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A new method for determination of joint roughness coefficient

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Abstract: Joint roughness is generally quantified as joint roughness coefficient (JRC) and JRC was determined by visual comparison of joint profile measured with standard roughness profile suggested by Barton & Choubey(1977). It is well understood that JRC determined by visual comparison is subjective and sometimes erratic. Recently, joint roughness can be measured very precisely as digital values by laser scanner or digital measuring equipments. The problem is how to convert these digital values to JRC exactly. We assigned points on surface of standard roughness profile by 0.1mm along the horizontal line and measured coordinates of points. Then, the lengths of profile and semi-variance function were measured with different divider spans and sampling intervals. The fractal dimensions and intercepts of slopes were determined by plotting the length(or variogram) vs divider span(or sampling interval) in log-log scale. Intercepts of slopes show better correlation with JRC than fractal dimensions and we derived new equations to estimate JRC from intercept. We measured joint roughness and shear strength of natural joint from 25 rock specimen. Shear strengths measured and calculated using Barton's criterion with JRC by new equations are well correlated below the normal stress of 2.5~3 MPa. Shear strengths calculated are a little bit higher than those measured above the normal stress of 2.5~3 MPa. This is expected because one specimen was sheared repeatedly under several normal stresses and therefore, joint roughness was crushed at high normal stress.

Résumé: La rugosité des joints est généralement zvaluée quantitativement comme coefficient de rugosité des joints (en anglais : JRC), et le JRC a été déterminé par comparaison visuelle du profil des joints mesurée au moyen d'un profil standard tel suggéré par Barton et Choubey(1977). Il est bien compris que le JRC, déterminé par la comparaison visuelle, est subjectif et parfois erratique. Depuis quelques temps, la rugosité des joints peut être mesurée de façon très précise sous la forme de valeurs numériques par un scanner au laser ou du matériel de mesure numérique. Le problème consiste à savoir comment convertir exactement ces valeurs numériques en JRC. Nous avons attribué des points à la surface du profil standard par 0,1 mm le long des lignes horizontales, et nous avons mesuré les coordonnées des points. Ensuite, les longueurs de la fonction du profil et de la semi-variance ont été mesurées à l'aide de différents empans fractionnés **1** et des écarts par tâtonnements. Les dimensions de la matière et les interceptions des dénivellements ont été établies en déterminant la longueur (ou variogramme) vs les empans fractionnés **1** (ou écarts par tâtonnements) à l'échelle log-log. Les interceptions des inclinaisons montrent une meilleure corrélation avec JRC que les dimensions de la matière. Nous avons alors obtenu une nouvelle équation pour estimer le JRC de l'interception. Nous avons mesuré la rugosité des joints et l'usure des joints naturels de 25 spécimens de roches. Les pertes de force mesurées et calculées avec JRC à l'aide des critères de Barton par la nouvelle équation sont bien mises en corrélation avec la pression normale de 2.5~3 MPa. Les pertes de force calculées sont un rien plus élevées que celles mesurées au-dessus de la pression normale de 2.5~3 MPa. C'est à prévoir car un spécimen a été à maintes reprises érodé sous l'effet d'un grand nombre de pressions normales et pour cette raison, la rugosité des joints a été écrasée à une pression plus haute que la normale.

Keywords: joint roughness, JRC, shear strength, fractal dimension, intercept, divider method, variogram method,

INTRODUCTION

Behaviour of rock mass is an important factor in rock engineering. It is necessary to investigate the behaviour of rock material as well as discontinuity to understand that of rock mass since rock mass consists of rock material as well as discontinuities. Properties of the discontinuities include orientation, strength of wall rock, asperities and roughness and so on. Among them, roughness has the most important influence on shear strength and dilatation as well as hydraulic characteristics. Therefore, accurate quantification of roughness is important in modelling strength, deformability and fluid flow. The joint roughness is generally quantified as joint roughness coefficient(JRC) suggested by Barton & Choubey(1977) using standard roughness profiles. JRC was determined by visual comparison of joint profile measured with standard roughness profile. However, it is well understood that JRC determined by visual comparison is subjective and sometimes erratic. Recently, joint roughness can be measured very precisely as digital values by laser profilometer or digital measuring equipments. The problem is how to convert these digital values to JRC.

Many researchers have used statistical parameters such as root mean square(RMS), RMS of the first derivatives(Z_2), RMS of the second derivatives(Z_3), structure function(SF), roughness profile index(R_p) and roughness angle(A_i) to quantify joint roughness(Wu & Ali, 1978; Tse & Cruden, 1979; Krahn & Morgenstern, 1979). Recently, fractal analysis, such as divider method, box counting method, variogram method, spectral method, have been suggested to quantify joint roughness(Feder, 1988; Orey, 1970; Berry & Lewis, 1980; Malinverno, 1990).

In this paper, we assigned points on the surface of standard roughness profile by 0.1mm along the horizontal line and measured coordinates of points. Then, the lengths of profiles(*L(r)*) were measured with different divider spans(*r*) using modified divider method and semi-variance functions(*V(h)*) were calculated with different sampling interval(*h*) using variogram method . The fractal dimensions as well as intercepts of slopes were determined from log *L(r)* – log *r* plot and log *V(h)* – log *h* plot. Correlation between fractal dimension and JRC and between intercept and JRC were examined. New equations to estimate JRC from fractal dimension and intercept were suggested. We applied new equations to the natural rock joints and compared shear strengths measured with those calculated using Barton's criterion.

FRACTAL DIMENSION USING DIVIDER METHOD AND VARIOGRAM METHOD

Divider method starts from measuring the length of profile(*L(r)*) using divider spans(*r*). The length of profile can be expressed as multiplication of number of divider(*N*) and divider span and is expressed as equation 1. It is clear that the smaller *r*, the larger *N* and *N* is expressed as equation 2.

$$L(r) = Nr \qquad (1)$$

$$N = ar^{-D} \qquad (2)$$

in which *D* is fractal dimension and *D*>0, and a is a proportionality constant. Inserting equation 2 into equation 1 yields equation 3.

$$L(r) = ar^{(1-D)} \qquad (3)$$

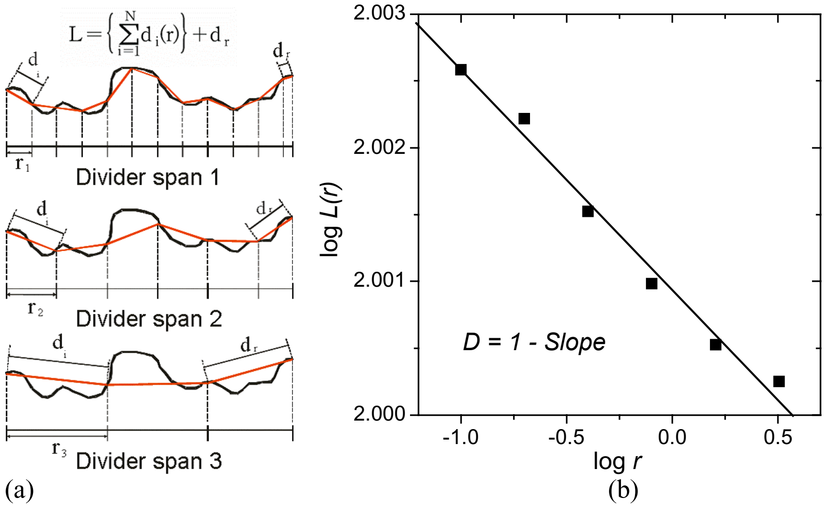
Thus

$$\log L(r) = \log a + (1-D)\log r \qquad (4)$$

Different length will be obtained if different divider span is used. When this procedure is repeated, a set of *L(r)* dependent on *r* will be obtained. If log *L(r)* is plotted against log *r*, the slope of this plot is *1-D* and the intercept is log *a* (Figure 1).

Divider method measures the length by walking along the surface of profile with specific divider span. In this method, the horizontal length for each divided portion is different and it is a little bit difficult to use in computerized work. Brown(1987) suggested a modified divider method in which profile is divided by equal horizontal divider span and length in each divider span was measured. Since the modified divider method is easier and more effective in processing of digitized profile than divider method, the modified divider method was used in this research.

Consider a profile shown in Figure 2. If a divider span is considerably shorter than feature size, divider span will virtually trace the profile without bridging any peaks or valley of profile. Therefore, for divider spans considerably shorter than the feature size, the length, *L(r)*, will be almost the same for all divider spans and the slope of log *L(r)* – log *r* plot will be flattened as shown in Figure 2. When the divider span is considerably larger than the feature size, the length will be close to the horizontal length of profile and the slope of log *L(r)* – log *r* plot will also be flattened. This indicates that the correct slope of log *L(r)* – Log *r* plot and thus the correct *D* can be obtained by fitting a regression line in the non-flatting portion of the log *L(r)* – log *r* plot. This range is called crossover length in which fractal dimensions can be estimated correctly.



(a) (b)

Figure 1. Modified Divider method. (a) Divider applied to profile (b) log *L*(*r*) – log *r* plot

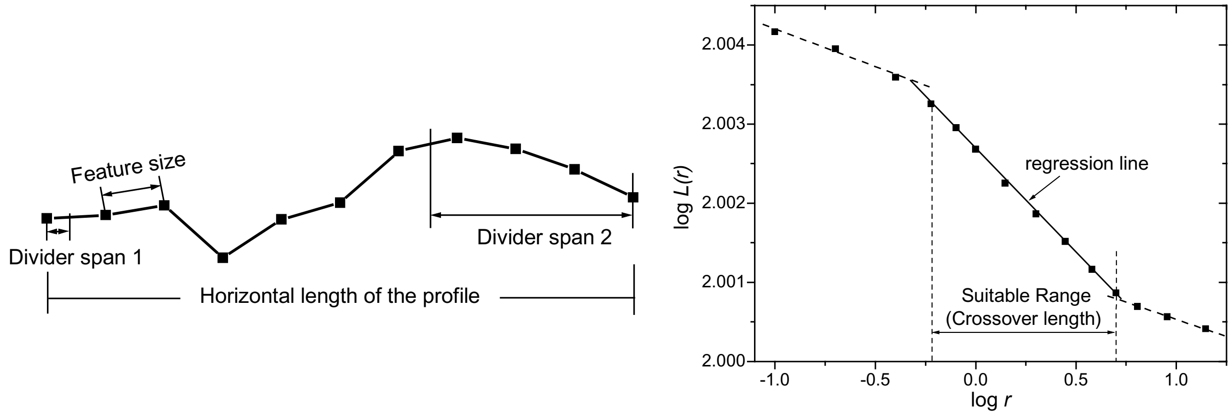


Figure 2. Suitable range of r for the estimation of fractal dimension with the divider method (Kulatilake *et al.,* 1997).

Huang *et al.*(1992) had used a variogram-based technique to estimate fractal dimensions for synthetic profiles as well as natural rock joints. Variogram method starts from calculating the semi-variance function, *V(h)* with sampling interval(*h*)(Figure 3). Let *Z(x)* be a Gaussian process with stationary increments, then semi-variance, *V(h)* is given by equation 5.

$$V(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_{i+1})]^2 \qquad (5)$$

where *h* is the lag distance along the x-axis and *N(h)* is the total number of pairs of roughness heights that are spaced at a lag distance *h*. Fractal dimension, *D* is related to semi-variance, *V(h)* as equation 6 and 7(Cox & Wang, 1993).

$$V(h) \approx h^{4-2D} \qquad (6)$$

$$D = 2 - \frac{\log V(h) / \log h}{2} \qquad (7)$$

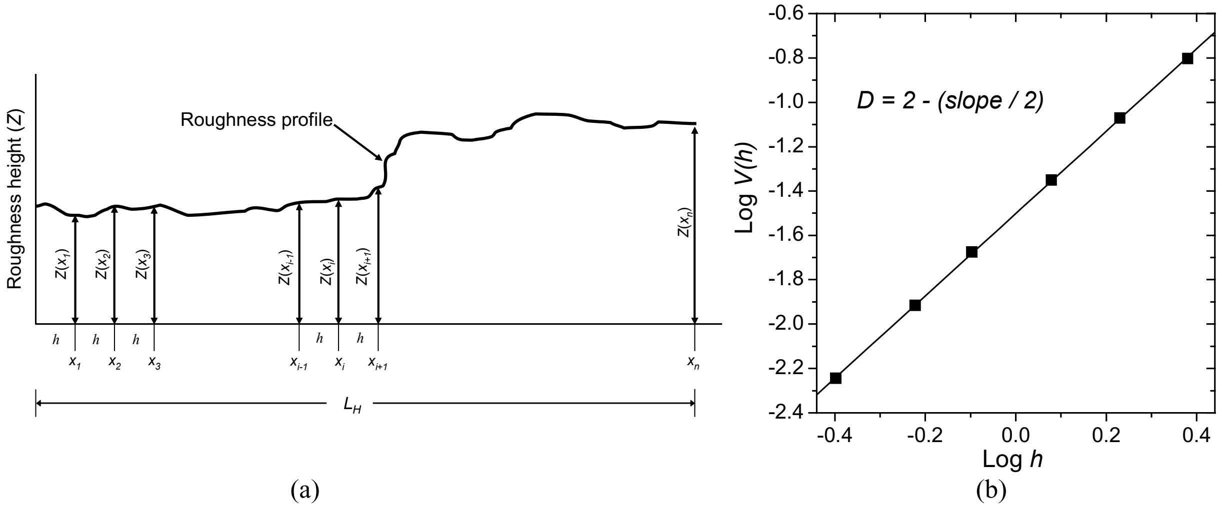


Figure 3. Variogram method. (a) The diagram used to define semi-variance function for a roughness profile. (b) log *V(h)* – log *h* plot.

DIGITIZATION OF STANDARD ROUGHNESS PROFILE AND NATURAL ROCK JOINTS

Standard roughness profiles suggested by Barton & Choubey(1977) were scanned using scanner and converted into image files. Then, points on the surface of standard profile by 0.1mm along the horizontal line were assigned and coordinates of points were measured using CorelDraw program. Because digitization of standard profile is the most important step in this research, Z_2 parameters (Myers, 1962) were calculated and compared with those calculated by Tse & Cruden(1977) in order to validate digitization(Figure 4). Although Z_2 parameters calculated in this research are lower than those calculated by Tse & Cruden under the JRC=4-6, Z_2 parameters in both researches are almost same above the JRC=6-8. This may be caused because the sampling interval in this research is 0.1mm, which was 0.5 mm in Tse & Cruden.

Roughness profiles of 25 natural rock joints were measured using mechanical profilometer. Specimens were NX sized cores and lengths of joints range from 4.7cm to 8.0cm. In case the spacing between points measured were not exactly 0.1mm, interpolated values were assigned to make spacing between points exactly 0.1mm.

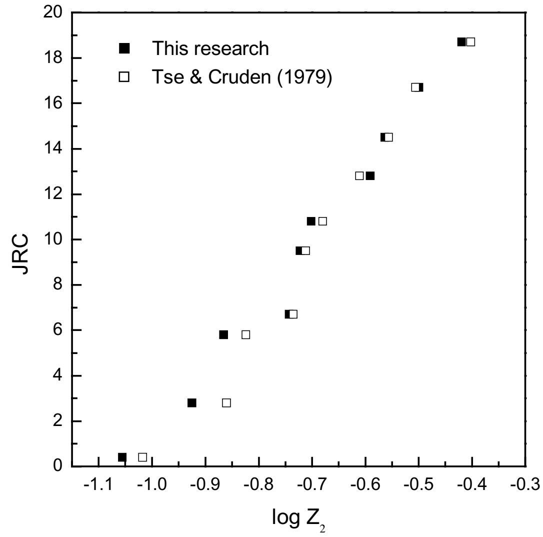


Figure 4. Z_2 parameters calculated in this research and in by Tse & Cruden (1979).

ESTIMATION OF JRC USING FRACTAL ANALYSIS

Fractal analysis of standard roughness profiles using modified divider method

Crossover length in which fractal dimensions can be estimated should be determined first in fractal analysis. Lengths of standard roughness profile using divider span from 0.1mm to 50mm were measured and log *L(r)* – log *r* were plotted as shown in Figure 5. Each curve can be divided into three segments as described above. Curves are nonlinear and flattened when divider spans were shorter than 0.4mm and larger than 2.4mm. Thus, crossover length was determined as between 0.4mm and 2.4mm.

Lengths of standard roughness profile were measured using 6 different divider spans(0.4mm, 0.6mm, 0.8mm, 1.2mm, 1.7mm, 2.4mm) and log *L(r)* – log *r* were plotted(Figure 6). Fractal dimensions, *D* and intercepts of slope, *a* were determined using equation 4. Table 1 shows *D* and *a* calculated in this research and others. *D* range from 1.00121 to 1.01278 and *a* range between 2.00069 and 2.02042. *D* and *a* generally increase as JRC increases. Note that *D* of JRC= 8 – 10 and JRC= 10 – 12 are less than *D* of JRC= 6 – 8. Also, *D* of JRC=14 – 16 is less than *D* of JRC= 12 – 14. This result is almost consistent with that of Kulatilake *et al.*(1995), although *D* in Kulatilake *et al.*(1995) are higher that those in this research. However, results from Lee *et al.*(1990) and Seidel *et al.*(1995) show no irregularities in fractal dimensions. *D* of JRC= 10 – 12 is less than that of JRC= 8 – 10 and *D* of JRC= 14 – 16 is less than that of JRC= 12 – 14 in result from Turk *et al.*(1995), which is almost the same as this result.

In standard roughness profile, horizontal lengths(L_H) of profiles are the same. However, in natural rock joints, L_H are different and the intercepts are dependent on L_H(Kulatilake *et al.*, 1995). Therefore, normalized intercepts, a_n ($a_n=a$ / log L_H) were used instead of *a* to normalize horizontal lengths of profile in this research. JRC against *D*, JRC against, a_n were plotted and best fit lines were drawn in Figure 7. Correlation coefficient(R^2) between JRC and *D* and between JRC and a_n are 0.731 and 0.989, respectively. This indicates that the intercept of slope has better correlation with JRC than fractal dimension. A new equation to estimate JRC using normalized intercept is suggested and shown in equation 8.

$$JRC = \frac{-256.22}{1+e^{(a_n - 0.9892)/0.00462}} + 21.42 \qquad (8)$$

Lee *et al.*(1990) and Wakabayashi & Fukushige(1995) also suggested equations to estimate JRC using *D*. They are equation 9 and equation 10. When their equations are drawn in Figure 7, they show much poorer correlation than equation suggested by this research.

$$JRC = -0.878 + 37.784\left(\frac{D-1}{0.0015}\right) - 16.93\left(\frac{D-1}{0.0015}\right)^2 \qquad (9)$$

$$JRC = \sqrt{\frac{D-1}{4.413\times10^{-5}}} \qquad (10)$$

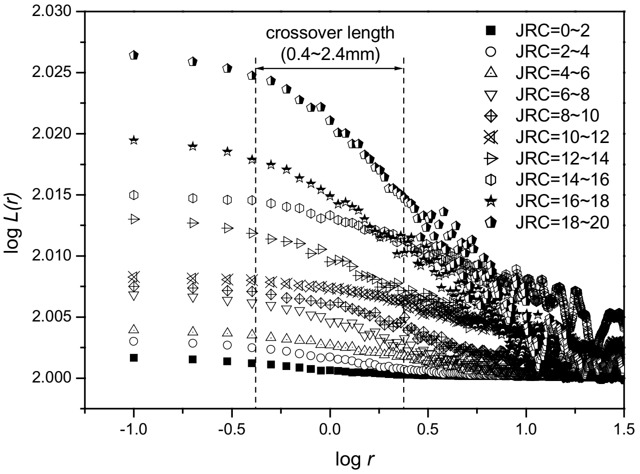


Figure 5. log *L(r)* – log *r* plot of standard profile and crossover length

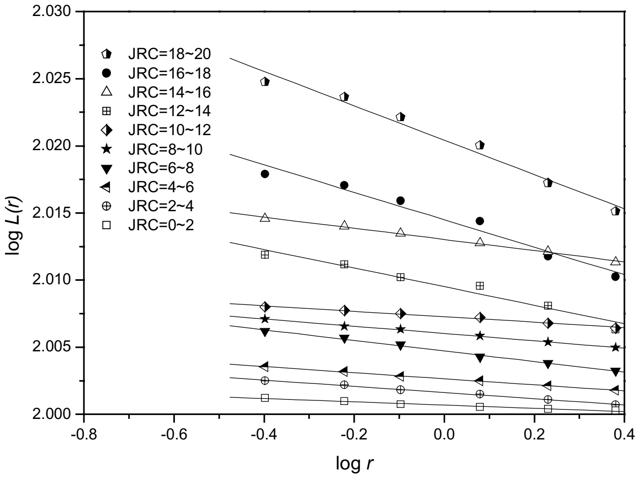


Figure 6. log *L(r)* – log *r* plot within crossover length

Table 1. Fractal Dimensions and intercepts of standard roughness profile measured using divider method

JRC	Lee *et al*[*].	Turk *et al.*[*]	Seidel *et al*[*].	Kulatilake *et al*[*].	This research[**]	
range	*D*	*D*	*D*	*D*	*D*	Intercept, *a*
0~2	1.000446	1.0000	1.00009	1.0060	1.00121	2.00069
2~4	1.001687	1.0019	1.00054	1.0053	1.00231	2.00162
4~6	1.002805	1.0027	1.00072	1.0077	1.00225	2.00265
6~8	1.003974	1.0049	1.00140	1.0093	1.00394	2.00472
8~10	1.004413	1.0054	1.00180	1.0085	1.00272	2.00602
10~12	1.005641	1.0045	1.00400	1.0075	1.00203	2.00727
12~14	1.007109	1.0077	1.00530	1.0144	1.00692	2.00951
14~16	1.008055	1.0070	1.00810	1.0113	1.00416	2.01303
16~18	1.009584	1.0104	1.00960	1.0142	1.01024	2.01449
18~20	1.013435	1.0170	1.01200	1.0185	1.01278	2.02042

[*] Divider method
[**] Modified divider method

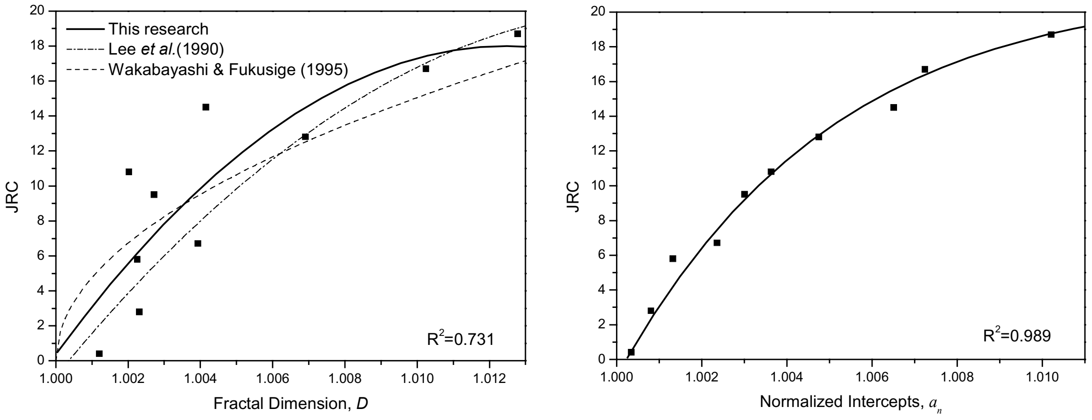


Figure 7. Relations between JRC and *D* and between JRC and a_n in modified divider method

Fractal analysis of standard roughness profiles using variogram method

Semi-variance functions, *V(h)* of standard roughness profile were calculated using 6 different sampling intervals, *h* (0.4mm, 0.6mm, 0.8mm, 1.2mm, 1.7mm, 2.4mm) and log *V(h)* – log *h* were plotted(Figure 8). Fractal dimension and intercept of slope were determined. Fractal dimensions, *D* range from 1.072 to 1.412 and intercepts of slopes, *a* range between -2.851 and -1.289. *a* generally increases as JRC increases but *D* decreases (or scattered) as JRC increases. JRC against *D* as well as JRC against *a* were plotted and best fit lines were drawn in Figure 9. Intercepts, *a* shows better correlation with JRC than fractal dimensions, the same as divider method and correlation coefficient was R^2=0.991. A new equation to estimate JRC using intercept is suggested and shown in equation 11.

$$JRC = 52.07 + 31.94a + 4.85a^2 \qquad (11)$$

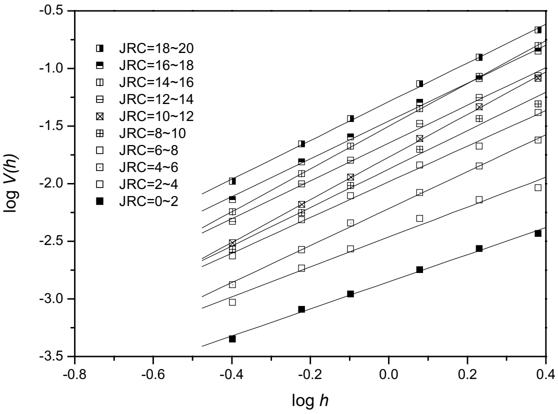


Figure 8. . log *V(h)* – log *h* plot within crossover length

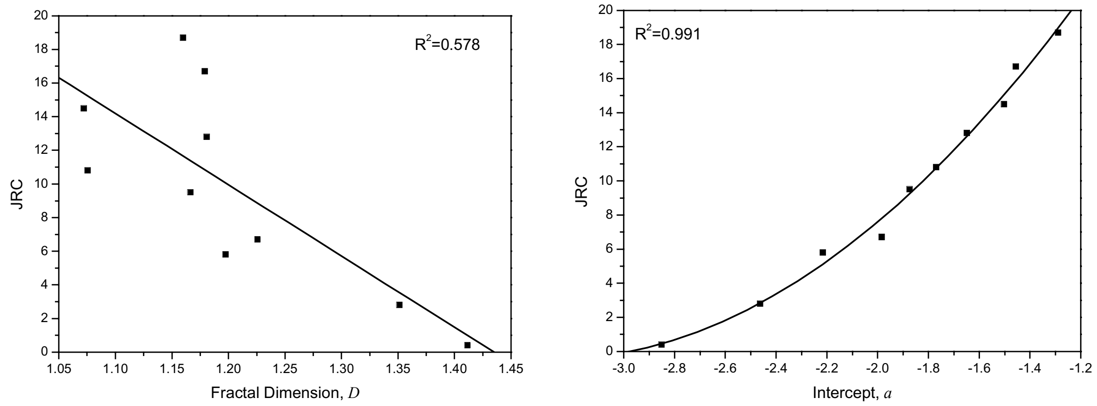


Figure 9. Relations between JRC and *D* and between JRC and *a* in variogram method

Equation suggested by Tse & Cruden(1979) using Z_2 parameter is generally accepted that it is highly correlated with JRC. JRC calculated using equation suggested by Tse & Cruden(1979) and using equation 8(modified divider method) and equation 11(variogram method) were compared(Figure 10). JRC calculated using equation 8 and equation 11 are closer to JRC in standard roughness profile than those calculated using equation suggested by Tse & Cruden(1979). For JRC=0~2, JRC=10~12, JRC=14~16 and JRC=16~18, JRC calculated using equation suggested by Tse & Cruden(1979) are lower than JRC range in standard roughness profile. JRC calculated using equation suggested by Tse & Cruden(1979) are higher than JRC range in standard roughness profile for JRC=6~8.

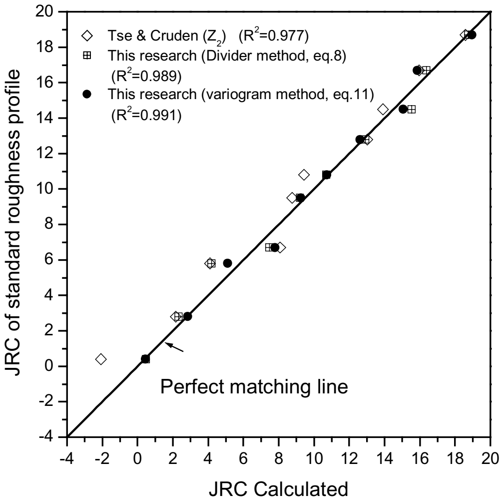


Figure 10. JRC calculated using equations suggested by Tse & Cruden and by this research for standard roughness profile.

Application of new equations to natural rock joints

We digitized roughness profiles of 25 natural rock joints and JRC were calculated using equations 8 and 11. Because JRC of natural rock joints were not known, unlike standard roughness profile, JRC using equation suggested by Tse & Cruden(1979) were also calculated and compared with those calculated in this research. Figure 11 shows JRC calculated using equations suggested by this research and Tse & Cruden(1979) for 25 natural rock joints. JRC are relatively similar. However, JRC calculated in this research are higher than those calculated using equation suggested by Tse & Cruden(1979) below JRC of 14 and are lower than those calculated using equation suggested by Tse & Cruden(1979) above JRC of 14. JRC calculated using equation suggested by Tse & Cruden(1979) are even negative if joints are flat, indicating that JRC calculated using equation suggested by Tse & Cruden(1979) may be unrealistic for flat joints. We also compared JRC calculated using variogram method(eq. 11) with those calculated using divider method(eq. 8). All data points are identical within 10% error range and R^2 is 0.994. JRC calculated using varigram method have a little bit higher values than those calculated using divider method when JRC is above 10(Figure 11).

We measured shear strengths of 25 natural rock joints and compared them with the Barton's criterion using JRC calculated using equation 8 and 11 and equation suggested by Tse & Cruden(1979). Figure 12 shows shear strengths measured and calculated. When JRC are low, shear strengths measured and calculated using all three JRC values are almost identical. However, When JRC are high, shear strengths calculated using JRC by Tse & Cruden(1979) are higher than those measured, indicating that JRC calculated using equations by this research is more effective. Although shear strengths measured are almost identical with those calculated below the normal stress of 2.5~3 MPa, shear strengths measured are lower than those calculated above the normal stress of 2.5~3 MPa. This is expected because one specimen was sheared repeatedly under several normal stresses and therefore, joint roughness was crushed at high normal stress.

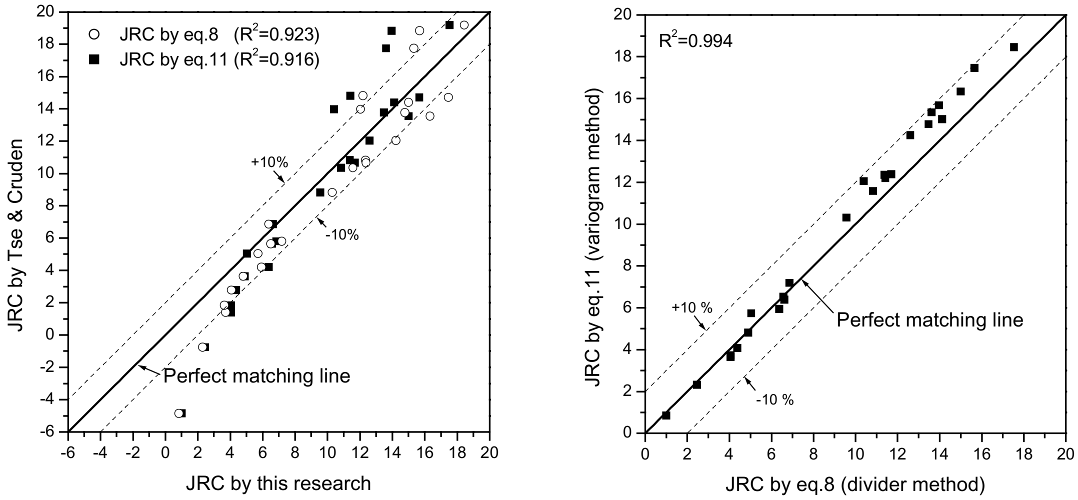


Figure 11. JRC calculated using equations suggested by Tse & Cruden and by this research for natural rock joints.

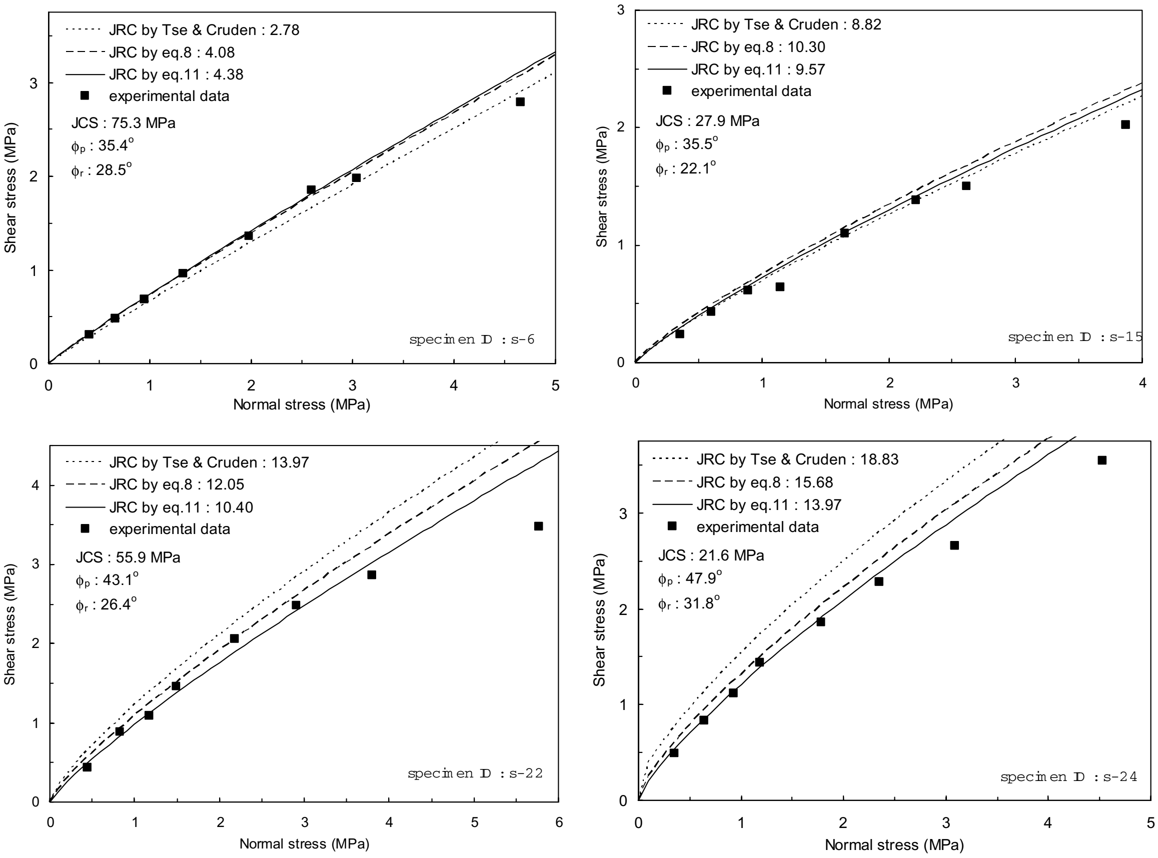


Figure 12. Shear strengths measured and calculated from Barton's criterion with JRC using three equations.

CONCLUSIONS

Fractal analysis using modified divider method and variogram method were performed to estimates joint roughness coefficient. Surfaces of standard roughness profile and 25 natural rock joints were digitized by 0.1mm along horizontal line. Crossover length in which the fractal dimension can be determined correctly was 0.4mm – 2.4mm. Lengths and semi-variance function of standard roughness profile were measured using 6 different divider spans(or sampling intervals) within crossover length and fractal dimensions and intercepts were calculated. JRC were better correlated with intercepts than fractal dimensions in both methods. Two new equations to estimate JRC using intercepts were suggested. JRC of 25 natural rock joints were calculated using equations suggested by this research and shear strengths measured and calculated from the Barton's criterion with JRC using equation suggested by this research and by Tse & Cruden(1979). Shear strengths measured are better matched with those calculated using equations suggested by this research than those by Tse & Cruden(1979), indicating that JRC calculated using equations by this research is more effective.

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