The hydraulic conductivity of the fractures intersecting Cambrian sandstone rock masses, central Jordan

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Abstract This paper outlines the hydraulic characteristics of fractured rock masses and their implication in engineering works. The hydraulic behavior of subsurface fracture systems has been evaluated by means of hydraulic testing using packer tests and by fracture analysis. A comparison of the borehole results with those of surface fracture mapping provides a reasonable correlation between the two methods of measuring fractured rock hydraulic conductivity. The mean hydraulic conductivity value obtained from the boreholes is 36.5 LU (9.26×10^{-5} m/s), while the mean value of hydraulic conductivity obtained from field mapping of fracture data is in the order of 1×10^{-5} m/s. Based on the hydraulic conductivity values the sandstone rock mass can be considered medium to highly conductive; nevertheless, it seems to be almost impervious at greater depth. The empirical relationships which have been derived between hydraulic conductivity and both rock quality designation (RQD) and rock mass rating (RMR) indices indicated that the mean value of hydraulic conductivity of the rock mass could be estimated to be in the order of 10^{-5} m/s, which is confirmed by the packer tests.

Keywords Fracture · Hydraulic conductivity · Rock mass rating

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Introduction

The fractures in fractured rock masses are of prime importance in a hydrogeological investigation. The flow through the intact rock matrix of these rocks is usually so low that significant fluid movement can only take place through the fractures (Witherspoon and Gale 1983). Therefore, to characterize the hydraulic conductivity of such a rock mass the fracture characteristics should be defined. In most studies the hydraulic properties are sampled by time-consuming and expensive programs of hydraulic testing (Long and Witherspoon 1985); therefore a simple approach based on the field mapping of fractures is proposed to assess the hydraulic conductivity of the fractured rock mass.

Kirlay (1969) has suggested a methodology to derive the hydraulic conductivity of the fractured rocks using mathematical formulas in which the terms in these formulas can be derived by a detailed mapping survey of the fractures. Several researchers have also verified the application of such methodology in different geological conditions (Snow 1968; Louis 1974; Rocha and Franciss 1977). In particular, an important application of the Kirlay method has been performed by Louis (1974) to determine the flow velocity within the rock masses, to study the water circulation in a rock mass in laminar and turbulent regimes, and to determine the hydraulic conductivity in such conditions. Louis (1974) has confirmed the validity of the Kirlay method with laboratory tests introducing some modification in the mathematical calculations to define the entity of water losses and infiltration in dam and tunnel projects.

The capability of the fractures to conduct groundwater varies greatly with respect to the interconnection degree and the opening and continuity. The amount of groundwater flow depends on the hydraulic conductivity, where the flow takes place under laminar conditions and mainly as parallel flow within the individual fractures (Carlsson and Olsson 1992).

The modern approaches of hydrogeologic investigation incorporate fracture parameters for the determination of the flow characteristics of a connected fracture system. The fluid flow through fractured rock masses may be modeled by a discrete approach, modeling flow through each fracture in the rock mass, or a continuum approach, statistically averaging fracture parameters to quantify an equivalent porous medium (Carlsson and Olsson 1992).

In this study I attempted to use the methodology proposed by Snow (1968) and Carlsson and Olsson (1992) to estimate the hydraulic conductivity of the fractured Cambrian sandstone at Wadi Mujib site. The hydraulic conductivity was estimated by means of field fracture data and packer tests. Both methods indicated that the hydraulic conductivity of the rock mass is in the order of 10^{-5} m/s. Furthermore, the hydraulic conductivity is correlated with some geotechnical indices such as RQD and RMR. The obtained relationships between hydraulic conductivity and RQD and RMR are more or less the same for both fracture field mapping and borehole data.

Geological conditions of investigated area

A proposed weir and tunnel will be constructed on the catchment area of Wadi Mujib, which covers an area of about 6,700 km^2 to the east of the Dead Sea largely comprising a semi-arid to arid plateau (Fig. 1). The eastern part of the catchment lies at an elevation of 700 to 900 m above sea level, while in the west part the wadis have cut through deep gorges where they join about 2.5 km upstream of the Dead Sea.

An extensive engineering geological investigation has been performed to study the geotechnical characteristics of the site. The rock masses outcropping in the area are of Cambrian sandstone at the abutments and alluvium at the wadi course. Alluvium consists of boulders, gravels of basalts, sandstones, limestones, and chert with sandy and silty materials. The thickness of the alluvium at the weir site is about 24 m, increasing downstream to reach about 40 m. The alluvial deposits are underlain by Cambrian sandstones which are called the Um Ishrin Formation. It consists of whitish, yellowish to beige rock. It is weathered and fractured at the surface with brownish color, but slightly weathered within the rock mass. These rocks can be classified as quartz arenite based on mineral composition. In addition to Cambrian sandstone, a few outcrops of Cretaceous sandstone located in the western area at high elevations can be found. They consist of medium to coarse-grained bedded sandstones. Furthermore, Lisan Marl rocks are located in small areas, and consist of clay-rich marls with some intercalations of pebble-size gravels.

The joint system of the Cambrian sandstones in the investigated area consists generally of three quite well-defined joint sets dipping vertically. Three major joint sets were recognized at the weir site trending NE–SW, NW–SE, and WNW–ESE and dipping NW, SW, and NNE, respectively; a minor joint set trending ENE–WSW dipping toward the SSE is also present.

Hydraulic properties of fractures

In order to evaluate the individual fractures, which intersect the rock mass, some characteristics of the fractures can be determined. Assuming that the fracture frequency and spacing are known it is possible to calculate the fracture aperture and the hydraulic conductivity. In addition, the kinematic porosity of the rock mass can be estimated. Many equations have been derived based on experimental studies to describe the flow in natural fractures. Moreover, laboratory tests have been carried out to study the relationship between the hydraulic conductivity and fracture characteristics (Snow 1965; Louis 1974). Assuming parallel flow within smooth fractures, the following relationship can be derived (Snow 1965; Louis 1974):

$$K = \frac{ge^3}{12\mu S} \tag{1}$$

where K is the hydraulic conductivity of the rock mass (m/s); g is acceleration due to gravity (m/s^2); e is the fracture aperture (m); μ is the kinematic viscosity of fluid (for water equals 1×10^{-6} m^2/s), and S is the fracture spacing (m). However, the reciprocal of fracture spacing is equal to the fracture frequency (λ), so the above equation can be written as:

$$K = \frac{\lambda ge^3}{12\mu} \tag{2}$$

The above formulas are valid for unfilled opened fractures but do not take into consideration the hydraulic conductivity of the filled fractures. Thus, Louis (1974) suggested taking into account the fill material, which may have higher hydraulic conductivity than the rock matrix. Thus, the above equation can be modified as follow:

$$\sum_{i=1}^{n} K_{mi} = \sum_{i=1}^{n} \frac{ge_i^3\lambda_i}{12\mu} + e_1\lambda_1k_1 + \cdots + e_n\lambda_nk_n \tag{3}$$

where e_i is the mean aperture of unfilled fractures (m); e_n is the mean aperture of filled fractures (m); λ_i is the fracture frequency of unfilled fractures (number/m); λ_n is the fracture frequency of filled fractures (number/m); k_n is the average hydraulic conductivity of the filled material (m/s), and μ is the kinematic viscosity of fluid (m^2/s). Considering the roughness of fracture walls that divert the flow, Louis' equation can be reduced to the following form (Carlsson and Olsson 1992):

$$K = \frac{ge^3}{12\mu CS} \tag{4}$$

$$C = \left(1 + 8.8\zeta^{1.5}\right) \tag{5}$$

The function C describes the effect of the relative fracture roughness on the conductivity. The term ζ represents the relative roughness of the joint and is normally of the magnitude of 0.4–0.5 for natural fractures. This gives a value for C approaching 4. This means that the conductivity in a rough fracture is 25% of that in smooth fractures. The hydraulic conductivity of a single fracture (unit hydraulic conductivity k') can be derived by dividing k by the number of fractures per unit length or the

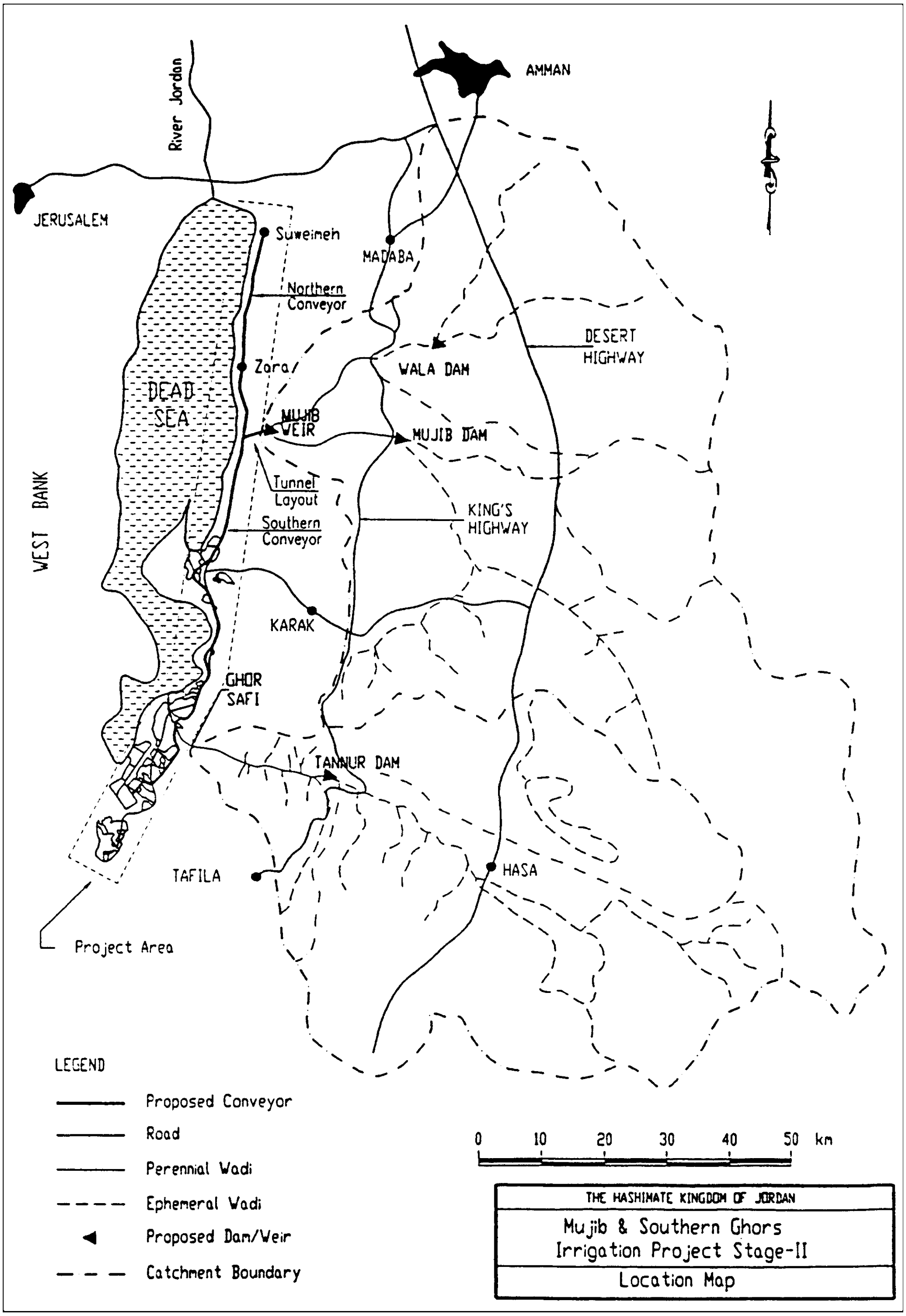

Fig. 1
Location map of the study area

fracture frequency (λ) which mathematically can be expressed as:

$$k' = \frac{k}{\lambda}$$

The relationship between fracture aperture and hydraulic conductivity is shown graphically in Fig. 2.
The fracture aperture can be estimated by rearrangement of equation (4).

$$e = \left[\frac{12\,\kappa\mu\,CS}{g}\right]^{\frac{1}{3}} \tag{6}$$

This relationship is used by Bianchi and Snow (1969) and Carlsson and Olsson (1978). The equation above can be used to evaluate the aperture of a number of fractures situated within a single test section. Thus, the fracture aperture obtained is a mean value of all

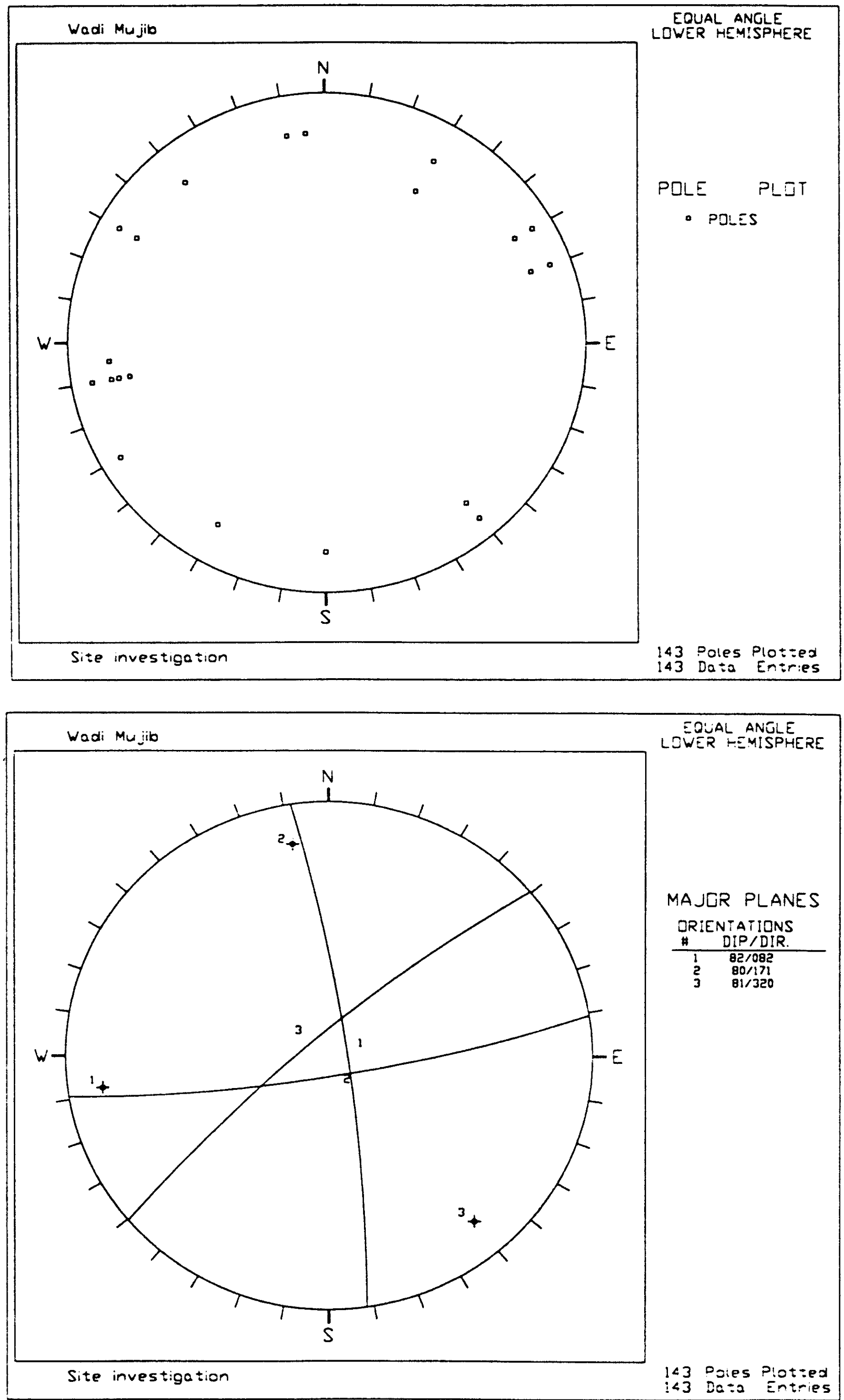

Fig. 2
Stereonets of fracture orientation data

fractures within the section (Carlsson and Olsson 1992).

Characterization of fracture system

The estimation of hydraulic conductivity in different directions can lead to different results due to different fracture parameters such as spacing and aperture values. The methodology of Snow (1969) and Louis (1974) was used which is based on: (1) selection of representative outcropping rocks, (2) recording of geometrical characteristics of fractures, and (3) calculation of the hydraulic conductivity of a single fracture and of the rock mass as a whole. Therefore, to collect the relevant fracture data the geometrical and physical parameters of the fractures were collected using scanline techniques (Piteau 1973) in which all fractures intersecting a reference line represented by a measuring tap and ranging in length from 3 to 10 m are noted. The following parameters were measured according to the norms given by the International Society of Rock Mechanics (ISRM 1978): orientation, number of joints sets, persistence, spacing, roughness, aperture, fill material, and hydraulic conditions. Nine sampling sites of fracture mapping (numbered JS1 to JS9) were selected where five joint sampling points were close to the weir site and the rest close to the tunnel route. Another source of mapping fracture data was performed through seven drilled boreholes along the proposed tunnel route and weir site. The geometrical characteristics of fracture data parameters are summarized as follows.

Fracture orientation

The fracture orientation is deduced statistically using the spherical Gaussian function. The stereonets of the fracture orientation are plotted in the form of lower hemispherical projection equal area contour plots of poles to fracture planes. The contouring of the frequency percentages was performed using the DIPS computer program (Hoek and Diederichs 1989). These stereonets can give an overall view of the orientation of the predominant fracture systems with in the rock masses. For each of the main fracture sets identified the statistical parameters and frequency are prepared. The orientation data were represented by poles and great circles to derive the principal systems of fracturing within a rock mass. The orientation data were recorded as (dip direction/dip), then they were treated statistically and plotted in the lower hemispheric projection net (Fig. 3). The stereonets of the mapped fractures identified three joint sets. The first set trends ENE–WSW (80°/80°) and dips toward SSE; the second joint set trends NNW–SSE (170°/80°) and dips toward WSW; and the third joint set trends NE–SW (320°/85°).
The main characteristics of the fracture analysis are summarized in Table 1. These parameters were interpreted statistically to derive the fracture statistics.

Fracture spacing

The fracture spacing on the surface outcrops is defined as the distance between consecutive intersections of the same set of fractures along a sampling line. The spatial locations of the fractures intersecting the drilled boreholes have been used to compute the spacing between every pair of consecutive fractures of the same set. In this case, I defined the spacing as distance between consecutive intersections

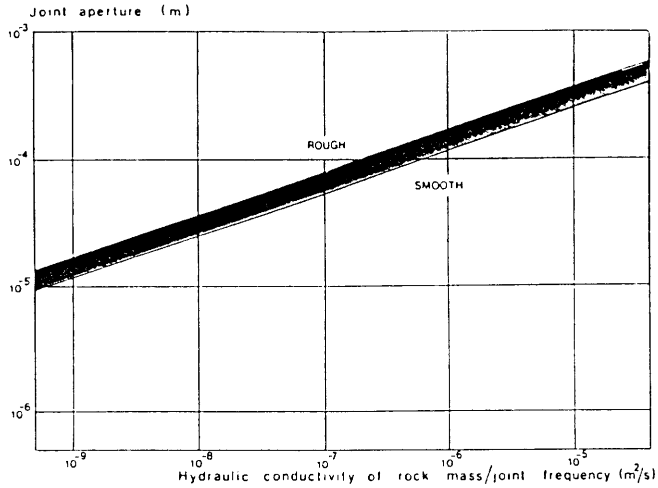

Fig. 3
The relationship between the fracture aperture and hydraulic conductivity. (After Carlsson and Olsson 1978)

of two fractures of the same set with the sampling line (i.e. borehole axis), multiplied by the cosine of the angle made by the sampling line and the pole of the average plane of the fracture set. Figure 4 shows the frequency histograms of spacing for every fracture set that has been defined for the rock mass. The fracture spacing values range from 0.05 m (close spacing) up to 0.65 m (wide spacing). It is worth mentioning that the spacing data were corrected for sampling bias using the Terzaghi method (Terzaghi 1965). Based on the shape of the histogram, the spacing values seem to follow the negative experiential distribution, where the frequency f(x) of a given value (x) of spacing is given by the following probability density (Hudson and Priest 1979):

$$f(x) = \lambda e^{-\lambda x} \quad (7)$$

The analysis of goodness of fit indicates that the negative exponential distribution fits most of the spacing data.

Fracture trace lengths

The second step of fracture analysis is to study the trace lengths. During the mapping of fractures the length of each fracture trace was measured. For each fracture set the trace lengths have been plotted as frequency histogram (Fig. 4). At each sampling site the trace length was fixed at an arbitrary height of 3 to 5 m (censoring) used to define the

Table 1
Fracture characteristics of Cambrian sandstone rock masses

Parameter	Sampling points		
	Joint set 1	Joint set 2	Joint set 3
Orientation	ENE–WSW (80°/80°)	NNW–SSE (170°/80°)	WNW–ESE (320°/85°)
Trace length (m)	5 to >50	5 to >50	>7
Spacing (m)	0.05 to 0.5	0.2 to 0.5	0.35 to 0.65
Aperture (cm)	0.1 to 15 sometimes sealed	3 to 20	0.1 to 1 sometimes sealed
Joint condition	No alteration	Rough, irregular	Rough

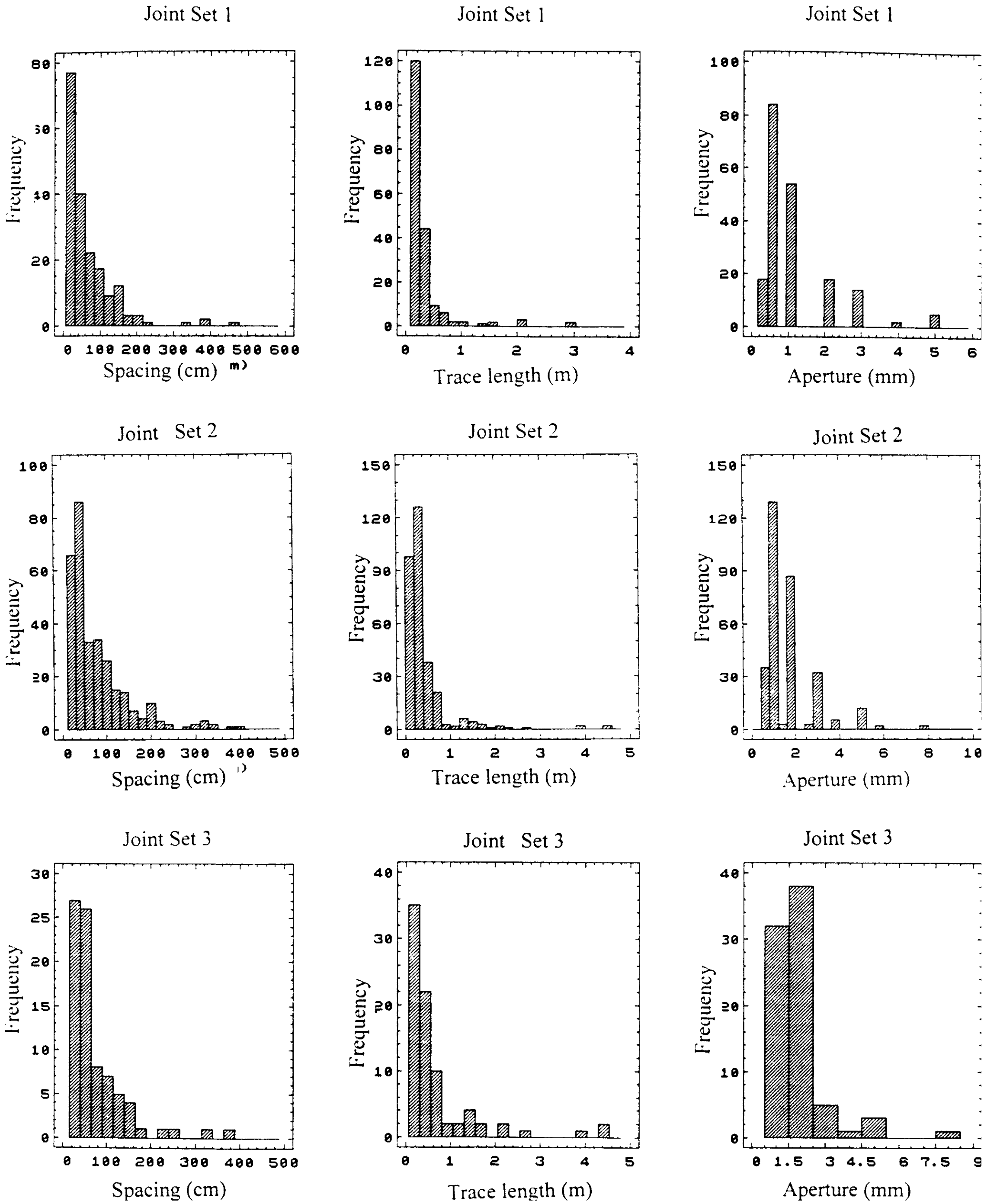

Fig. 4
Frequency histograms of fracture parameters of major fracture sets

maximum measurable semi-trace length of fractures. The measurements of semi-trace length were, however, corrected with respect to orientation of the scanline and treated statistically to obtain the mean trace length for each fracture set. It is assumed that the fracture trace lengths follow a negative exponential distribution as suggested by Priest and Hudson (1981). The collected data of fracture trace length showed that the trace length ranged from about 5 to more than 50 m.

Fracture aperture

The fracture aperture is defined by the ISRM (1978) as the perpendicular distance between the adjacent rock walls of a fracture in which the intervening space is air or water filled. Generally, fracture aperture is quite difficult to define in terms of true width since the joint roughness also affects the aperture opening size (Lee and Farmer 1993). Furthermore, the aperture controls the water-bearing capacity of the joint.

The measurements of joint aperture were carried out on the outcrops of the considered rock masses, using a feeler gauge . The fracture aperture data were represented as frequency histograms (Fig. 4). They showed that variable values range from 0.1–0.25 mm (tight joints) to 15–20 cm filled with air (extremely wide joints) according to Barton's classification of apertures (1973).

Estimation of fracture hydraulic conductivity

The fracture hydraulic conductivity of the rock masses intersected by any number of fracture systems can be estimated applying the aforementioned formulas proposed by Snow (1965, 1968, 1969) and Louis (1974). The estimation of hydraulic conductivity is based on the fracture parameters that were collected during fieldwork such as fracture spacing, fracture aperture, and fracture frequency. Table 2 summarizes the obtained values of hydraulic conductivity values of the rock masses. The hydraulic conductivity ranges from 1.15×10^{-6} to 2.34×10^{-5} m/s with an average value of 1.03×10^{-5} m/s. This implies that the sandstone rock masses have relatively high hydraulic conductivity due to the high degree of fracturing.

This also is evident from the values of the rock mass classification indices RQD and RMR. These indices are obtained based on the fracture field mapping and are summarized in Table 2.

The RQD system was proposed by Deere (1964) to determine the rock quality from drilled boreholes and ranges from very poor quality (<25) to excellent quality (90–100). In the absence of boreholes the RQD values can be estimated from fracture spacing data using the Priest and Hudson (1976) method. The calculated RQD of the sandstone rock masses ranges from 22 (very poor quality) to 80 (good quality), with a mean value of 50 (fair quality).

The RMR system was proposed by Bieniawski (1973, 1974, 1976, 1989) and based on the collected fracture data. The RMR incorporates six parameters to predict the quality of the jointed rock masses: (1) uniaxial compression strength, (2) RQD, (3) fracture spacing, (4) condition of fractures, (5) groundwater condition of fractures, and (6) orientation of fractures. Certain weighted values are assigned for each parameter so that the rock mass rating is the sum of these values, which gives the RMR quality of the rock mass. On the basis of the value of the RMR, the rock mass is subdivided into five classes, to each of which a global strength characteristic of the rock mass (i.e., cohesion and internal friction angle) is assigned. The values of RMR varied from <20 (very poor) to 81–100 (very good) rock mass quality.

The RMR value of sandstone rock masses ranges between 35 (poor quality) and 69 (good quality) with an average value of 53 (fair).

Table 2
Estimation of hydraulic conductivity and geotechnical indices from field fracture mapping

Joint survey no.	RQD	RMR	Hydraulic conductivity (m/s)	Hydraulic conductivity (LU)
JS1	45	60	9.00×10^{-6}	69.23
JS2	40	42	1.70×10^{-5}	130.77
JS3	22	35	2.34×10^{-5}	180.00
JS4	43	40	1.82×10^{-5}	140.00
JS5	55	60	4.30×10^{-6}	33.08
JS6	55	60	4.29×10^{-6}	33.00
JS7	80	69	1.15×10^{-6}	8.85
JS8	45	55	7.15×10^{-6}	55.00
JS9	54	55	8.45×10^{-6}	65.00
Min.	22	35	1.15×10^{-6}	8.85
Max.	80	69	2.34×10^{-5}	180.00
Mean	50	53	1.03×10^{-5}	79.43
SD	14.66	11.31	7.50×10^{-6}	57.68

Hydraulic testing of rock masses

The hydraulic conductivity tests were conducted on seven boreholes, five boreholes at the Mujib weir site (BH1 to BH5) and two boreholes along the proposed tunnel (BH6 and BH7; Table 3). The boreholes at the weir site were drilled at the bottom of the valley to a depth ranging from 15 to 35 m, where at the cliffs the boreholes inclined inwards at an angle of 30°. The boreholes drilled along the tunnel route are horizontal.

The Lugeon packer and constant head tests were performed to determine the hydraulic conductivity of the sandstone and thus indirectly the stress reduction in the rock mass. These tests were performed by the consulting firm, International Geological Engineering Center (1996). The results of these tests are summarized in Table 3. From this table it is evident that the hydraulic conductivity ranges from 2.2 LU (2.86×10^{-7} m/s) to 110.5 LU (5.6×10^{-4} m/s), with a mean value of 36.5 LU (9.26×10^{-5} m/s). The hydraulic conductivity of sandstone can be considered medium to high. In general, the sandstone rock mass at the depth of the studied site seems to be almost impervious. This is indicated by the low hydraulic conductivity, and the expected inflow to the proposed weir was preliminary calculated as 2 L/min/m<Q<14 L/min/m (International Geological Engineering Center 1996).

The RQD and RMR values are also summarized in Table 3. As can be seen from this table, the RQD values of the sandstone rock masses range between 12 (very poor quality) and 91 (excellent quality) with a mean value of 55 (fair quality). The RMR values range from 26 (poor rock quality) to 69 (fair rock quality) with an average value of 53 (fair rock quality). It is apparent that the two indices indicate that the sandstone has a fair rock mass quality.

Estimation of fracture porosity from hydraulic testing

The porosity of a rock mass is defined as the volume of voids in the intact rock plus the volume of discontinuity openings divided by the total volume of rock mass. The porosity of fractures is difficult to measure since they have variable apertures.

Many studies are found in the literature to determine the kinematics porosity from fracture data (Carlsson and Olsson 1981). These authors proposed that the kinematics

Table 3
Estimation of hydraulic conductivity and geotechnical indices from borehole data

Borehole no.	Depth (m)	RQD	RMR	Hydraulic conductivity coefficient	Test type
BH1	6–10	31	60	97.5 LU (1.27×10^{-5} m/s)	Packer test
	10–15	58		40.8 LU (5.3×10^{-6} m/s)	Packer test
BH2	5–11	37	57	5×10^{-4} m/s	Constant head
	11–15	53		52.2 LU (6.79×10^{-6} m/s)	Packer test
	15–20	31		20.1 LU (2.6×10^{-6} m/s)	Packer test
BH3	10–11	–	57	4.7×10^{-4} m/s	Constant head
	17–18	–		5.6×10^{-4} m/s	Constant head
	25–29	–		110.5 LU (1.44×10^{-5} m/s)	Packer test
BH4	5–6	62	55	5.1×10^{-4} m/s	Constant head
	10–11	–		No build of pressure	Packer test
	11–15	23.5		67.3 LU (8.75×10^{-6} m/s)	Packer test
BH5	2–6	12	52	22 LU (2.86×10^{-6} m/s)	Packer test
	6–11	42		34.5 LU (4.49×10^{-6} m/s)	Packer test
	11–15	18		30.8 LU (4×10^{-6} m/s)	Packer test
BH6	0–5	30	55	No build of pressure	Packer test
	5–10	90		55 LU (7.15×10^{-6} m/s)	Packer test
	10–15	25	26	38 LU (4.94×10^{-4} m/s)	Packer test
	15–25	0		No build of pressure	Packer test
	25–30	40	65	23 LU (2.99×10^{-6} m/s)	Packer test
	30–35	59		9 LU (1.17×10^{-6} m/s)	Packer test
	35–40	85		7 LU (9.1×10^{-7} m/s)	Packer test
BH7	0–5	55	37	–	–
	5–10	0		No build of pressure	Packer test
	10–15	81	60	43 LU (5.59×10^{-6} m/s)	Packer test
	15–20	42		No build of pressure	Packer test
	20–25	89		23 LU (2.99×10^{-6} m/s)	Packer test
	25–30	91	69	2.2 LU (2.86×10^{-7} m/s)	Packer test
	30–35	86		8 LU (1.04×10^{-6} m/s)	Packer test
	35–40	85		10 LU (1.3×10^{-6} m/s)	Packer test
Min.	–	12	26	2.2 (2.86×10^{-7} m/s)	–
Max.	–	91	69	110.5 (5.6×10^{-4} m/s)	–
Mean	–	55	53	36.5 (9.26×10^{-5} m/s)	–
SD	–	26.6	14.5	29.8 (1.96×10^{-4} m/s)	–

porosity depends on the penetration of joint sets by vertical or inclined boreholes. The kinematic porosity can be expressed as follows (Carlsson and Olsson 1992):

$$\Theta_K = \alpha n e \quad (8)$$

where α is a function which depends on the penetration in the different sets and the differences in frequency and apertures between the sets; and n and e are frequency and aperture within a specific section of drilled boreholes.

The fracture porosity of hard crystalline rocks is typically less than 10^{-4} (Knapp 1975). Witherspoon and Gale (1983) proposed a procedure to determine the effective fracture porosity based on the fracture parameters spacing, aperture, and trace length. The process to do this is (1) to identify the set to which each fracture belongs, (2) from the statistical correlation for that set, randomly select a trace length and spacing for the given fracture, and (3) randomly select an aperture for each fracture from the fracture distribution model. Then the estimation of effective porosity using aperture data is computed from borehole tests using Eq. (6). This procedure was used to determine the fracture porosity for the sandstone rock masses encountered in seven boreholes. The results are summarized in Table 4 and indicate that the rock mass has a mean effective fracture porosity of the order of 10^{-4}.

Table 4
Estimation of effective porosity from fracture parameters

Borehole no.	Fracture spacing (m)	Fracture aperture (m)	Effective porosity
BH1	0.05	1.45e–4	6.96e–3
	0.07	1.21e–4	4.15e–3
BH2	0.05	4.9e–4	0.0235
	0.064	1.28e–4	4.8e–3
	0.046	8.33e–5	4.344e–3
BH3	–	–	–
	–	–	–
	–	–	–
BH4	0.076	5.71e–4	0.018
	–	–	–
	0.042	1.21e–4	6.914e–3
BH5	0.04	8.0e–5	4.2e–3
	0.06	1.05e–4	5.484e–3
	0.04	9.14e–5	2.4486e–3
BH6	–	–	–
	0.18	1.836e–4	2.448e–3
	0.043	4.675e–4	0.026
	0.052	9.086e–5	4.194e–3
	0.072	7.38e–5	2.46e–3
	0.145	8.585e–5	1.42e–3
BH7	–	–	–
	–	–	–
	0.125	1.498e–4	2.876e–3
	–	–	–
	0.172	1.35e–4	1.88e–3
	0.19	6.38e–5	8.06e–4
	0.15	9.09e–5	1.44e–3
	0.145	9.669e–5	1.6e–3

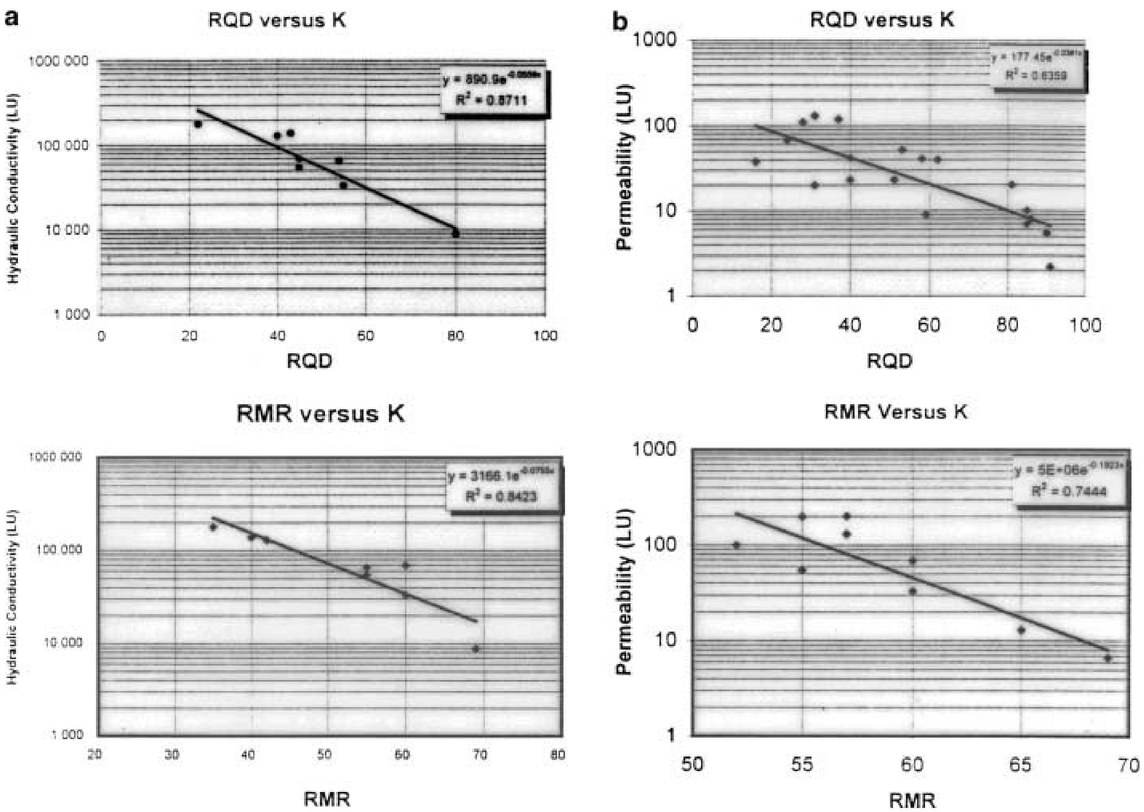

Fig. 5
Correlation between hydraulic conductivity and RQD and RMR. **a** field data; **b** boreholes

Statistical analysis

This research attempts to correlate the hydraulic conductivity with some of the geotechnical indices such as RQD and RMR, because the derivation of these indices depends mainly on the relevant fracture characteristics. Furthermore, these parameters are easy to obtain either from boreholes or from field mapping of fractures from surface outcrops. Therefore, a regression analysis has been performed to derive a relationship between the hydraulic conductivity and the RQD and RMR from both field mapping of fractures and boreholes, as shown in Fig. 5. The following empirical relationships were derived from borehole data which have been fitted to exponential regression:

$$K = 177.45 \times e - 0.0361 \times \mathrm{RQD}(r = 0.64)$$

$$K = 5 \times 10^6 \times e - 0.1923 \times \mathrm{RMR}(r = 0.74)$$

The same relationships from field mapping data were obtained with a highest correlation using exponential regression as follows:

$$K = 890.9 \times e - 0.0559 \times \mathrm{RQD}(r = 0.87)$$

$$K = 3166.1 \times e - 0.0755 \times \mathrm{RMR}(r = 0.84)$$

From these relationships, the hydraulic conductivity shows a progressive increase with the decrease of RQD, as the degree of fracturing increases. Furthermore, the mean value of hydraulic conductivity of sandstone rock mass could be estimated using the mean values of the RQD and RMR obtained from the borehole and field mapping. The predicted values of hydraulic conductivity based on the RQD and RMR are summarized in Table 5. From this table, using the derived empirical relationships, the predicted values of hydraulic conductivity from the adopted methodology that is based on fracture field mapping are in the order of 10^{-6} m/s.

Discussion and conclusions

The fractured rock masses characteristics are of utmost important to predict the hydraulic conductivity within the rock masses. The analysis of fracture data indicated that the trace length and spacing data are best fitted by a negative exponential distribution. These data were used to

Table 5
Predicted values of hydraulic conductivity using derived empirical equations

Source of fracture data	Geotechnical index	Hydraulic conductivity (m/s)
Borehole	Average RQD = 55	3.167×10^{-6}
	Average RMR = 53	2.44×10^{-5}
Field mapping	Average RQD = 50	7.07×10^{-6}
	Average RMR = 53	7.52×10^{-6}

estimate the hydraulic conductivity coefficient of the rock mass.

The hydraulic conductivity values obtained using this methodology can be considered valid for the areas around the sampling site and in the surroundings if the geo-structural conditions of the rock masses are not changed. The maximum values of the hydraulic conductivity were encountered in the direction of ENE–WSW and NNW–SSE with inclination varying between 80 and 85°, which is in accordance with the structural domain of the area. A comparison of the borehole results with those of surface fracture mapping provides a reasonable correlation between the two methods of measuring fractured rock hydraulic conductivity. The mean hydraulic conductivity value obtained from the boreholes is 36.5 LU (9.26×10^{-5} m/s), while the mean value of hydraulic conductivity obtained from field mapping of fracture data is in the order of 10^{-5} m/s. Based on the hydraulic conductivity values, the sandstone rock mass can be considered medium to highly conductive; nevertheless, it seems to be almost impervious at a greater depth.

The statistical correlation between the hydraulic conductivity and RQD and RMR indices derived from fracture field mapping indicated that the mean value of hydraulic conductivity of the rock mass is in the order of 10^{-6} m/s, which is confirmed by the almost identical value of packer tests.

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