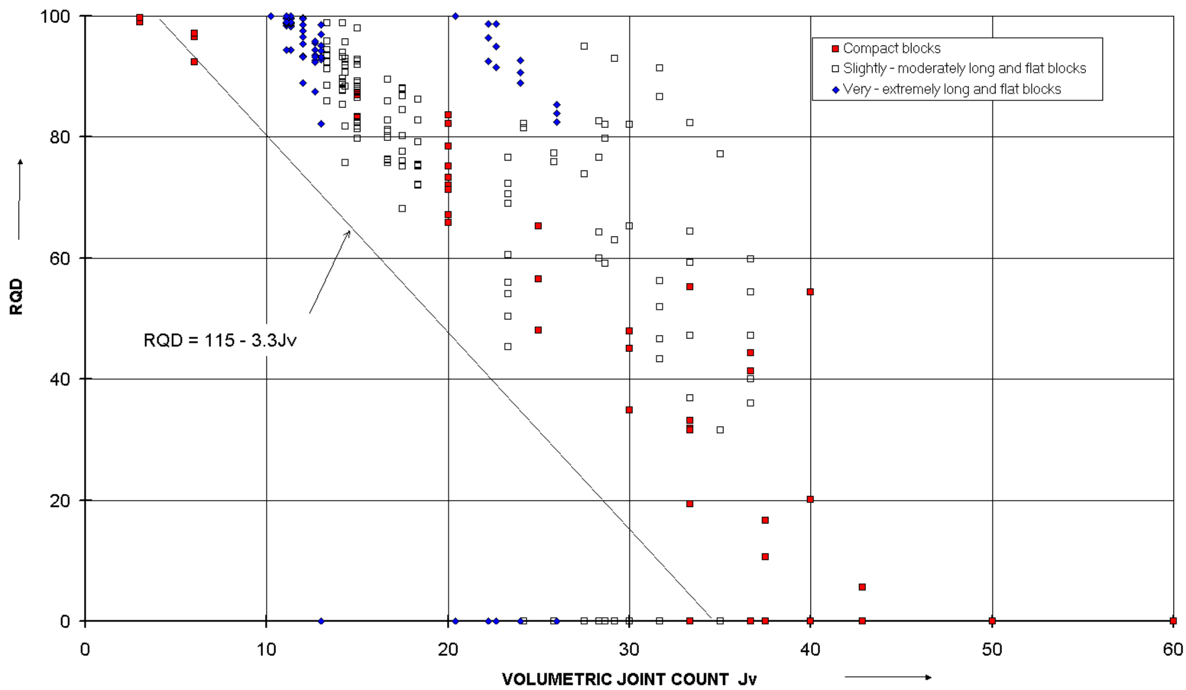

Fig. A4-12 Comparison between RQD and Jv

Sen and Eissa (1991) have made theoretical studies of the connection between Jv and RQD. Fig. A4-13 also shows that there theoretically is a non-linear connection between RQD and Jv contrary to the 'original', linear eq. (A3-21) of Palmström (1982). According to Sen and Eissa this expression is acceptable for long (bar) blocks up to Jv = 25 (RQD = 25). For the high jointing density (Jv > 25) the threshold value has a significant influence on RQD and accurate measurements of RQD is therefore important. Another important fact is that in such highly jointed rock there are often difficult to obtain accurate core length measurements as the dense jointing often affects the drilling process and hence the size of the core bits. This may lead to inaccurate RQD values for highly jointed rock.

Another fact is that, in order to record RQD values in the range of 1 - 10, long measuring sections are required. (For instance, only one 10 cm long core bit in a 10 m long measuring section will give RQD = 1.)

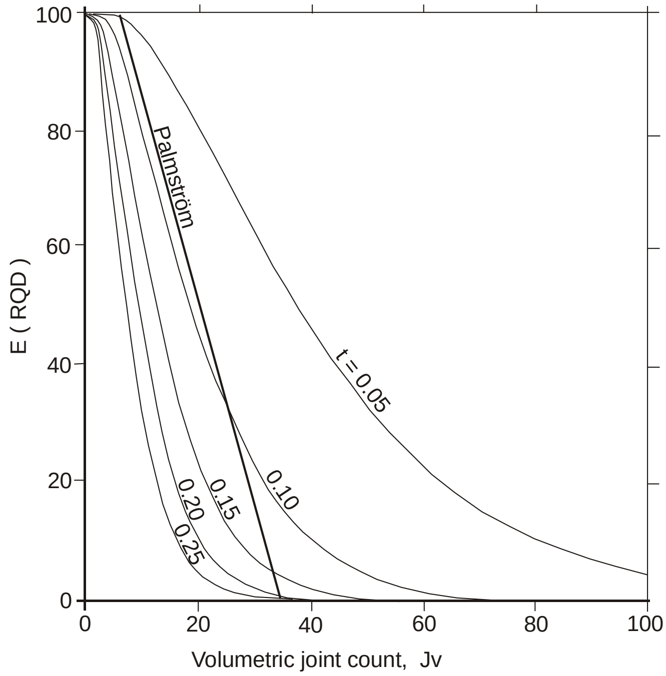

Fig. A4-13 Connection between RQD and Jv for various thresholds (t) for long (bar) blocks. The eq. (A3-21) of Palmström (1982) for a threshold of t = 0.1 m is indicated (from Sen and Eissa, 1991).

The main outcome from the investigations in this section is, as mentioned earlier, that it is important to realize that RQD can vary largely. The way that it is defined and the fact that it is a one-dimensional measurement and cause that there is generally inaccuracy connected to RQD.

6.2 Connection between block volume and "block size" expressed as RQD/Jn in the Q system

Barton et al. (1974) have, in their Q system, modified the RQD by dividing it by a factor representing the number of joint sets occurring at each location. This quotient (RQD/Jn) is meant to represents the overall structure of the rock mass as a crude measure of the relative *block size* within the two extreme values 200 and 0.5, representing crude but recognisable approximations of "particle size" (diameter) varying between 2 m and 0.005 m respectively.

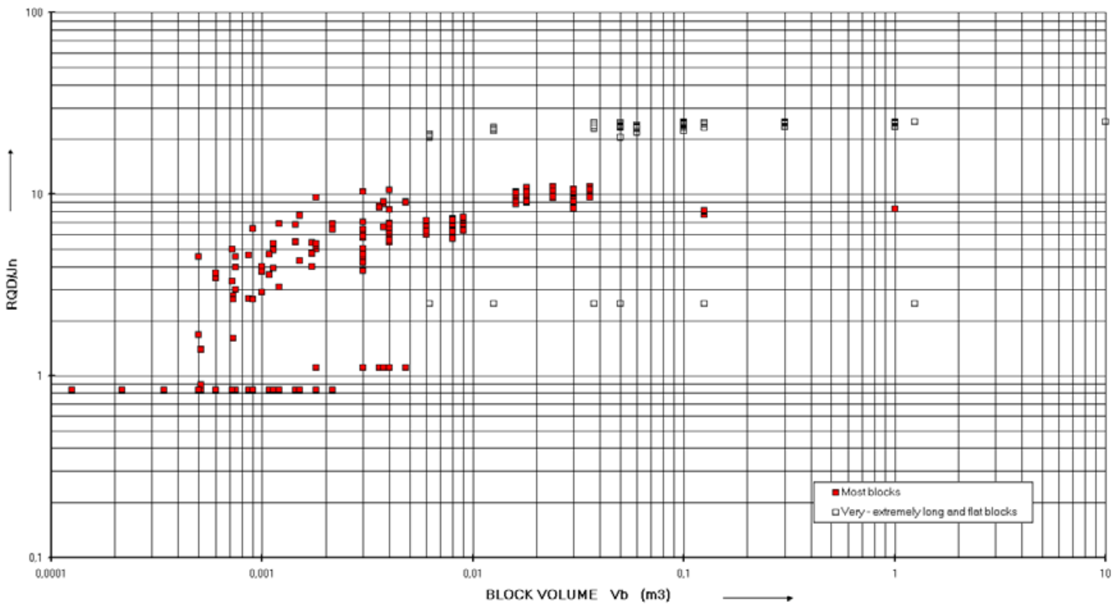

Fig. A4-14 Connection between RQD/Jn in the Q-system and block volume, Vb.

As is shown in Fig. A4-14 there is a very poor connection between the block size (Vb) and the ratio RQD/Jn. This is not unexpected, remembering the inability of RQD to give accurate measurement of the density of joints (and hence the block size).

The factor Jn in the Q system can be considered as a factor representing the block shape as it is varying with the number of joint sets. Jn can, therefore, crudely be compared with the block shape factor β. As pointed out by Cecil (1970) the number of joint sets in a rock mass is an important indication of the degree of freedom of blocks in a rock mass.

8 SUMMARY

The correlation between block volume (Vb) and volumetric joint count (Jv) found in Appendix 3 have been applied to develop transitions between block volume and the following joint measurements:

- 1-D frequency observation in boreholes or scanlines;
- 2-D frequency observations in surface areas;
- RQD measures in boreholes; and
- Weighted joint density measurements in boreholes or in surface areas.

Important in the correlation $Vb = \beta \times Jv^{-3}$ is β, the block shape factor. Where regular jointing with 3 joint sets occurs, β may easily be found from the spacings. In other cases an estimate of it can be made from

$$\beta = 20 + 7\ a3/a1$$

where a3 is the length of the block, and a1 the thickness of the block.

2-D frequency registrations (in surfaces) characterizes, as expected, generally the degree of jointing (i.e. block size) better than 1-D measurements (in boreholes and scanlines). The errors can be as large as (+500%, -50%) especially for very to extremely flat blocks.

The weighted joint density measurements introduced in this work give better accuracy than the existing 1-D and 2-D registrations. In surface observations the error is in the order ±30%; in boreholes and scanlines +35, -50%.

Another result from the investigation is that it is almost impossible to estimate the block volume from RQD registrations within reasonable accuracy.

The introduction of the ratio RQD/Jn (Jn is the joint set number in the Q-system) improves the RQD's possibility to characterize jointing, but still the use of RQD for volume estimates is highly uncertain. The conclusion drawn is that RQD often expresses unreliable values of the degree of jointing. RQD measurements should generally be regarded as very crude measurements, and it is therefore difficult to recommend any better transition from RQD to block volume than eq. (A3-27) (RQD = 115 - 3.3 Jv) where RQD is the only registration available on the jointing density.