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EVALUATION OF ROCK DISCONTINUITY SHEAR STRENGTH CRITERIA BASED ON THE LABORATORY DIRECT SHEAR TESTS

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Abstract: The shear strength of rock discontinuities is an important parameter to consider in the stability analysis and design of engineering structures in rock masses, slopes, tunnels, open pit mine and foundations. In this study, the shear strength of rock discontinuities involving both bedding planes and joint surfaces at the Bakhtiary dam site was measured through 106 laboratory direct shear tests under the constant normal load (CNL) boundary condition. Also, the surface parameters of rock discontinuities for each test were specified, and shear strength of rock discontinuity was estimated by different empirical failure criteria. Finally, using different statistical approaches, the proper failure criteria for estimating the shear strength of rock discontinuities were proposed.

Keywords: *Shear strength; direct shear tests; rock discontinuity; empirical failure criterion.*

1.0 Introduction

In rock engineering works, discontinuities such as joints, bedding planes, and faults are the most important structural features helping to understand the mechanical behavior of rock masses. The mechanical properties of rock masses are strongly dependent on the property and geometry of the rock discontinuities. Shear strength of rock discontinuity is one of the key properties in the stability analysis and design of engineering structures in rock masses, e.g. slopes, tunnels and dam foundations (Hoek and Brown, 1980). Reliable characterization of the strength and deformation behavior of rock discontinuities is important for the safe and economical design (Sitharam *et al*., 2001). The shear behavior of discontinuities is dependent on the boundary conditions that affect them (Ohnishi and Dharmaratne, 1990; Indraratna and Haque, 2000; Seidel and Haberfield, 2002; Jiang *et al*., 2004). Generally, there are two approaches to the quantitative description of the mechanical properties of rock discontinuities: (a) the theoretical approach, which adopts known theories (e.g. plasticity, contact theory, etc.) to simulate the observed behavior of a discontinuity; and (b) the empirical approach, in which experimental data are analyzed to derive correlations between influential variables, and models are formulated according to the observed behavior. Direct shear tests are commonly used to determine the mechanical properties of rock discontinuities. The shear strength of the clean joints has been investigated by Patton (1966a), Barton (1971), Bandis *et al*. (1981). Also, the peak shear strength criteria have been developed by Ladanyi and Archambault (1969), Barton and Choubey (1977) and Amadei and Saeb (1990).

Jaeger (1959), Lane and Heck (1964) and Patton (1966b) have investigated the shear strength of non-planar rock fractures based on their dilatant behavior. To date, several empirical and theoretical models have been developed to predict the shear strength of discontinuity in rock masses, such as (Jaeger, 1971; Goodman, 1974, 1975; Barton, 1976, 1985, 1990; Pande, 1985; Plesha, 1987; Hutson and Dowding, 1990; Jing *et al*., 1993; Kana *et al*., 1996; Wang *et al*., 2003; Grassellia and Egger, 2001, 2003; Samadhiya *et al*., 2008; Asadollahi and Tonon, 2010; Sanei *et al*., 2013).

Considering the above discussions, the aim of this work was to estimate the shear strength of rock discontinuity using different empirical failure criteria based on direct shear tests under the CNL boundary condition. In order to overcome the problems and to propose a more useful and general failure criterion compared with the previous criteria, the authors carried out a large number of shear tests. At first, the shear strength of rock discontinuities, involving both bedding planes (50 samples) and rock joints (56 samples) at the Bakhtiary dam site, was measured by laboratory direct shear tests. Then, the shear strength of rock discontinuities was estimated by different empirical criteria which are suitable for real discontinuity. Finally, using statistical analyses the useful failure criteria for estimating shear strength of rock discontinuities were propose. .

2.0 Bakhtiary Dam Site

The site of Bakhtiary dam and Hydroelectric Power project is located in Lorestan Province, in the southwest of Iran, northeast of the Tang-e-Panj railway station on the Tehran - Ahwaz railway, with the following coordinates: 48° 46’ 50” E / 32° 57’ 41” N (see Figure 1). The hydroelectric power plant project includes the design and construction of a 315m high, double curvature, concrete dam and an underground power house, with a nominal capacity of 1500MW (Stucky Pars Engineering Co. report, 2009).

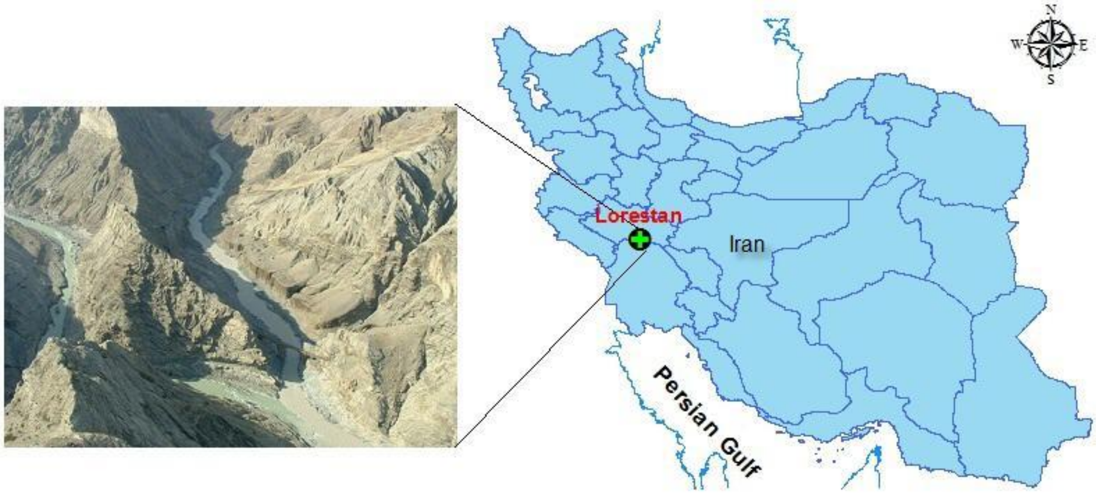

Figure 1: Location of the Bakhtiary dam site

2.1 Geological Characterization of the Dam Site

Limestone layers of Sarvak formation, which are Mid-Cretaceous marine sediments, form the foundation of the dam, powerhouse and other appurtenant structures. These layers are generally tightly folded. The bed rock consists of limestone and marly limestone that contains nodules of siliceous limestone (or Chert). These deposits sedimented between the formations of Garau (at the bottom) and Gurpi (at the top), are marked as a Bangestan Group (Kazhdomi, Sarvak, Surgah and Ilam formations) of Cretaceous age. The limestone of the Bakhtiary dam reservoir, which is overlying Garau formation and underlying Gurpi formation, has been considered to be Sarvak formation. The Sarvak formation is divided into 7 geological units. The 6 formation units, which are within the dam area, can be considered as Sarvak formation. The units Sv2 to Sv7 have outcrops in dam site, the appurtenant structures and the powerhouse area. Sv1 has no outcrops in this area as it is completely covered by Sv2. The geology longitudinal profile of the Bakhtiary dam site is shown in Figure 2.

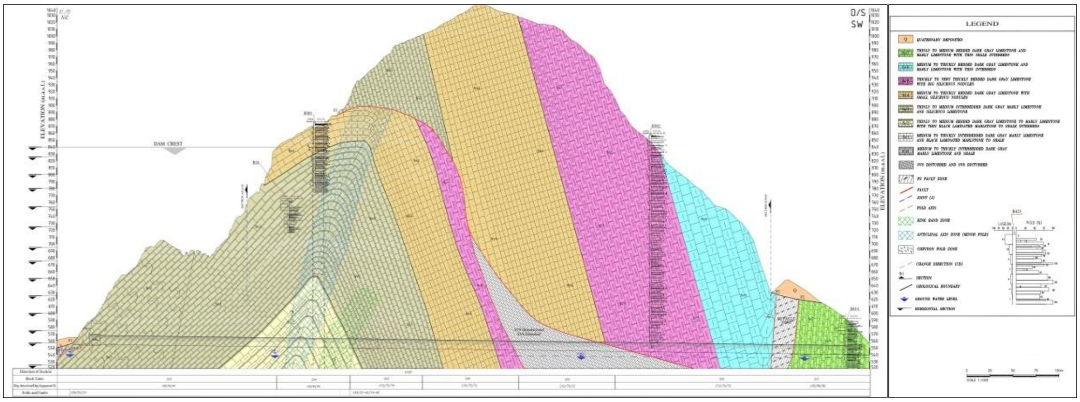

Figure 2: Geology longitudinal profile of the Bakhtiary dam site (Stucky Pars Engineering Co. Report, 2009)

2.2 Intact Rock Properties

Based on laboratory tests on core samples of the 6 Sarvak formation units, namely Sv2–Sv7, the mechanical characteristics of the intact rocks were measured from different geological units. Table 1 shows the physical and mechanical properties of intact rock specimens.

Table 1: Physical and mechanical properties of intact rock specimens

Physical and mechanical properties	*Index*	*Unit*	*Value*
Density	ρ	g/cm^3	2.61-2.74
Uniaxial compressive strength	σ_c	MPa	77-133
Modulus of elasticity	E	GPa	55-73
Poisson’s ratio	ν	-	0.3
Tensile strength	σ_t	MPa	6.3-11.2
Cohesion	C	MPa	29-36
Friction angle	ϕ	deg.	35-45

2.3 Discontinuities

In this study, the orientation (dip direction/dip) of rock discontinuities was measured by surface outcrop mapping and the measurements were done by a geological compass. In order to characterize discontinuities, some geotechnical site investigations, including borehole drilling, extension of exploration galleries, surface and gallery mapping, geophysics and in-situ rock mechanics tests as well as laboratory tests were performed. The rock mass of the dam site is intersected by four main discontinuity types consisting of bedding planes and three joint sets (J_1, J_2 and J_3), which affect its stability and the bearing capacity. A compilation of the orientation of the different discontinuities is shown in Figure 3.

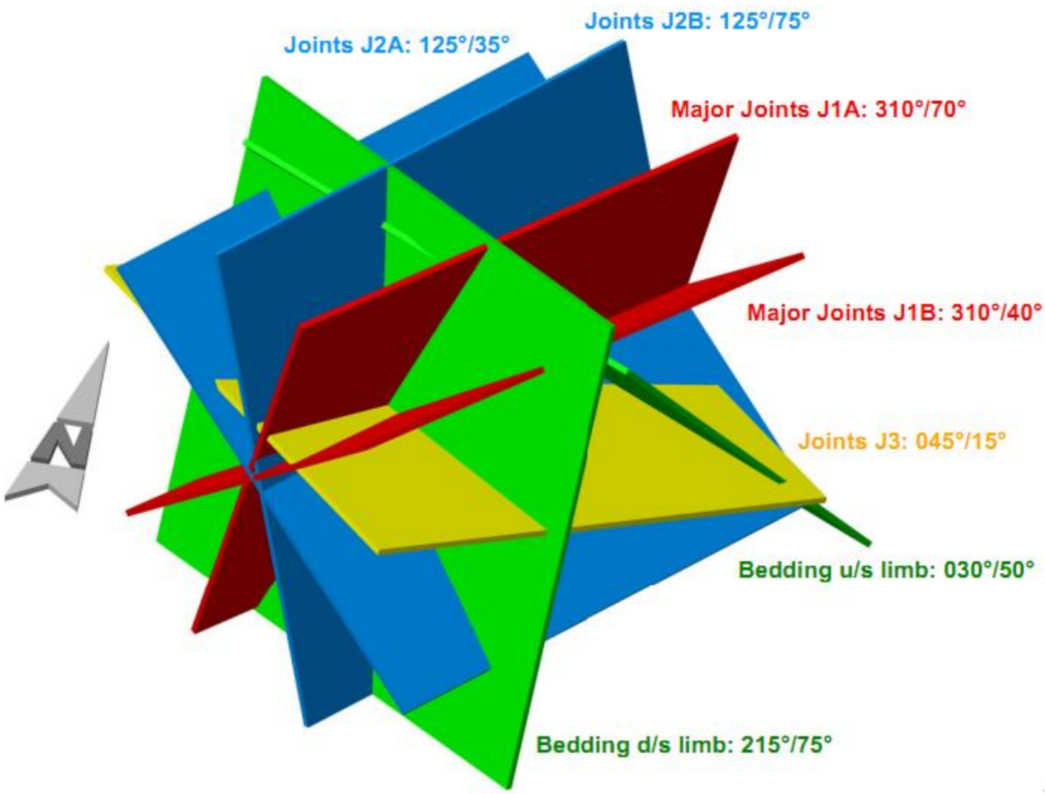

Figure 3: Schematic 3D presentation of the discontinuities at the Bakhtiary dam site area (Stucky Pars Engineering Co. report, 2009)

3.0 Direct Shear Test on Rock Discontinuities

The most commonly used method for the shear testing of discontinuities in rocks is the direct shear test. Direct shear tests on core specimens containing both bedding planes and joint surfaces were performed using the instrumented SBEL direct shear machine DR-44. Figure 4 shows the laboratory direct shear test apparatus.

The purpose of this test was to measure the peak and residual direct shear strengths as a function of stress normal to the sheared plane. For conducting a shear test on joint surfaces, at first the lower half and then the upper half were encapsulated in separate molds. Two sides of the specimen were fixed inside the shear box using a cement mortar. The shear tests were conducted by applying manually operated, normal and shear. Methods of preparing samples and carrying out these various tests are discussed by the ISRM (1974) commission. Shear strength determination comprised at least three tests on the same test horizon with each specimen tested at a different but constant normal load.

In other words, more than 106 direct shear tests were performed separately on core samples containing both bedding planes (50 samples) and rock joints (56 samples) of the 6 units (Sv2–Sv7) at the Bakhtiary dam site. The laboratory test sample ranged from 5.4 to 14.8 cm in length. The direct shear tests under constant normal load (CNL) conditions were carried out; in addition, the normal stress ranged between 0.47 to 3.2 MPa. The shear force was applied continuously in such a way as to control the rate of shear displacement. Approximately more than 10 sets of reading were taken before reaching the peak strength. Moreover, surface characteristics of each test sample such as joint roughness coefficient (JRC), joint compressive strength (JCS) were measured.

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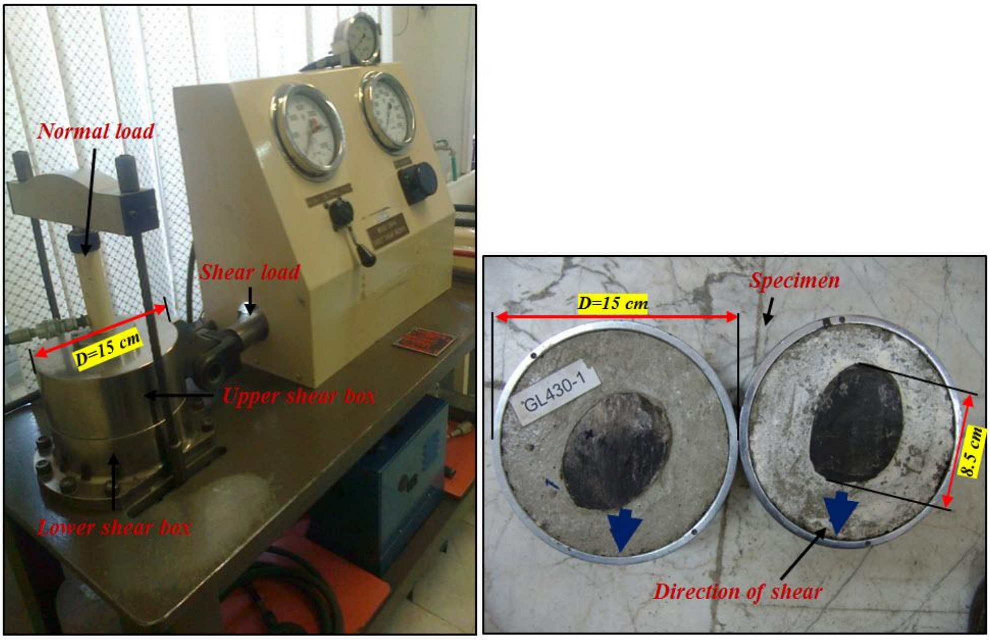

Figure 4: Laboratory direct shear test apparatus

4.0 Evaluation of the Shear Strength Using Empirical Criteria

Discontinuity is an important factor employed to estimate the mechanical behavior of rock masses. The difference of the strength and deformation characteristic of discontinuity will lead to difference in the strength and deformation of the rock masses. Several empirical and theoretical constitutive models have been developed for estimating the shear strength of rock discontinuities. In this study, the shear strength of rock discontinuity was evaluated by using Mohr-Coulomb, Jaeger and Barton's failure criteria.

4.1 Mohr-Coulomb's Criterion for Estimating the Shear Strength of Discontinuities

The relationship between the shear strength and the normal stress can be represented by the Mohr-Coulomb criterion as:

$$\tau = c + \sigma_n \tan\phi \tag{1}$$

Where τ , σ_n , ϕ and c are shear strength, normal stress, friction angle and cohesion, respectively. Figure 5 shows that a case example of direct shear test was conducted on core sample taken from the Bakhtiary dam site, with the determination of shear properties of discontinuity by use of Mohr-coulomb criterion.

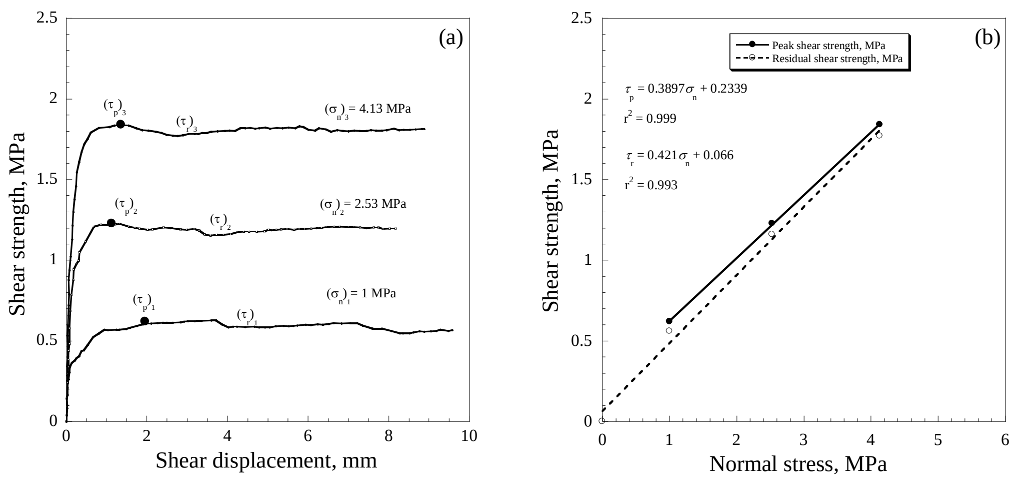

Figure 5: Mohr-Coulomb's criterion for estimating the shear strength: (a) plot of shear strength vs. shear displacement, (b) plot of peak and residual shear strengths vs normal stress

In this study, the residual and peak friction angle and cohesion for each shear test were determined by using Mohr-Coulomb failure criterion. Distribution of Mohr-Coulomb strength parameters of discontinuities at the Bakhtiary dam site are shown in Figure 6. Due to relatively high scatter in the direct shear test results on rock joints, it was decided to classify the test results based on the surface characteristics of the joints. Based on the statistics of JRC measurements on joint surfaces, the tests on joint samples were divided in two groups in terms of their joint roughness coefficient (JRC) value, with JRC = 6 being the cut-off number. The average discontinuity strength parameters based on shear box tests of all direct shear tests on beddings and joints are given in Table 2.

Table 2: Average discontinuity strength parameters based on shear box tests at the Bakhtiary dam site

Discontinuity type	*Peak*		*Residual*		*JCS (MPa)*	*JRC*
	Cohesion (MPa)	ϕ_p *(deg.)*	*Cohesion (MPa)*	ϕ_r (deg.)		
Bedding	0.028	41	0	33	27	7
Joints (JRC≤6)	0.025	35	0	32	27	4
Joints (JRC>6)	0.045	38	0	36	24	9

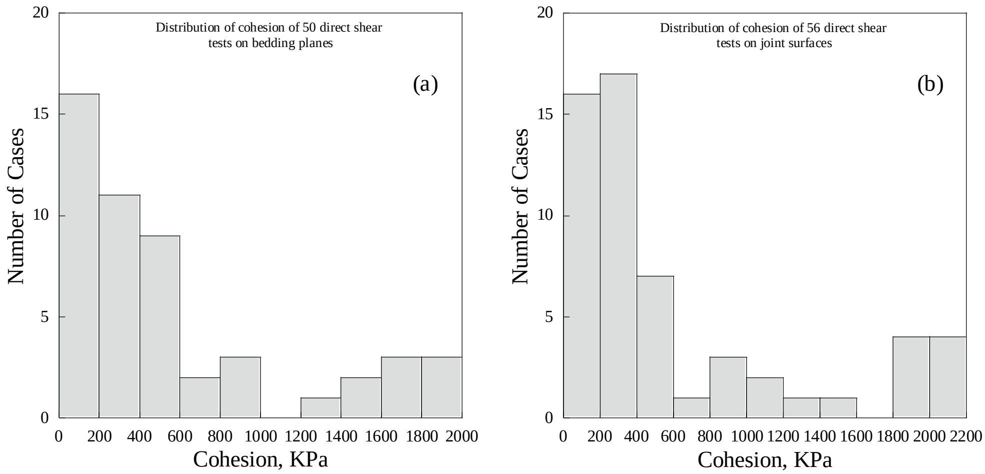

Figure 6: Distribution of Mohr-Coulomb strength parameters of discontinuities at the Bakhtiary dam site; (a) cohesion of bedding planes, (b) cohesion of rock joints

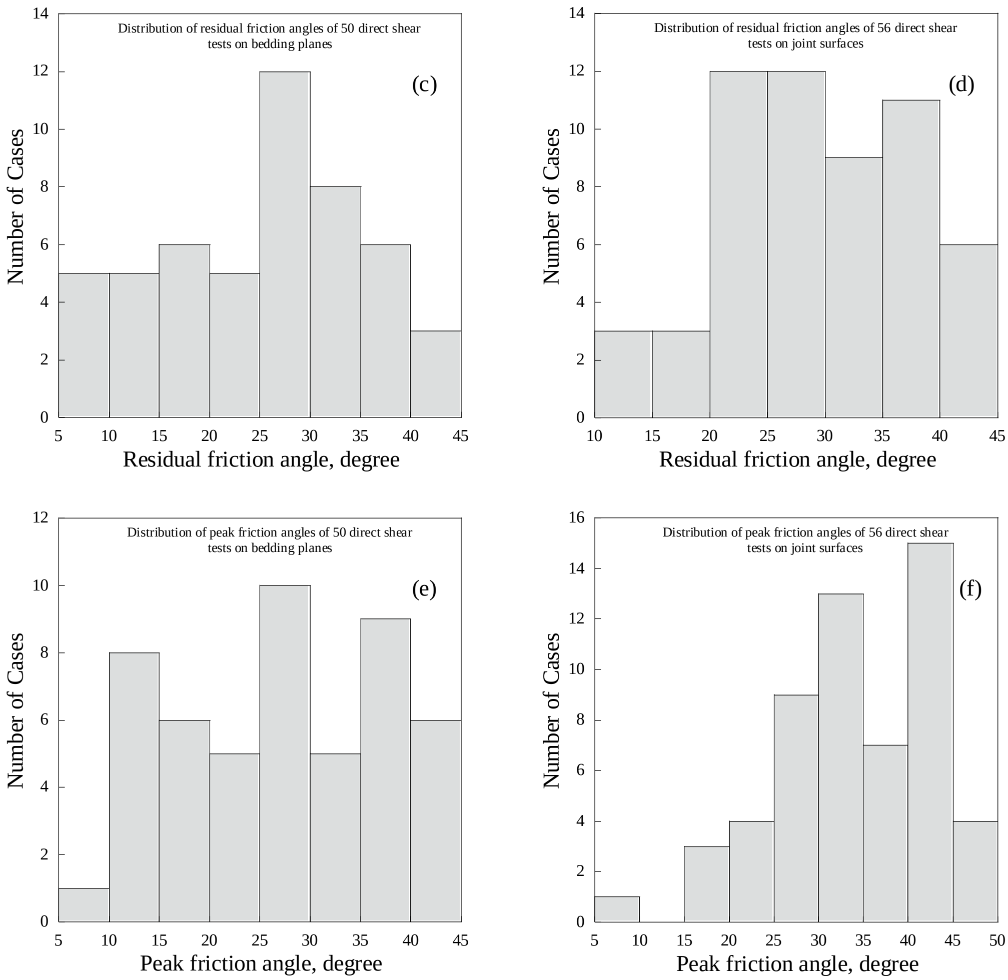

Figure 6 (cont'): (c) residual friction angle of bedding planes, (d) residual friction angle of rock joints, (e) peak friction angle of bedding planes, (f) peak friction angle of rock joints

4.2 Jaeger's Criterion for Estimating the Shear Strength of Discontinuities

The behavior of a fracture under shear depends very strongly on the normal stress acting across the fracture. The peak shear stress and the residual shear strength increase with increasing normal stress. This is roughly consistent with the experimental measurements made by authors on discontinuities rock samples taken from Bakhtiary dam site. The variation of peak shear stress as a function of normal stress is called the shear strength curve. At low normal stresses, shear deformation is assumed to take place predominantly by asperities sliding over each other. At higher normal stresses, the fracture possesses cohesion (c) that is due to the inherent shear strength of the asperities and has an effective angle of internal friction. Jaeger (1971) suggested the following empirical criterion for estimating the shear strength of rock discontinuities, which approximately considered as well the small and large normal stresses.

$$\tau = c\left[1-\exp\left(-b.\sigma_n\right)\right]+\sigma_n \tan\phi_r \qquad (2)$$

Where τ , σ_n , ϕ_r and c are shear strength, normal stress, residual friction angle and cohesion, respectively. The value of *p* and *b* are obtained from Figure 7.

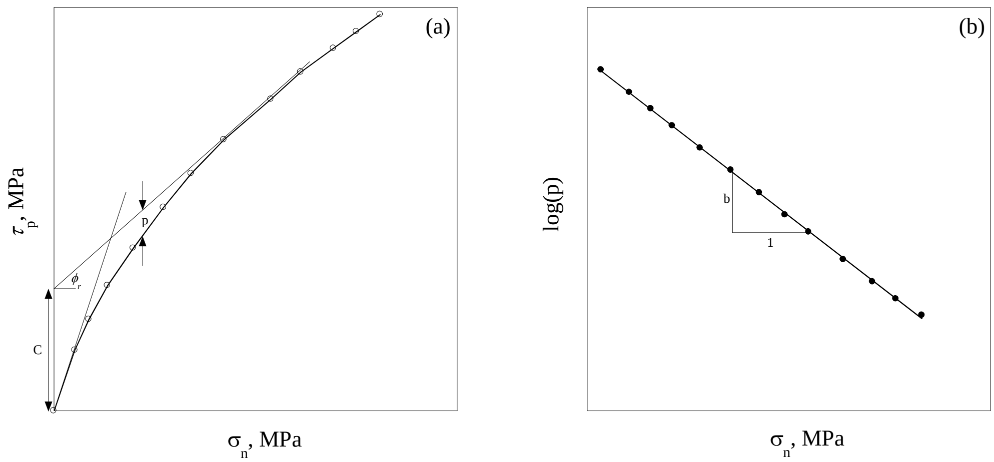

Figure 7: Jaeger empirical shear strength criterion: (a) plot of shear strength vs. normal stress, (b) plot of log (p) vs. normal stress

4.3 Barton's Criterion for Estimating the Shear Strength of Discontinuities

The empirical shear strength criterion proposed by Barton was used to describe the shear strength of discontinuities at the site. To use this criterion, the three input parameters of JRC, JCS and residual friction angle of discontinuity have to be determined. Barton and his co-workers (1971-1990) suggested the following empirical criterion for estimating the shear strength of rock joints:

$$\tau = \sigma_n \tan\left[JRC \log_{10}\left(\frac{JCS}{\sigma_n}\right)+\phi_r\right] \qquad (3)$$

Where τ, σ_n, ϕ_r, JCS and JRC are shear strength, normal stress, residual friction angle, joint compressive strength and joint roughness coefficient, respectively. For unweathered rock fractures, the residual friction angle (ϕ_r), is equal to base friction angle (ϕ_b), which can be obtained from shear tests on smooth unweathered joint surfaces.

4.3.1 Estimation of Joint Roughness Coefficient (JRC)

JRC is a number estimated by comparing the appearance of a discontinuity surface with standard profiles published by Barton and Choubey (1977). However, it is obvious that JRC determined by visual comparison is subjective and sometimes erratic. Many researchers have attempted to calculate the JRC value from the profile geometry such as root mean square (RMS), RMS of the first derivatives (Z2), RMS of the second derivatives (Z3), structure function (SF), roughness profile index (RP) and fractal dimension (Wu and Ali, 1978; Tse and Cruden, 1979; Krahn and Morgenstern, 1979; Mandelbrot, 1983).

In this study, fractal dimension method was used because of its accuracy in measuring JRC, and also the modified divider method was selected since it has not only proved to be accurate but also easy to use. In fact, the roughness profile was divided by equal horizontal divider span, and the length in each divider span was measured (Brown, 1987). Finally, the value of dimension was obtained by using Equations 4 and 5. Therefore:

$$L(r) = ar^{(1-D)} \quad (4)$$

Where L(r), r, a, and D are the length of the profile, a divider span, a proportionality constant, and the fractal dimension, respectively.

$$\log L(r) = \log a + (1-D)\log r \quad (5)$$

The parameters (1-D) and (Log a) can be estimated from the slope and intercept, respectively, of the plot between Log L(r) and Log r. The plot of the modified divider method is shown in Figure 8.

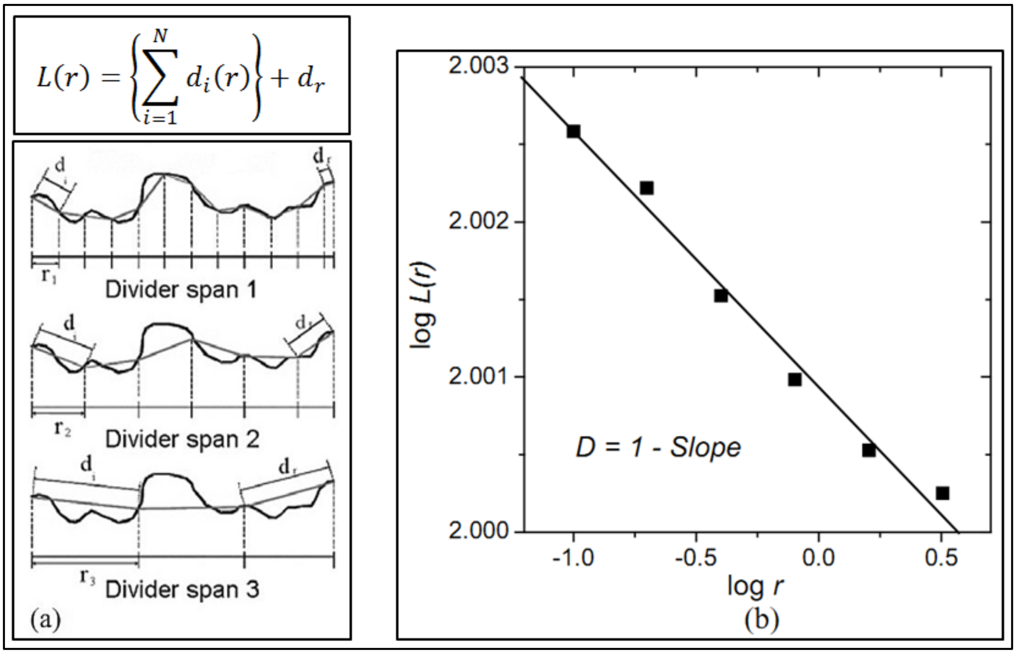

Figure 8: Modified Divider method: (a) Divider applied to profile and (b) log L(r) – log r plot (Jang *et al*., 2006)

Moreover, the fractal dimension was determined by a new programming code, written in Microsoft Visual Studio C# language. This new code used the modified divider method to determine the fractal dimension. In fact, this method requests a lot of divider spans ranging from least to most from roughness profiles in order to come up with a suitable answer. Therefore, the fractal dimension of standard roughness profiles of Barton was determined with 10 cm length for two reasons. First, the result and accuracy of fractal dimension in this study compared with other work dictated so, and second, the value of JRC of fractal dimension was obtained by analyzing the relationship between them.

On the other hand, the input data for new programming code, named FDM (Fractal Dimension Measurement), was the image of roughness profile obtained by scanning the roughness profile in (BMP, JPG and GIF) format, and the output of programming code was the value of fractal dimension. In other words, the image of surface roughness of rock discontinuity was taken using a profile gauge in shear direction and was scanned for the new programming code. The surface topography was mapped using a profile gauge in shear direction of the sample test and at 1 cm distance along the perpendicular direction to the shear direction. The surface roughness of each sample was obtained from the average surface roughness of 2 dimensional cross-sectional lines. This was done because the average surface roughness of each sample can be an appropriate representative of the discontinuity roughness. Then, in FDM program, the image of profile as an input data was received, and the value of L(r) was determined based on the different values of divider spans (r). In addition, the fractal dimension was determined from the slope log L(r) – log r plot. A standard roughness profile (JRC range, 18-20) was chosen as an example; then by using FDM program, the fractal dimension was obtained to be 1.015083. Figure 9 shows FDM program output schema.

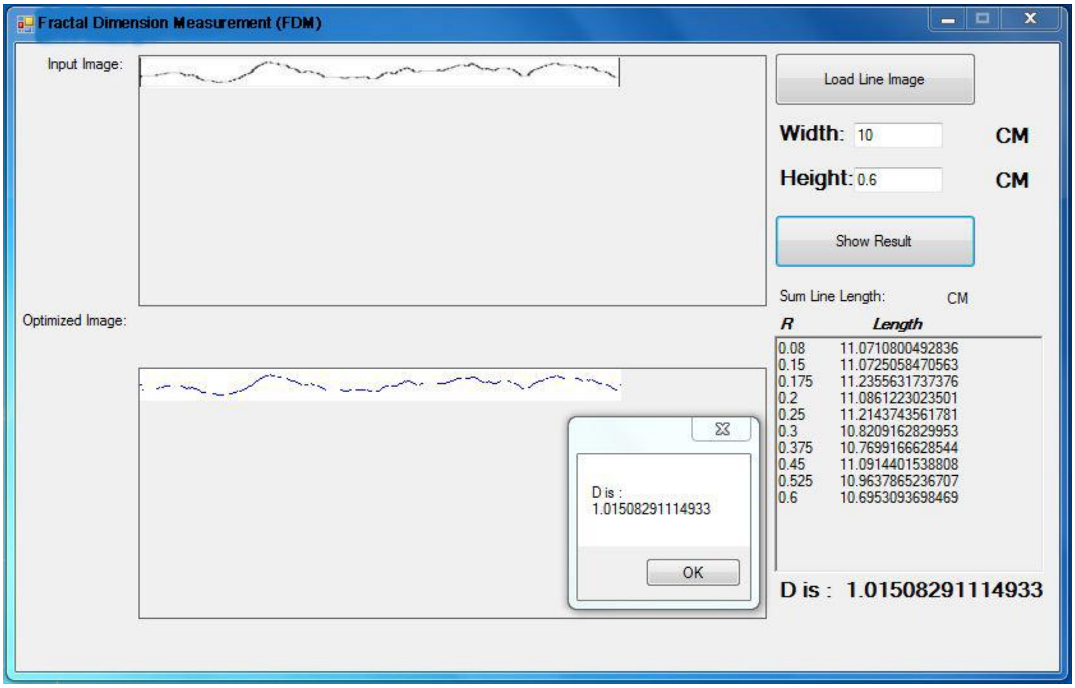

Figure 9: The FDM program output schema

Based on Barton's joint roughness profiles, the values of fractal dimension were measured. Table 3 shows the fractal dimensions (D) measured by different methods compared with the values obtained in this study.

Table 3: Comparison of fractal dimension (D) measured by different methods with the values obtained in this study

JRC	*Turk et al. (1987)*	*Lee et al. (1990)*	*Seidel et al. (1995)*	*Kulatilake et al. (1997)*	*Jang et al. (2006)*	*This study*
Range			*D*			
0 – 2	1.0000	1.000446	1.00009	1.0060	1.00121	1.000545
2 – 4	1.0019	1.001687	1.00054	1.0053	1.00231	1.001673
4 – 6	1.0027	1.002805	1.00072	1.0077	1.00225	1.002858
6 – 8	1.0049	1.003974	1.00140	1.0093	1.00394	1.004112
8 – 10	1.0054	1.004413	1.00180	1.0085	1.00272	1.005447
10 – 12	1.0045	1.005641	1.00400	1.0075	1.00203	1.006882
12 – 14	1.0077	1.007109	1.00530	1.0144	1.00692	1.008443
14 – 16	1.0070	1.008055	1.00810	1.0113	1.00816	1.010171
16 – 18	1.0104	1.009584	1.00960	1.0142	1.01024	1.012134
18 – 20	1.0170	1.013435	1.01200	1.0185	1.01278	1.015083

Using statistical analysis, Equation 6 was developed between fractal dimension and JRC values and the best displayed behavior represented the second-order polynomial. Also, the correlation coefficient, and the standard error calculated for this equation were 0.984 and 0.941, respectively.

$$JRC = -37580D^2 + 77018D - 39438 \qquad (6)$$

Where JRC and D are joint roughness coefficient and fractal dimension, respectively. The relationship between fractal dimension D and JRC is shown in Figure 10. The vertical axis is the JRC range presented by Barton and Choubey (1977) and the horizontal axis is the fractal dimensions of Barton roughness profiles measured in this study.

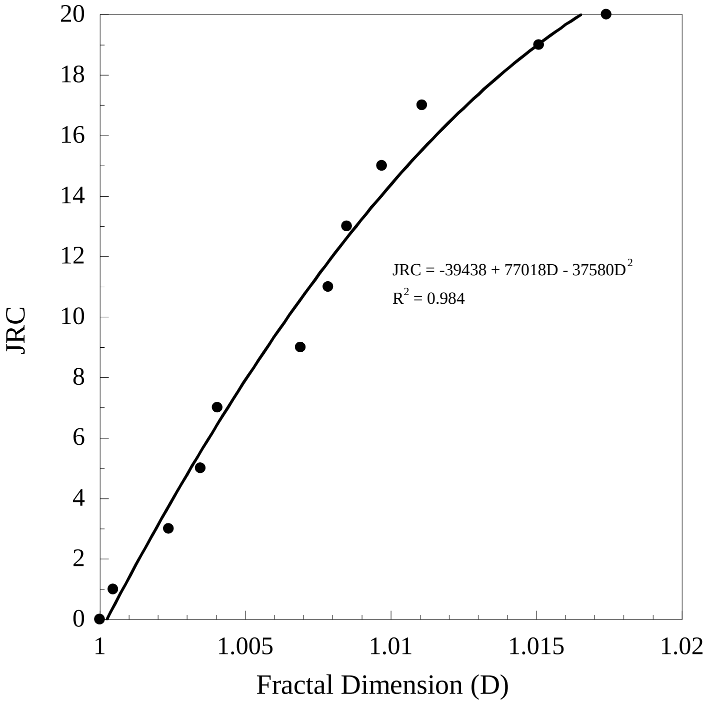

Figure 10: Fractal dimension (D) vs. JRC range

4.3.2 Measurement of Joint Compressive Strength (JCS)

The suggested methods for estimating the JCS has been published by the ISRM (1978). The use of the Schmidt rebound hammer for estimating joint compressive strength was proposed by Deere and Miller (1966). In this study, the values of JCS were measured using Schmidt rebound hammer. Distribution of Barton shear strength parameters of discontinuities (JRC and JCS) at the Bakhtiary dam site is shown in Figure 11.

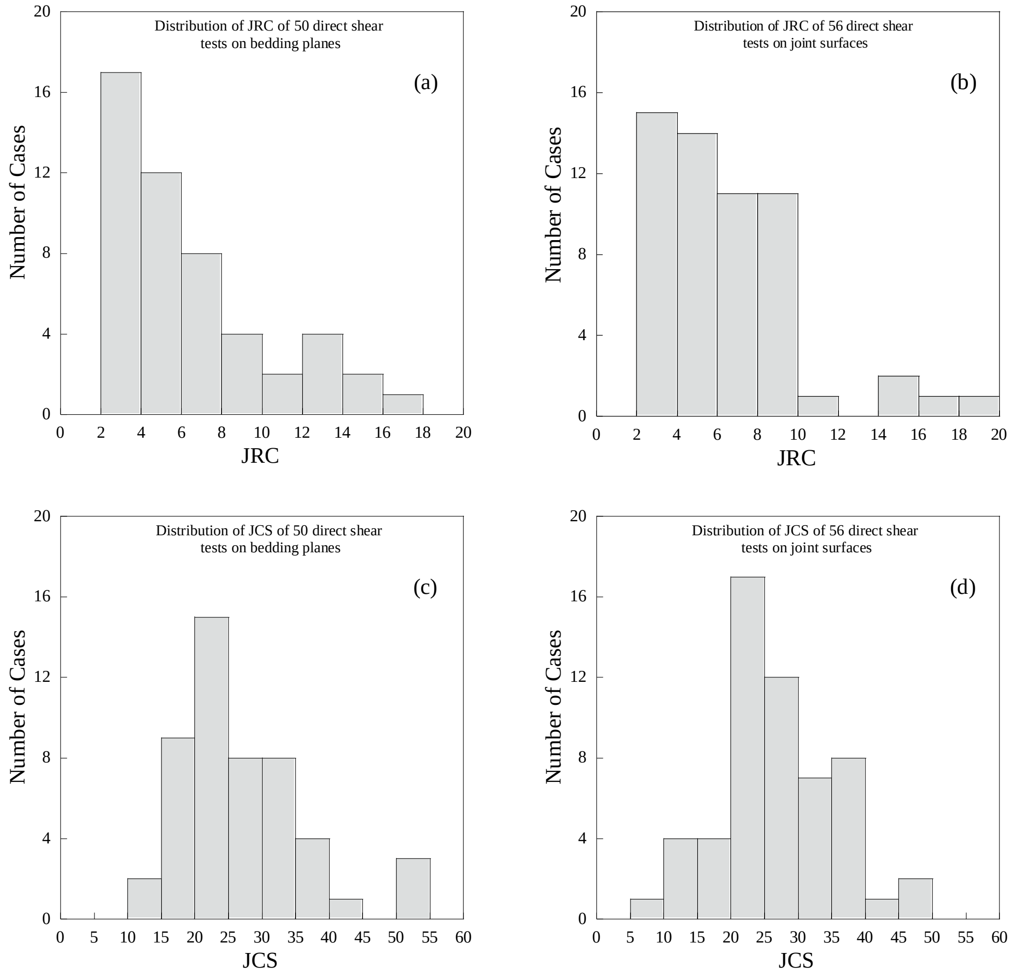

Figure 11: Distribution of Barton shear strength parameters of discontinuities at the Bakhtiary dam site; (a) JRC of bedding planes, (b) JRC of joint surfaces, (c) JCS of bedding planes, (d) JCS of joint surfaces

4.3.3 Estimation of Residual Friction Angle (ϕ_r)

The residual friction angle was determined by using the Mohr-coulomb criterion. In the case of the residual strength, the cohesion (c) was dropped to zero and the relationship between the residual shear strength τ_r and the normal stress σ_n could be represented by the following equation:

$$\tau_r = \sigma_n \tan\phi_r \quad (7)$$

Where τ_r, σ_n and ϕ_r are residual shear strength, normal stress and residual friction angle, respectively. Distribution of residual friction angle previously is shown in Figure 6.

5.0 The Useful Criterion for Estimating Shear Strength

In order to take care of the large number of measurements, the standard descriptive measure of goodness-of-fit was employed to evaluate the accuracy of shear strength calculated from empirical equations. The root mean square error (RMSE) and mean absolute relative prediction error (MARPE) and the error ratio (ER) were defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\tau_{m_i} - \tau'_{m_i}\right)^2} \quad , \quad i = 1,2,...,n \quad (8)$$

Where n, τ_{m_i} and τ'_{m_i} are the number of data i, measured value of shear strength, and estimated value of shear strength by empirical equations, respectively. Also, Mean Absolute Relative Prediction Error (MARPE) is:

$$MAPRE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\tau_{m_i} - \tau'_{m_i}}{\tau_{m_i}}\right| \quad , \quad i = 1,2,...,n \quad (9)$$

Furthermore, the Error Ratio (ER) or Mean Error Ratio (MER) is:

$$ER = \frac{\tau'_{m_i}}{\tau_{m_i}} \quad (10)$$

The RMSE index is a measure of the bias between the measured and predicted data. The lower the RMSE, the better the model performance. Ideally, the value of RMSE and MARPE should be zero and *ER* should be one. In this study, based on the above equations and the values of RMSE and MARPE indexes which are close to zero and the value of ER or MER equation which is close to one, the general useful empirical criterion was suggested in order to carefully estimate the values of shear strength.

6.0 Results and Discussion

After measuring and estimating the shear strength of rock discontinuities using different empirical criteria, the most useful empirical criterion (Equations 8, 9 and 10) for estimating the shear strength of discontinuities was finally proposed. Some of the empirical criteria for choosing the suitable one are given in tables 4 and 5.

Table 4: The empirical criteria for estimating shear strength of bedding planes

Empirical criterion	*Shear strength calculated from equations*	*RMSE*	*MARPE*	*MER*
Mohr-Coulomb	0.32-3.23	0.573	0.426	1.285
Jaeger, (1971)	0.25-2.14	0.339	0.195	0.856
Barton, (1973-1990)	0.21-3.54	0.442	0.284	0.933

In this study, based on the values of RMES and MARPE in Table 4, the criterion with RMSE=0.339, MARPE=0.195 was Jaeger criterion. On the other hand, based on the value of MER, the criterion with MER=0.933 was Barton criterion. Considering the combined results of all 50 test specimens of bedding planes, the most appropriate empirical criteria for estimating the shear strength were decided to be Jaeger and Barton criteria (Figure 12).

Table 5: The empirical criteria for estimation of shear strength of joint surfaces

Empirical criterion	*Shear strength calculated from equations*	*RMSE*	*MARPE*	*MER*
Mohr-Coulomb	0.33-2.89	0.576	0.439	1.402
Jaeger, (1971)	0.23-2.39	0.294	0.206	0.906
Barton, (1973-1990)	0.22-2.44	0.324	0.272	0.964

Based on the values of RMES and MARPE in Table 4, the suitable criterion with RMSE=0.294, MARPE=0.206 was Jaeger criterion. On the other hand, based on the value of MER, the suitable criterion with MER=0.964 was Barton criterion. Considering the combined results of all 56 test specimens of joint surfaces, the most appropriate empirical criteria for estimating the shear strength were decided to be Jaeger and Barton criteria (Figure 12).

Based on Tables 4 and 5, the three empirical criteria were validated. The results showed that the Jaeger and Barton criteria were useful to estimate the shear strength of rock discontinuities. The comparison between the measured and estimated shear strength by Mohr-coulomb, Jaeger, and Barton criteria are shown in Figure 12. As shown in this Figure, due to the relatively low scatter in the measured shear strength data compared with the shear strength estimated by Jaeger (Figure 12a and 12c) and Barton (Figure 12e and 12f) criteria, we proposed these two empirical equations as generally useful for estimating the shear strength of rock discontinuities.

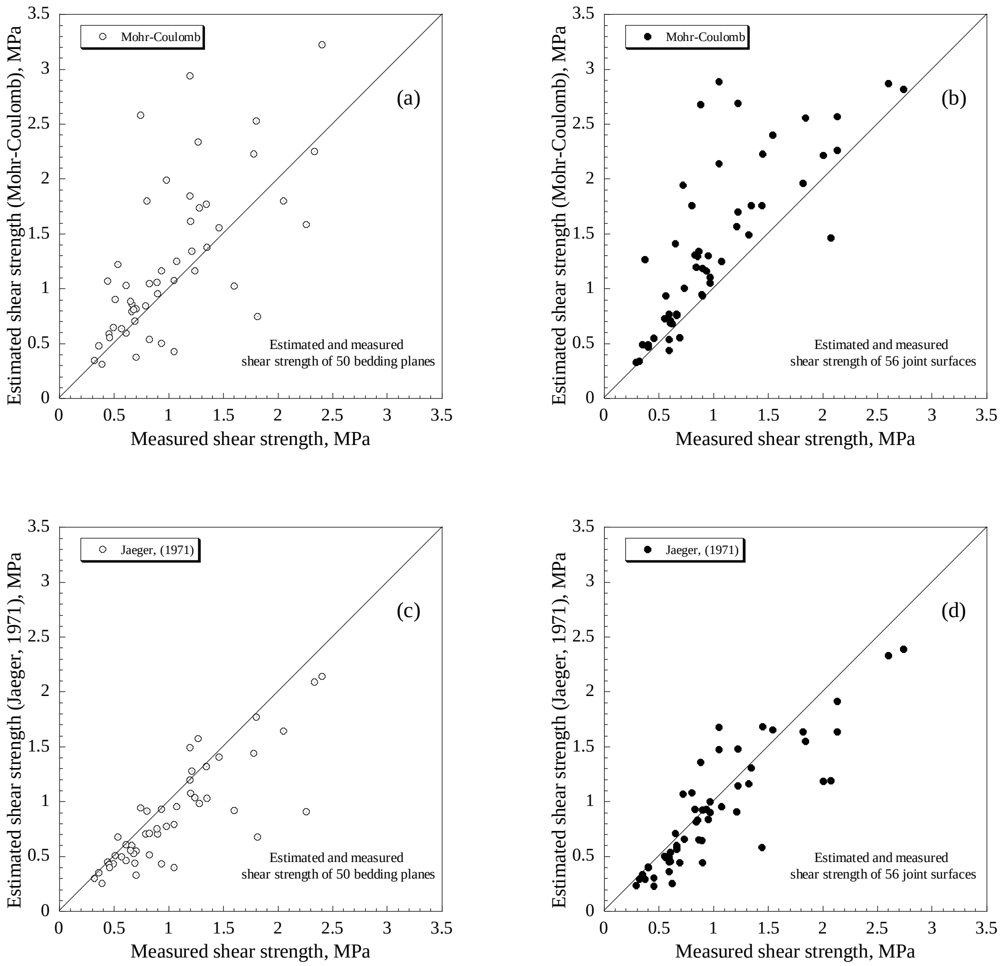

Figure 12: Comparison between the measured and estimated shear strength; (a) shear strength of bedding plane estimated by Mohr-coulomb criterion, (b) shear strength of joint surfaces estimated by Mohr-coulomb criterion, (c) shear strength of bedding plane estimated by Jaeger criterion, (d) shear strength of joint surfaces estimated by Jaeger criterion,

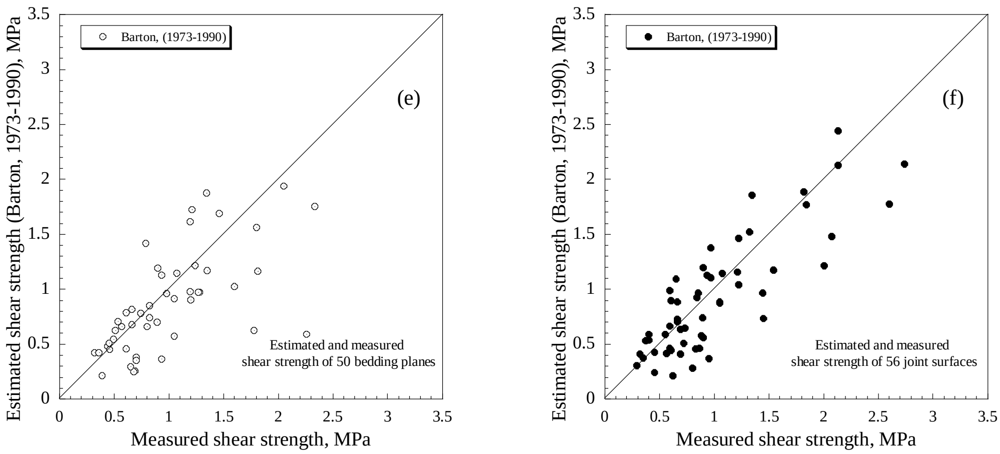

Figure 12 (cont'): (e) shear strength of bedding plane estimated by Barton criterion, (f) shear strength of joint surfaces estimated by Barton criterion

Based on what was mentioned above, comparisons made between all the measured data and shear strength data estimated by Jaeger and Barton criteria are illustrated in Figures 13a and 13b. The estimated results were in a good agreement with the measured results. The relationship between shear strength estimated by Jaeger and Barton empirical criteria are also shown in Figures 13c and 13d.

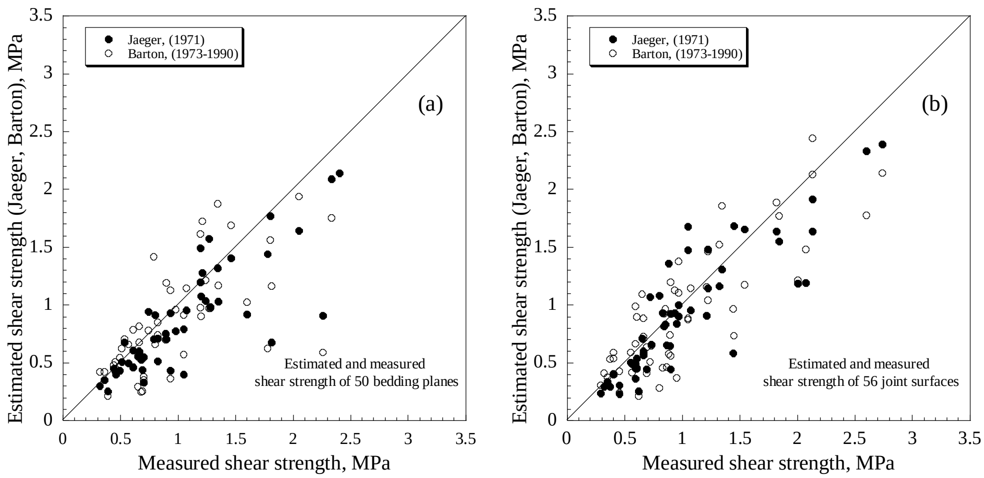

Figure 13: Comparison between measured and estimated shear strength of discontinuities; (a) shear strength of bedding planes measured and estimated by Jaeger and Barton criteria; (b) shear strength of joint surfaces measured and estimated by Jaeger and Barton criteria;

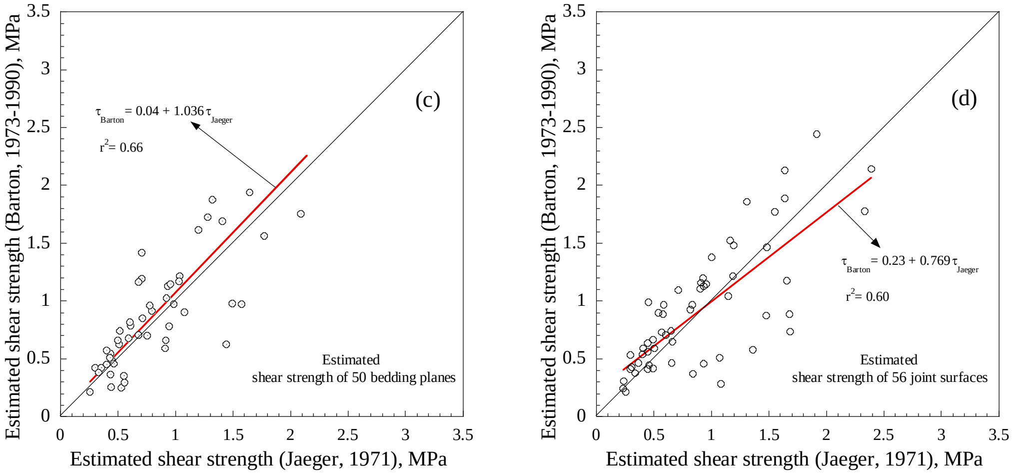

Figure 13 (cont'): (c) shear strength of bedding planes estimated by Jaeger and Barton criteria; (d) shear strength of joint surfaces estimated by Jaeger and Barton criteria

As shown in these Figures, the scatter between shear strength of bedding planes estimated by these empirical criteria is lower than the estimated shear strength of rock joint surfaces. It can be pointed out that the joint roughness coefficient (JRC) has an effect on the shear strength estimated by different empirical criteria. Also, JRC effect on shear strength exerts an influence on internal friction of discontinuities predominant in joint surfaces compared to bedding planes. From explanations above, it can be concluded that Jaeger criterion may be more useful for estimating shear strength of joint surfaces with low roughness (JRC≤6), and Barton criterion will be suitable for estimating shear strength of joint surfaces with high roughness (JRC>6) in sedimentary rock formations at the Bakhtiary dam site. In addition, both Jaeger and Barton criteria will be suitable for estimating shear strength of bedding planes in sedimentary rock formations at the Bakhtiary dam site.

7.0 Conclusions

The shear strength of rock discontinuities, involving both bedding planes and joint surfaces at the Bakhtiary dam site was estimated through 106 laboratory direct shear tests using different empirical criteria. Through statistical analyses (RMSE, MARPE and ER), the shear strengths of discontinuities estimated by empirical criteria were compared with the measured shear strengths. As shown in Figure 12, due to the relatively low scatter of measured shear strength compared with the shear strength estimated by Jaeger (Figures 12c and 12d) and Barton (Figures 12e and 12f) criteria, we proposed two empirical equations generally useful for estimating the shear strength of rock discontinuities.

It was also found that the joint roughness coefficient (JRC) has an effect on the shear strength estimated by different empirical criteria. JRC effect on shear strength in turn exerts an influence on internal friction of discontinuities predominant in joint surfaces compared to bedding planes. Thus it can be concluded that Jaeger criterion may be more useful for estimating shear strength of joint surfaces with low roughness (JRC≤6), and Barton criterion will be suitable for estimating shear strength of joint surfaces with high roughness (JRC>6) in sedimentary rock formations at the Bakhtiary dam site.

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