

JOINT APERTURE AND ROUGHNESS IN THE PREDICTION OF FLOW AND GROUTABILITY OF ROCK MASSES

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ABSTRACT

Changes in the geometry of rock joints following changes in the state of normal and shear stresses affect rock to rock contacts, roughness, aperture and tortuosity of flow channels. The paper discusses the role performed by the effective physical aperture E (or ΔE) and its relation with the theoretical aperture e (or Δe) used in the parallel plate analogy for flow in rock joints. The influence of joint wall roughness is discussed in terms of the joint roughness coefficient JRC (Barton and Choubey, 1977) and the relative roughness concept (Lomize, 1951). The behaviour of the ratio E/e and the simultaneous influence of roughness and aperture on flow through rock joints is analysed in terms of the hydraulic conductivity of a joint for varied JRC and relative roughness, using empirical equations derived from laboratory work. Grouting prediction and behaviour of the ratio E/e after grouting is also discussed.

KEYWORDS

Rock joints, aperture, roughness, shearing, flow, coupled processes, JRC , hydraulic conductivity, relative roughness, groutability.

1 INTRODUCTION

Changes in the hydraulic conductivity of rock joints induced by changes in normal or shear stresses are important for the evaluation of the hydromechanical behaviour of rock masses and grouting prediction.

Basic phenomena related to these problems have been studied by many authors, since the 1970's (Jouanna, 1972; Louis, 1974; Gale, 1975; Iwai, 1976; Whitherspoon et al., 1979, among others). These researchers aimed most of the time to evaluate the effect of normal stress on the hydraulic conductivity of the rock joints.

Coupled methods related to changes in normal or shear stresses however, increased substantially only in the last 15 years probably due to the needs of the nuclear waste and petroleum industries, and due to the advent of personal computers and consequent advances in numerical modelling of rock masses and rock joints. There was therefore a need for extensive experimental testing to obtain relevant input data and behavioural laws.

Following this trend, some of the major factors controlling flow through rock joints were extensively studied in the laboratory and simulated by modelling (Gale, 1982; Bandis et al., 1983; Barton, 1985; Barton et al., 1985; Makurat and Barton, 1985; Raven and Gale, 1985, Hakami and Barton, 1990; Esaki et al., 1995, Makurat and Gutierrez, 1995, among others).

Barton et al. (1985) proposed an empirical equation for the analysis of the relationship between the effective physical aperture E and the theoretical aperture e , related to the parallel plate analogy (cubic law), using the

joint roughness coefficient **JRC** as reference. Deviations from the cubic law are observed when comparing this model with experimental results, and these deviations can be understood as a change of E/e caused by the increased tortuosity of flow as hydraulic and physical apertures reduce.

2 LAMINAR FLOW IN ROCK JOINTS

Laboratory experiments have shown that the roughness and aperture of a rock joint are the most important factors governing fluid flow through the joint. Roughness is an important factor in both the mechanical and hydraulic behaviour. However, due to the impossibility of measuring this parameter directly in a flow process, its influence is usually allowed for through the use of coefficients such as the relative hydraulic roughness (r_a/dh) or the physical joint roughness coefficient (**JRC**).

The relative hydraulic roughness is defined by the ratio (r_a/dh), where r_a is the difference between the highest "peak" and the lowest "valley" of the physical wall roughness (Louis, 1969) and dh is the hydraulic diameter. According to the theory of flow between two smooth parallel plates (Poiseuille law), $dh = 4 rh$ where $rh = e.l/2.l$, $e.l$ is the area normal to the flow and $2.l$ is the perimeter where viscous friction takes place. We can write r_a/dh as $r_a/2.e$.

The joint roughness coefficient (**JRC**) proposed by Barton and Choubey (1977) for description of the shear strength of rock joints is the most used at the moment for normal deformation and shearing analysis of rock joints (Barton, 1982, Bandis et al., 1983; Barton and Bandis, 1990). Due to the extensive use of **JRC** in the analysis of rock engineering problems and the possibility of quantification of this parameter using the simple methods proposed in Barton and Choubey, this coefficient would seem to be a potentially useful practical tool to characterize the hydraulic conductivity of rock joints taking into account the effects of roughness on flow.

The coefficient **JRC** and the relative roughness r_a are each related to the roughness profile and the height of asperities. However **JRC** basically describes the roughness of correlated potentially interlocking surfaces while r_a describes an uncorrelated roughness. A joint of a given physical aperture (E) and roughness profile defined by the height of asperities and the parameter **JRC**, will have a corresponding theoretical smooth walled aperture (e), which could be determined by means of the cubic law (1), based on the parallel plate analogy as referred to before. According to this law,

$$k = \frac{ge^2}{12\nu} \quad (1)$$

where k = isotropic coefficient of hydraulic conductivity (LT^{-1})
 g = gravity (LT^{-2})
 e = joint aperture (L)
 ν = coefficient of kinematic viscosity of the fluid (L^2T^{-1})

In order to compute the effect of roughness on flow through simulated rock joints, semi-empirical flow laws have been derived from laboratory tests. The following Eqns. 2, 3 and 4 relate in general to hydraulic tests on glass, rock or concrete discontinuities with uncorrelated roughness.

$$k = \frac{ge^2}{12\nu} \frac{1}{1 + 17 \left(\frac{r_a}{2e} \right)^{1.5}} \quad \text{Lomize (1951)} \quad (2)$$

$$k = \frac{ge^2}{12\nu} \frac{1}{1 + 8.8 \left(\frac{r_a}{2e} \right)^{1.5}} \quad \text{Louis (1969)} \quad (3)$$

$$k = \frac{ge^2}{12v} \frac{1}{\left[1 + 20.5 \left(\frac{r_a}{2e}\right)^{1.5}\right]} \quad \text{de Quadros (1982)} \quad (4)$$

In these equations the term in the brackets is a coefficient which we will call the coefficient of hydraulic roughness C . Figure 1 shows the relationship between this coefficient C and the relative hydraulic roughness $r_a/2e$. As observed in the Figure 1, C approaches 1 when $r_a/2e \sim 0.033$, the limit for parallel flow. The cubic law is supposed to be adequate to describe flow in a rock joint only when the hydraulic aperture e is such that the ratio $r_a/2e$ approaches 0.033, i. e. when $r_a \leq 0.066 e$, or when $e \geq 15.15 r_a$. This describes a situation similar to the sketch in the inset to Figure 1.

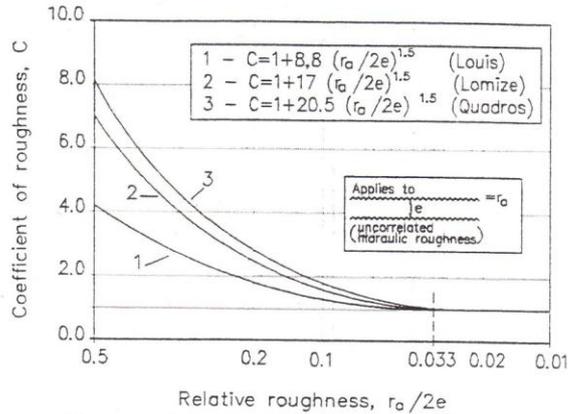


Figure 1 - Relationship between the coefficient of roughness (C) and the relative roughness $r_a/2e$.

In the analysis of flow and coupled shear-flow behaviour of rock joints the model proposed by Barton et al. (1985) is derived from the relationship between the physical aperture (E), the hydraulic aperture (e) and JRC, through the use of Eqn. 5.

$$e = \frac{JRC^{2.5}}{(E/e)^2} \quad (5)$$

where JRC = joint roughness coefficient (-)
 E = physical aperture of the joint (L)
 e = hydraulic aperture (L)
(E and e are expressed as μm in this equation)

Figure 2 shows the relationship of E/e versus e based on laboratory results of several authors. Figure 3 is a detailed plot for hydraulic apertures $e > 0.01$ mm.

The results illustrated in these two figures are evidence that even for smooth natural joints or artificial fractures with absolute roughness varying from 60 to 100 μ (Louis, 1969 and de Quadros, 1982) the ratio E/e tends to be > 1.0 . This behaviour is explained by increased head losses which occur under the influence of the roughness and the tortuosity of the flow channels. The later will tend to be accentuated by the asperities that are in physical contact at the particular stress level. Both affect the frictional drag. The influence of roughness and tortuosity decreases as the fracture opens (increasing E) and E/e approaches 1.0. Even for extremely rough surfaces the ratio E/e approaches 1.0 when the joint opens and the relative hydraulic roughness $r_a/2e$ tends to 0.033.

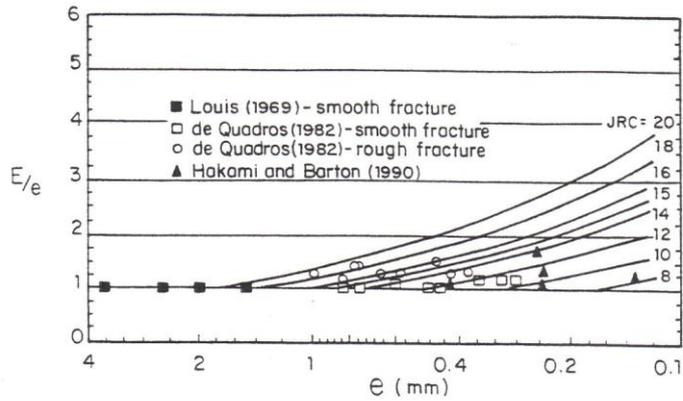


Figure 3 - Relationship between the ratio E/e and e (parallel plate analogy) in terms of JRC for apertures $e > 0.1$ mm. E = physical aperture.

Using the model described by Eqn. 5 and the flow laws showed in Eqn. 1 and 4, Figure 4 was developed relating the hydraulic conductivity k (m/s) of a single joint to the ratio E/e , for varied JRC values. From Eqn. 1 and 5:

$$k = \frac{g(e^2)}{12\nu} = 8175 e^2 \text{ (at } 20^\circ\text{C)} \quad (6)$$

$$k = 8175 \left[\frac{JRC^{2.5}}{(E/e)^2} \right]^2 10^{-8} \text{ m/s} \quad (7)$$

Note that with $C = 1.0$, Eqn. 4 becomes Eqn. 1 and according to Figure 1 the hydraulic aperture e is equal to $15.15 r_s$. This is equivalent to $E/e = 1.0$ in Figures 2 and 3.

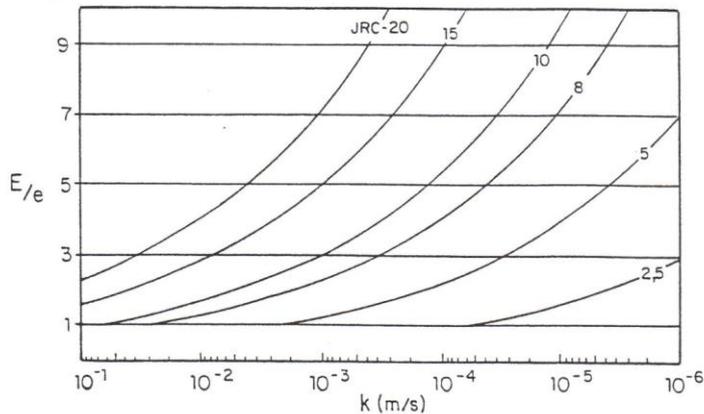


Figure 4 - Substitution of hydraulic conductivity k (m/s) for hydraulic aperture e in the E/e - JRC relationship.

The parameter JRC describes the relative roughness of rock joint walls which have correlated roughness, i.e. there is a considerable degree of potential interlock when the joint is "closed" by increased normal stress. The contacting walls tend to increase the tortuosity of the flow channels that remain within the plane of the joint.

The E/e concept already accounted for the associated head losses which are seen to increase rapidly with increased JRC (Figures 2 and 3). It would not therefore be correct to make an additional head loss correction using the $r_a/2e$ relative roughness concept, which applies specifically to planar rock surfaces having small scale, uncorrelated roughness (viz. inset to Figure 1).

JRC can be estimated using three different techniques which include matching of roughness profiles (drawn with profilometers or even brush gauges) (Barton and Choubey, 1977; ISRM, 1978) or gravity tilt testing (shearing) which requires an estimate of the joint wall strength JCS (measured with a Schmidt hammer). A third technique which resembles the maximum roughness amplitude r_a is to place a straight edge along the joint and record the maximum amplitude (a) for a measured profile length (L) (Barton, 1982). This should be done along several representative profiles and the average a_{max} is then used. For simplicity we will write $a = a_{max}$.

At 100 mm scale:

$$JRC = 400 a/L \quad (8)$$

Although r_a has no specific scale of measurement in the way that a has, the two can be roughly equated when L is of limited dimensions. Since the relative hydraulic roughness is equal to $r_a/2e$, we can substitute from Eqns. 5 and 8 and obtain:

$$r_a \sim a \sim JRC \frac{L}{400} \quad (9)$$

and

$$e = \frac{E^2}{JRC^{2.5}} \quad (10)$$

(where e and E are in units of microns)

Therefore the relative hydraulic roughness can be expressed in approximate terms as:

$$\frac{r_a}{2e} = \frac{JRC^{3.5} \cdot L}{800 \cdot E^2} \quad (11)$$

Let us suppose $r_a/2e$ is equal to 0.033 (from Figure 1 this is the apparent limiting magnitude for parallel flow for which $e > 15.15 r_a$).

If we assume an interlocking joint with a typical JRC value of 10, and $L = 100$ mm (a in units of mm) we obtain for the limiting physical aperture :

$$E = \sqrt{\frac{10^{3.5} \cdot 100}{800 \cdot 0.033}} \text{ (}\mu\text{m)} \quad (12)$$

limiting value of $E (= e)$.

The limiting value of $E (= e)$ predicted is $109\mu\text{m}$, which judging by the data in Figures 2 and 3 is a little less than expected. With $JRC = 2.5$ (a very smooth joint) the predicted limit of $E (= e)$ for parallel (cubic law) flow is $9.7\mu\text{m}$ which corresponds fairly closely to the value predicted in Figure 3. At the other extreme, with $JRC = 20$ (as for an extremely rough interlocking tension fracture) the result is $368\mu\text{m}$.

It will be noted that these three results are each indicating a little smaller aperture than the interlocked joint data (for $E = e$) given in Figures 2 and 3. We may well be witnessing the fact that for interlocked natural joints with correlated roughness a lower relative hydraulic roughness $r_a/2e$ is required for parallel, cubic law

flow. In the table below we give limiting values of E based on Eqn. 9, but with three values of $r_a/2e$ defining the plateau in Figure 1.

TABLE 1
PREDICTED LIMITS FOR E (= e) IN MICRONS FOR PARALLEL FLOW
IN INTERLOCKED NATURAL JOINTS USING THREE RELATIVE
HYDRAULIC ROUGHNESS LIMITS (L = 100 mm, E = μm).

JRC	$r_a/2e$		
	0.033	0.02	0.01
E (μm)			
2.5	9.7	12.4	17.6
10	109	141	199
20	368	473	669

It would appear that for the roughest interlocking joint imaginable (JRC = 20) an even lower relative hydraulic roughness limit would fit the data better, while for joints of moderate roughness a higher hydraulic roughness limit (i.e. 0.033 or 0.02) fits the data quite well. We thus have managed in approximate terms to couple the classic hydraulic experiments on rock surfaces of different roughness with the JRC concept which is more usually associated with strength and stiffness modelling of rock masses. The limiting value of $r_a/2e$ for cubic law behaviour obtained from tests on uncorrelated rock surfaces has been shown to give similar values to the limiting value ($e = E$) for flow in joints with correlated (matching) surfaces. With smaller apertures than this there is an increasing divergence between E and e (or increasing C value from Figure 1).

It is of interest to investigate this other extreme of $r_a/2e = 0.5$, in other words closed but uncorrelated surfaces having $r_a = e$. From Eqns. 9 and 10 we have:

$$\frac{r_a}{2e} = 1 = \frac{\text{JRC}^{3.5} \cdot L}{400 E^2} \quad \text{or} \quad E = \sqrt{\frac{\text{JRC}^{3.5} \cdot L}{400}} \quad (13)$$

Table 2 shows the predicted values of physical and hydraulic apertures for closed joints with correlated surface roughness of JRC varying from nearly planar (JRC = 2.5) to extremely rough (JRC = 20). It will be noted that the divergence from the cubic law (increasing ratio of E/e) increases with the roughness of these correlated surfaces due to the increasing tortuosity and frictional drag associated with high JRC values in the closed (mated) condition. Implicitly, as for $r_a/2e$ values of 0.5 in Figure 1, these results are for closed but unstressed samples.

TABLE 2
PREDICTED VALUES OF PHYSICAL APERTURE (E) AND
HYDRAULIC APERTURE (e) FOR CORRELATED SURFACES THAT
GIVE THE SAME FLOW LOSSES AS $r_a = e$ (C = 8.0, FIGURE 1).

JRC	E (μm)	e (μm) (Eqn.10)	E / e
2.5	2.5	0.63	4.0
5	8.4	1.25	6.7
10	28.1	2.5	11.2
15	57.2	3.75	15.2
20	94.6	5.0	18.9

3 COUPLED DEFORMATION-FLOW PROCESSES

In this concluding discussion of coupled deformation-flow processes, we will examine firstly interlocked joints under varying normal stress. This will be followed by joints that are subjected to shearing from an initially interlocked position.

Figure 5 illustrates typical stress-closure curves for the physical aperture changes (ΔE) and for the hydraulic aperture changes (Δe). The higher the JRC value the larger will be the ratio E/e in such closure-flow tests.

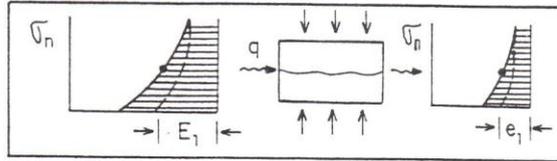


Figure 5 - Changes of E and e for joints under normal loading cycles.

When interlock is destroyed by shearing, we arrive in a new situation because of a potentially dramatic increase in void space. However this may be rapidly blocked by gouge production if σ_n is large compared to JCS.

Figure 6 illustrates shearing and dilation which may be associated with this gouge production. The ratio JCS/σ_n will determine whether dilation (and increased E and e) or gouge production (and reduced E and e) are the dominant factors.

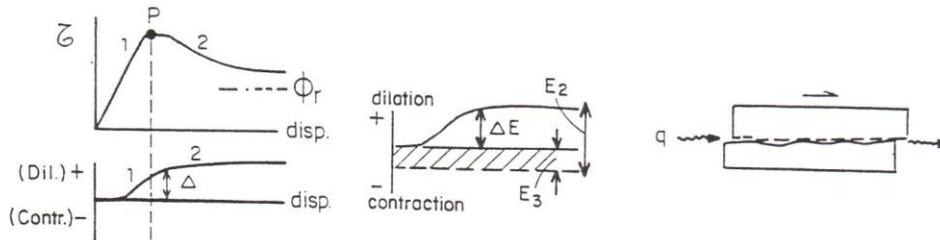


Figure 6 - Shear, dilation and flow coupling.

Figure 7 is a conceptual indication of the reducing porosity of the joint void as gouge is produced (when JCS/σ_n is low).

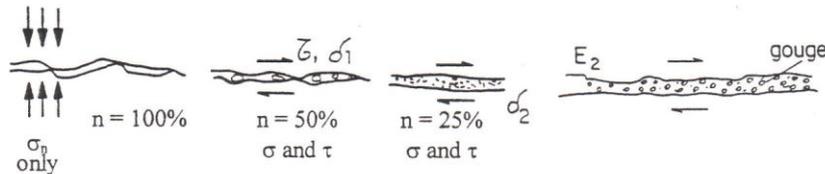


Figure 7 - Conceptual reduction of joint porosity with increasing gouge production.

Gouge can be developed in the whole dilation-flow coupling, however full development of gouge will be after JRC_{peak} and for low values of the ratio JCS/σ_n where contact area and damage is large. When there is evidence of a lot of gouge and when the infilling is obviously governing the magnitude of permeability most probably it could be interpreted by the simple use of Darcy law.

4 PREDICTION OF GROUTING IN JOINTED ROCK MASSES

The volume of a rock mass that can be grouted is related both to the hydraulic conductivity k of the network of the interconnected discontinuities and to the physical aperture E of the joints in each family.

Figure 8 illustrates the idealized cubic network of joints in a given rock mass (Snow, 1968). The theoretical apertures e in this model have to be converted to physical apertures E using data from field hydraulic tests and the E/e diagram shown in Figure 4 (Barton, 1985) or from Eqn. 5.

In order to evaluate potential grouting volume for practical purposes, the following steps could be followed:

- JRC is estimated from tilt tests in natural joints selected from drill cores;
- hydraulic conductivity k is determined from in situ water pressure or suction tests;
- E/e is evaluated from JRC and k using Figure 4.

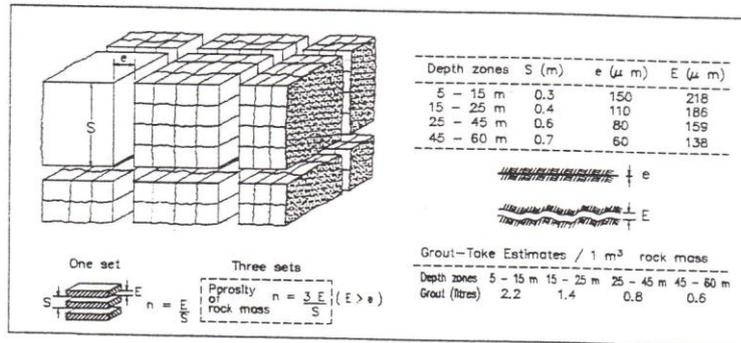


Figure 8 - Example of grout-take estimation by converting theoretical hydraulic apertures e obtained from in-situ hydraulic tests to physical apertures E using cubic law and empirical Eqn. 5 (assumed cubic network of rock mass volume as idealized by Snow (1968) (Barton, 1985).

5 CONCLUSIONS

1. Classical hydraulic tests on planar and artificially roughened discontinuities in rock, concrete and glass have uncorrelated roughness or non-interlocking surfaces. Nevertheless the concept of relative hydraulic roughness ($r_s/2e$) from these tests has been shown to give equivalent results to flow between the interlocked roughness of real rock joints, which are described by JRC and the ratio of physical (E) to hydraulic (e) aperture.
2. Flow through rough interlocked joints that are closed show increasing divergence from the cubic law the greater the JRC value. The increasing ratio of E/e can be equated to reducing permeability. The flow losses are due to the increased tortuosity of the flow paths in addition to the losses due to frictional drag.
3. Interlocked, closed joints that are subjected to normal stress show reduced (e) and increasing E/e and maintain a constant JRC value. Results cited from the literature range from $e = 2 \mu\text{m}$ to $E = 6 \text{mm}$.
4. When an interlocked closed joint is subjected to shear stress, there is a conflict between the opposing effects of dilation and gouge production. Instruments may suggest that the physical aperture (E) increases in both cases, but the hydraulic aperture (e) may only increase in the case of gouge-free dilation. Gouge production systematically reduces joint porosity and (e), and may demand a change from parallel plate or channel flow to porous medium flow concepts.
5. Groutability can be estimated from JRC estimation and E/e calculation using core logging (for JRC) and packer tests (for e).

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