2. Measurement of discontinuity characteristics

General things about joint survey

- It is recommended to measure and record as many items as possible for the joints (discontinuities). Additional afterward survey for the missed items makes the survey inefficient and costly.
- Image processing technique for site investigation has been continuously developed but it has to still go further to catch up with human ability of observation. Ex.) Papers of image processing
- 150 ~ 350 discontinuities are known by experience to be reasonable for one sampling location. This means that 1,000 ~ 2,000 discontinuities are adequate for a site consisting of 5 ~ 15 sampling locations.
- Precise analysis is as important as precise joint survey.

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New directions in rock mechanics - report on a forum sponsored by the American Rock Mechanics Association

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Abstract

TheAmericanRock MechanicsAssociation (ARMA) and the ARMA Foundation sponsored a forumon **New Directions for US Rock Mechanics** which was held at the Asilomar Conference Center in Pacific Grove, **California**, USA,during18-20,October **1998**. ThegoaloftheForumwastofocuson:(1)astrategicvisionfor thefuture ofrockmechanicsintheUnitedStates;(2)theidentificationanddelineationofcriticalissuesfacing the rock mechanics community; (3) the role of research in addressing these issues;and(4)criticalareas of researchineachofthetopicareasaddressedattheforumincludingexamplesofspecificresearchinitiatives.Toa large degree, rock mechanics has been used successfullytomodel and predictthebehavioroffractured rock masses for building large structures. However, improvements on present success, and future advances in modeling and construction, are predicated **on better characterization of fractured rock masses**. This will require increasing **emphasis on non-linearand discontinuity-based models** to reflectthemechanismsat work in fractured rock masses. For example, relevant characterization schemes, as well as field, laboratory, and logging techniques have yettobedevelopedforweakrockconditionsandforallbutthesimplestfluidflow conditions.

ThisreportsummarizestwodaysofdiscussionheldduringtheForum.ItwasthesenseoftheForumparticipants that **fundamentalimprovementsinin-siturockmass characterizationisof the utmostimportance.** Everysession emphasizedthatobtainingvalidinformationfromlargevolumesofrockistheprerequisitefortheeffectiveand improved practice of rock mechanics. **Research and application of remote imaging and non-destructive evaluationofthesubsurface** shouldprovideasourceofeconomicallyrealizabledatafromlargevolumesofrock. **Thisareashouldbeaprimarygoaloffutureresearch**. **Associatedwiththequestionofsitecharacterizationisthe degreeofuncertaintyassociatedwiththe data, andwiththechoseninterpretivemodel.Forumparticipants also recommended conducting research to find implementations of stochastic techniques, which would allow uncertaintytobedealtwithinarationalmanner.**

Survey methods of rock mass - borehole sampling andexposedrockface sampling.

(1) Borehole sampling

Advantage/application :

① (Economically) applicable to the deeppartofrockmass

② Borehole coresareavailablefor RQD evaluationandvarious lab tests.

③ Jointorientation can bemeasuredinboreholecore(usingadoubletube core barrel)orwall

④ In-situ stress/deformabilityofrockmass(hydrofracturing,Goodmanjack)

⑤ Ground water level/pressure and rock masspermeability

⑥ Evaluation ofore grade/geologicalstructure

Disadvantage/notes :

① Borehole TV is more convenient to measure the jointorientation with than borehole core

② Joint (trace)sizeisnormally notabletobemeasured

③ Carefullydifferentiate thenaturaldiscontinuitiesfrom artificialones.

④ Infill materials can beeasilydisturbed/contaminated at core recovery.

Description/logging :

Rock material, corebarrel, RQD, commentsondiscontinuities, test results etc.(Fig.2.1)

Measuring jointorientation : when theboreholeisinverticaldirection

① With rock core (p.29)

② On horehole wall

Measuring joint roughness :

① With rock core

② On horehole wall(refer to nextpage)

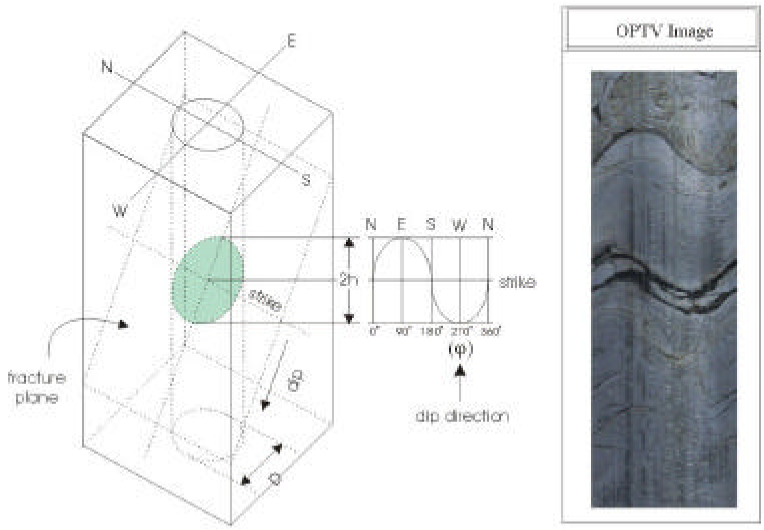


Fig. Application of borehole television

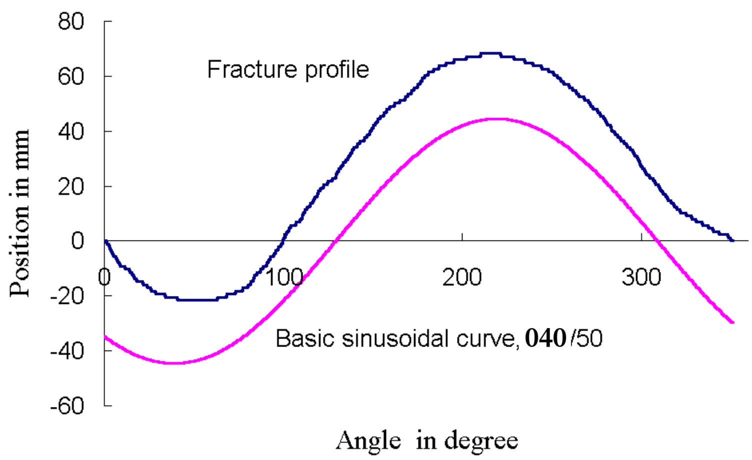


Fig. Joint trace on the borehole wall and its corresponding sine wave

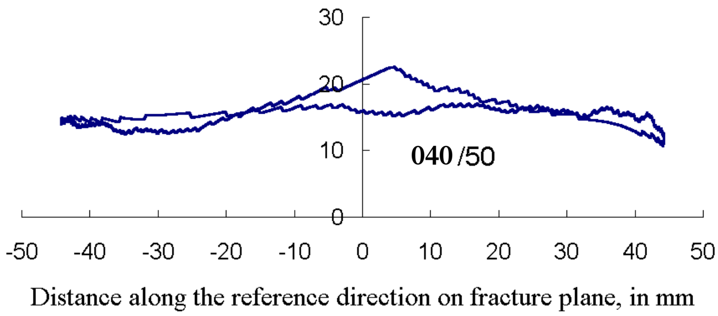


Fig. Joint profile projected on a specifically oriented plane

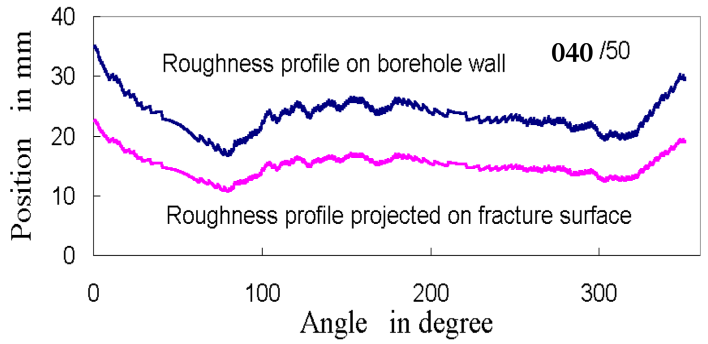


Fig. Joint roughness profile on borehole wall and another roughness profile projected on fracture surface

Borehole TV logging system

TV in "Borehole TV Logging System" is an abbreviation of two different words: television and televiewer. The former uses optical lenses while the latter uses ultra sonic waves to observe (survey) the borehole wall.
The borehole television logging system is frequently referred to as "Borehole Image Processing System (BIPS)". BIPS provides the direct view of a target with a straightforward mechanism. This enables BIPS to be applied to dry boreholes or cavities and to show ground water flow in borehole, while suspending materials in the water prevent it from observing water flow or borehole wall.
The borehole televiewer has a unit to detect the magnetic north (Zemmanek etc, 1969) as BIPS dose. The televiewer sends a stream of ultra sonic waves (thousands per second) towards the borehole wall as it is lifted up with rotation. The reflected sonic waves are continuously recorded. Through their amplitude and traveling time, we can measure borehole radius, joint orientation and mechanical properties of rock. The observed or analysed images are normally recorded with depth in digital formats. Both techniques/systems complement well each other.

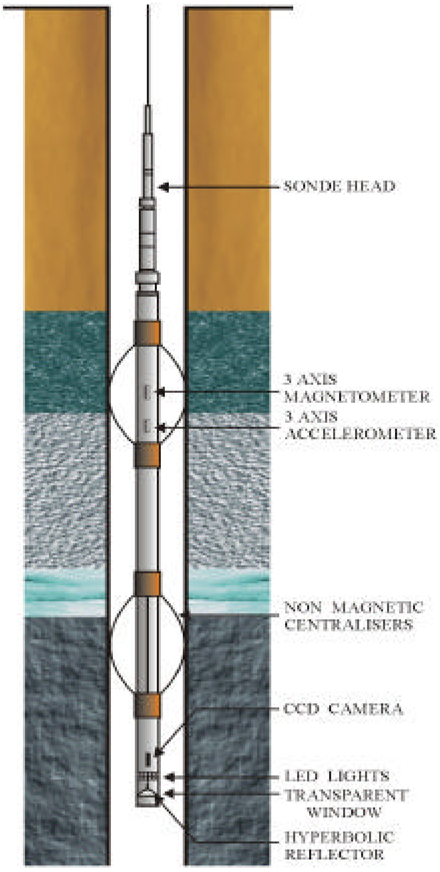


Fig. Application of BIPS

● Logging with optical television

The optical television records the borehole view reflected by hyperbolic mirror attached to the probe. CCD camera continuously takes photos whose width is 5 *mm* and each photo consists 720 pixels. The camera is lifted up with a constant speed of about 0.5~1.5 *m/min*. The magnetic north is measured by a 3-axis magnetometer and recorded with photo images. Joint traces on the borehole wall show sinusoidal waves when their image is unrolled into a plane. By reference to the north, dip direction can be determined and the dip angle can be calculated by using the amplitude of joint trace and borehole radius.

Advantages of optical television
- Applicable to dry boreholes
- Ground water flow cab be observed.
- Rock type variation, infilling materials, geological structure can be observed.
- Aperture of joints can be measured.
- No special software is needed for analysis.

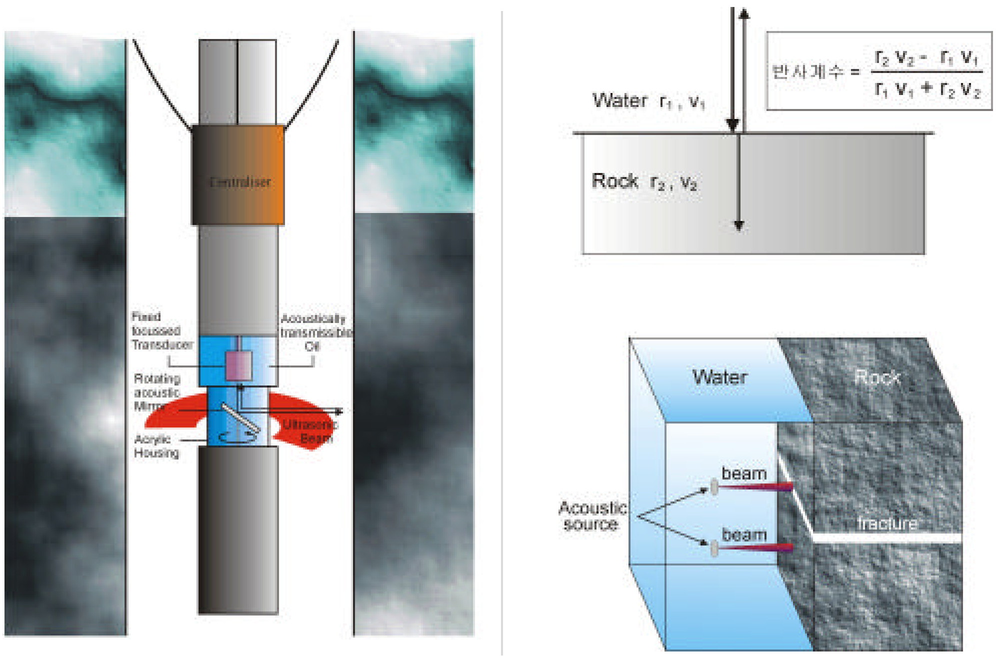
● Logging with televiewer

The televiewer is said to be an acoustic borehole scanner which periodically shoots ultra sonic beam (1.5 MHz) to borehole wall and records its reflected waves for the energy (amplitude) and travel time.

The magnitude of energy of the reflected wave depends on reflection coefficient which is a function of material density and traveling velocity as shown in the figure below. When the acoustic beam reflects from a joint plane its energy is dispersed on the surface and impeded by joint infilling materials resulting in a weak signal to the sensor. Open joints make the acoustic wave travel farther than in-filled joints do. This helps to confirm the existence of a joint.

A joint trace is shown as a sine curve on the borehole wall. By the magnetic north stored in televiewer record, the scanning data is arranged according to orientation: N-E-S-W-N. Dip direction and dip angle of the joint can be obtained from the joint trace, borehole size and the information of north.

The televiewer record includes the amplitude of reflected waves, travel time and location of sensor. The wave amplitude is affected by discontinuities and rock strength. The travel time is used to measure the borehole radius or to correct the measurement. The sensor location can be determined by depth which is measured by a depth counter attached to winch and orientation which is measured by 3 axis magnetometer and 3 axis clinometer.



(a) (b)

Fig. Principle of televiewer logging

Advantages of televiewer

▶ Young's modulus of rock can be estimated.

▶ Applicable even in unclean water

▶ Less chance to incorrectly identify the rock type due to not relying on surface observation

▶ The amount of record is smaller than that of BIPS.

▶ Variation of borehole radius can be detected.

(2) Exposed rock face sampling

Pros and Cons

① Relatively larger sampling area is available.

② Lower cost

③ Not applied to the area that is unexcavated, damaged by blasting/weathering or covered with bush/plants

Scanline sampling

Standard regulation/rule forsamplingisnotset up yet.

(1) Selection of sampling area

- Place(s) representing the site
- Large enough to include 150 ~ 350 joints (50% of joints should have one or two endpoints within the sampling area)
- Safety: safe from rock failure, ground water flow and traffic)

(2) Installation of scanlines

- Length: 2 m ~ 30 m
- Orientation: Parallel to the strike or dip of the sampling plane
- Reducing sampling bias: select a sampling plane perpendicular to the previous ones
- Close to the face: make the scanline close to the rock face (required to measure short joint traces).
- Splitting a scanline: when a scanline deviates from a straight line more than 20 °
- Photographing: photos from several view points with scales

  ex.) markers attached to the scanline at 1*m* interval (Fig. 2.4, p.34).

  Different distance between camera and surface points of sampling area makes its image distorted (Fig. 2.5).

  → 1) Long focal length lens/tilt shift lens (hardware solution)

  2) Photogrammetry: image matching and orientation with scale information gives 3D coordinates of every point on

the image

(3) Recording joint intersection points

- Origin point: measurement starts from zero at either end of the scanline and the intersecting points are recorded in order of location.
- Target: natural joints
- Fracture zone: record the extent, location and nature of the zone.
- Closely spaced/sub-parallel joints: record representative measurements, extent and count

(4) Joint orientation

- Measuring point: intersection points of joints and a scanline
- Tool: clinocompass (clinometer + magnetic compass + spirit level (Fig. 2.7, Fig. 2.8)
- Representation: dip direction/dip, strike/dip
- Error: ±10° for dip direction and ±5° for dip angle.

(5) Semi-trace length

- Definition: distance between a joint-scanline intersection and either end of the joint trace. The counting points of joint traces should be within the same part of the sampling plane : ex.) left (right) or upper (lower) part of the scanline.
- Uncertainty : The average length of semi-trace is half of the mean joint trace length, which means there is uncertainty in estimation of the complete trace length especially when the sample size is small.
- Advantage over complete trace length measurement: Simple and rapid
- Terms for filtering:
  ① trimming - excluding traces shorter than a lower limit
  ② curtailment - excluding traces longer than a upper limit
  ③ truncation - not recording the number of excluded traces
  ④ censoring - recording the number of excluded traces

Window sampling

(1) Pros and cons

- Pros: Bias according to the orientation and size of joints is smaller than that of scanline sampling.
  ▶ Orientation - Joints parallel to scanline or sampling window are not observed. In case of window sampling only the joints with a specific orientation are missed in the window.
  ▶ Joint size - The number of observed joint traces decreases as the joint size decreases. The decreasing rate is lower in case of window sampling.
- Cons: There are more joint traces in the sampling window than in the

scanline, which means the window sampling requires more time to count and record joints.

→ automated process is useful - photogrammetry,
laser profiling (hard to find joint trace),
radar, seismo-acoustic (resolution problem).

(2) Classification of joint traces according to the no. of end points in a window

① Contained trace (양끝내포선) - both ends are in the window

② dissecting trace (한끝내포선) - either end is in the window

③ transecting trace (양끝외포선) - both ends are out of the window

Application ofgeostatistics to discontinuityanalysis

- A kind of applied statistics dealing with varied spatial data sets.
- Variogram: a measure of the continuity of spatial phenomena expressed as an average squared difference at different locations (Fig.2.10).
- Kriging: a stochastic interpolation technique based upon a generalized least square algorithm using variograms as weighting functions. With the least square algorithm, the estimate becomes unbiased and its variance becomes minimized.
- Difficulty in application: As for the joints it is usual to analyze their features for each joint set such as size and spacing. As the investigation area is extended, however, the joint orientation and accordingly the definition of set change. This makes it difficult to analyse the joint set features with variogram or Kriging.

Rock mass classification

(1) RMR/Q system

- RMR(Bieniawski, 1973), Q-system (Barton etal,1974):Providingguidelines of support,excavationmethodandstrengthand deformabilityof rockmass. Quantitative and simple description ofrockmass isprovided.
- Somewhat subjective andqualitativefactors involved: Description of discontinuitycondition(RMRandQ) - very (slightly)rough,slightly (highly) weathered, rough orirregular, smooth,undulating...
- Lack ofstatisticalinformation ofjointsandrelevantanalysistechnique:Rock massclassification schemes wasdevelopedin1970'sandhas proceeded independentlyofresearchondiscontinuitysampling and analysis.

(2) RQD

- Fundamental factor ofrockmassclassification:20/100 in RMR. 100inQ

- Relation with spacing: closely and most directly related with spacingorlinear frequency.Itshows,however, similarvaluesforthejointshaving more than 30*cm* of spacing.
- Dependance on the orientation ofascanlineorborehole:RQDmaychange significantlybythescanningorientationinthesitewhereonly1~2 joint sets aredominant.RMR/Qarenotcareful aboutthisproblem.

(3)RMi(RockMass index)

- Suggested by Palmstrom (1995).
- Factors: Joint roughness,alteration,size/termination,density,uniaxial compressive strength
- Feature:Noconsiderationofstress and jointorientation → assuming rock massasanisotropicmaterial.RMi indicates a rockmassstrength. Subjective judgement may intervene in theevaluation process.

The Rock Mass index (RMi)

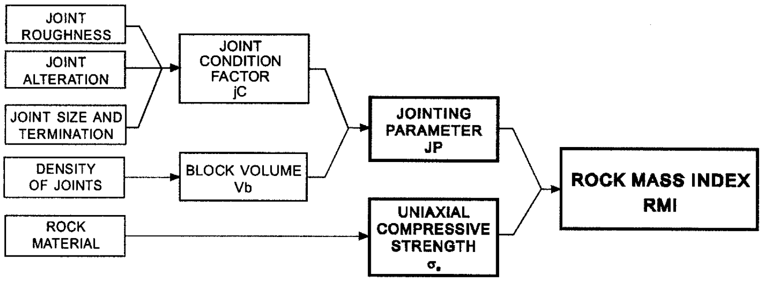


Figure 1 The main inherent parameters in the rock mass are applied in the RMi (from Palmström, 1995).

RMi is based principally on the reduction in strength of a rock caused by jointing [1] and is expressed as:

$$\text{RMi} = \sigma_c \times \text{JP} \qquad \text{eq. (1)}$$

where σ_c = the uniaxial compressive strength of intact rock measured on 50 mm samples;
JP = the jointing parameter which is a reduction factor representing the block size and the condition of its faces as represented by their friction properties and the size of the joints.

$$\text{JP} = 0.2\sqrt{\text{jC}} \times \text{Vb}^{D} \qquad \text{eq. (2)}$$

where Vb is given in m^3, and $D = 0.37\,\text{jC}^{-0.2}$ has the following values:

for jC =	0.1	0.25	0.5	0.75	1	1.5	2	2.5	3	4	6	9	12	16	20
D =	0.586	0.488	0.425	0.392	0.37	0.341	0.322	0.308	0.297	0.28	0.259	0.238	0.225	0.213	0.203

The joint condition factor is expressed as jC = jL (jR/jA) where jL, jR and jA are factors for respectively, joint length and continuity, joint wall roughness, and joint surface alteration.

Table 4. Classification of RMi (from Palmström, 1995)

TERM		
for RMi	**related to rock mass strength**	**RMi VALUE**
Extremely low	Extremely weak	< 0.001
Very low	Very weak	0.001 - 0.01
Low	Weak	0.01 - 0.1
Moderate	Medium	0.1 - 1
High	Strong	1 - 10
Very high	Very strong	10 - 100
Extremely high	Extremely strong	> 100

Table 1. The ratings of the joint roughness factor, (jR, found from smoothness and waviness (from Palmström, 1995) (The ratings of jR are similar to Jr in the Q-system)

small scale smoothness of joint surface	large scale waviness of joint plane: planar	slightly undulating	strongly undulating	stepped	interlocking (large scale)
very rough	3	4	6	7.5	9
rough	2	3	4	5	6
slightly rough	1.5	2	3	4	4.5
smooth	1	1.5	2	2.5	3
polished	0.75	1	1.5	2	2.5
slickensided*)	0.6 - 1.5	1 – 2	1.5 – 3	2 – 4	2.5 – 5
	For filled joints: jR = 1		For irregular joints a rating of jR = 5 is suggested		

*) For slickensided joints the value of jR depends on the presence and appearance of the striations; the highest value is used for marked striations.

Table 2. Characterization and rating of the joint alteration factor, jA, (from Palmström, 1995) (jA is similar to Ja in the Q-system, except for the grade of alteration)

A. CONTACT BETWEEN THE TWO ROCK WALL SURFACES

TERM	DESCRIPTION	jA
Clean joints		
-Healed or "welded" joints	Softening, impermeable filling (quartz, epidote etc.)	0.75
-Fresh rock walls	No coating or filling on joint surface, except for staining	1
-Alteration of joint wall:		
· 1 grade more altered	The joint surface exhibits one class higher alteration than the rock	2
· 2 grades more altered	The joint surface shows two classes higher alteration than the rock	4
Coating or thin filling		
-Sand, silt, calcite etc.	Coating of friction materials without clay	3
-Clay, chlorite, talc etc.	Coating of softening and cohesive minerals	4

B. FILLED JOINTS WITH PARTIAL OR NO CONTACT BETWEEN THE ROCK WALL SURFACES

TYPE OF FILLING MATERIAL	DESCRIPTION	**Partial wall contact** thin fillings (< 5 mm*)) jA	**No wall contact** thick filling or gouge jA
-Sand, silt, calcite etc.	Filling of friction materials without clay	4	8
-Compacted clay materials	"Hard" filling of softening and cohesive materials	6	10
-Soft clay materials	Medium to low over-consolidation of filling	8	12
-Swelling clay materials	Filling material exhibits clear swelling properties	8 - 12	12 - 20

*) Based on joint thickness division in the RMR system (Bieniawski, 1973)

Table 3. The joint size and continuity factor, jL, (from Palmström, 1995).

JOINT LENGTH	TERM	TYPE	jL: continuous joins	discontinuous joints**)
< 0.5 m	very short	bedding/foliation partings	3	6
0.1 - 1.0 m	short/small	joint	2	4
1 - 10 m	medium	joint	1	2
10 - 30 m	long/large	joint	0.75	1.5
> 30 m	very long/large	(filled) joint, seam*) or shear*)	0.5	1

*) Often occurs as a single discontinuity, and should in these cases be treated separately. **) Discontinuous joints end in massive rock

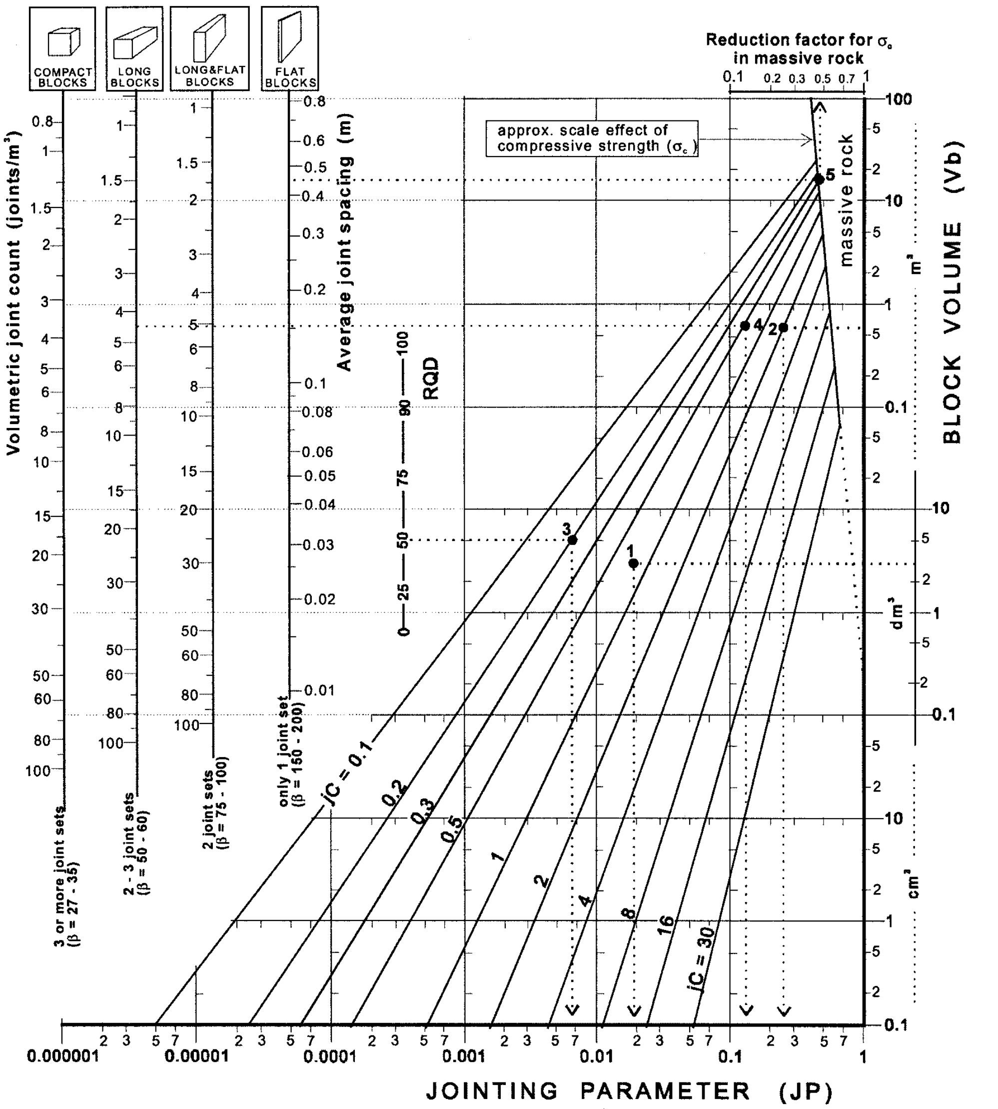


Figure 3. The jointing parameter (JP) found from the joint condition factor (jC) and various measurements of jointing intensity (Vb, Jv, RQD). The determination of JP from Vb (or RQD or Jv) in the examples are indicated (from Palmström, 1995).