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EFFECT OF BOUNDARY CONDITIONS ON THE STRENGTH AND DEFORMABILITY OF REPLICAS OF NATURAL FRACTURES IN WELDED TUFF: DATA ANALYSIS

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ABSTRACT

Assessing the shear behavior of intact rock & rock fractures is an important issue in the design of a potential nuclear waste repository at Yucca Mountain, Nevada. Cyclic direct shear experiments were conducted on replicas of three natural fractures and a laboratory-developed tensile fracture of welded tuff. The tests were carried out under constant normal loads or constant normal stiffnesses with different initial normal load levels. Each test consisted of five cycles of forward and reverse shear motion. The complete set of experimental results can be found in a data report by Wibowo et al. (1993a). Based on the results of the shear tests conducted under constant normal load, the shear behavior of the joint replicas tested under constant normal stiffness was predicted by using the graphical analysis method of Saeb (1989), and Amadei and Saeb (1990). Comparison between the predictions and the actual constant stiffness direct shear experiment results can be found in a report by Wibowo et al. (1993b). In this report, the results of the constant normal load shear experiments are analyzed using several constitutive models proposed in the rock mechanics literature for joint shear strength, dilatancy, and joint surface damage. It is shown that some of the existing models have limitations. New constitutive models are proposed and are included in a mathematical analysis tool that can be used to predict joint behavior under various boundary conditions.

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1.0 INTRODUCTION

Modeling the mechanical response of the rock masses is an important issue in the design of a potential nuclear waste repository at Yucca Mountain, Nevada. Knowledge of both intact rock and fracture properties is required in the analyses. One of the investigations providing properties has examined the mechanical behavior of fracture replicas tested in direct shear. The experiments were designed to study the effect of boundary conditions on the strength and deformability of fractures.

The response of a rough joint to shear loading depends on its surface properties as well as the boundary conditions that are applied by the surrounding rock mass. These boundary conditions can exist in a variety of forms as shown in Figure 1. A constant normal load (stress) boundary condition can be used, for instance, in rock slope stability problems to model the sliding of a block along a critical joint plane [Figure 1(a)]. On the other hand, if a system of rock bolts or cables is installed to stabilize the same block as shown in Figure 1(b), the dilatancy of the joint is now constrained and controlled by the stiffness of the reinforcement. Similarly, a rock block constrained between dilatant joints that slides into an underground excavation, as shown in Figure 1(c), does not move as freely as in Figure 1(a). As the block moves, dilation of the joints is restricted by the surrounding rock mass, and the joint shear behavior is controlled by the rock mass stiffness, i.e., the capacity of the rock mass to deform.

The range of joint normal loading conditions shown in Figure 1 can best be represented by assuming that the reinforcement in Figure 1(b) and the rock mass surrounding the joints in Figure 1(c) are modelled by a spring with stiffness, K , defined as the ratio between the increments in joint normal load (stress) and the increments in joint normal displacement. The applied stiffness may vary between zero for a constant normal load (stress) condition and infinity for a constant normal displacement condition. The applied stiffness is constant if the change in joint normal load (stress)

remains proportional to the change in joint normal displacement during shearing. However, the applied stiffness may also vary with the load history of the rock mass. Note that the applied stiffness, K , is a property of the rock mass or the reinforcement system and should not be confused with the joint normal stiffness.

In general, joint shear strength under constant (nonzero) or variable normal stiffness is higher than joint shear strength under constant normal load (stress). The main reason for the increase in

Figure 1. Simulation of different in situ boundary conditions in direct shear tests (adapted from Lechnitz, 1985).

shear strength is that under nonzero normal stiffness, joint dilatancy created by the joint surface roughness is inhibited. As a result, the joint normal load (stress) increases as shear takes place, which, in turn, raises the amount of needed shear stress to continue deformation. The effect of normal stiffness boundary conditions on the shear behavior of rock joints has been investigated theoretically or experimentally by Obert et al. (1976), Lechnitz (1985), Goodman and Boyle (1985), Hutson (1987), by Archambault et al. (1990), Bandis (1990), Benmokrane et al. (1991), Ohnishi and Dharmaratne (1990), and Skinas et al. (1990).

In two recent publications, Saeb (1989) and Amadei and Saeb (1990) proposed mathematical and graphical methods to predict the shear behavior of a rock joint under constant or variable normal stiffness boundary condition from the results of conventional constant normal load (stress) direct shear tests. An experimental research program was initiated to test these methods using the data collected on several fractures in welded tuff from Yucca Mountain in the southwest corner of the Nevada Test Site in southern Nevada and on one fracture in rock from Rainier Mesa. Cyclic direct shear tests and normal compression tests were conducted on replicas of three natural fractures and a laboratory-developed tensile fracture of welded tuff. A total of 20 direct shear tests were carried out under constant normal loads ranging between 0.6 and 25.6 kips (2.7 and 113.9 kN) equivalent to nominal normal stresses ranging between 40 and 800 psi (0.2 and 3.6 MPa). Also 15 direct shear tests were carried out under constant normal stiffnesses ranging between 14.8 and 187.5 kips/in. (25.9 and 328.1 kN/cm) with different initial normal loads. Each direct shear test consisted of five cycles of forward and reverse shear motion. The experimental schedule is summarized in Tables 1(a) through 1(d). The experimental results can be found in the data report by Wibowo et al. (1993a). By using the response curves of the shear tests performed under constant normal load, the shear responses of the joint replicas tested under constant normal stiffness were predicted by applying the graphical method of Saeb (1989) and Amadei and Saeb (1990). Comparison between the predictions and the actual constant stiffness direct

Table 1a
Experimental schedule for G2 specimens.

Sample	Normal Load (kips)	Init. Normal Stress (psi) *	Const. Stiffness (kips/in)
R1G2	1.3	40	0
R4G2	6.4	200	0
R2G2	12.8	400	0
R3G2	25.6	800	0
KR5G2	1.3	40	32
KR6G2	6.4	200	64

* Area = 32.00 in²

Table 1b
Experimental schedule for F2 specimens.

Sample	Normal Load (kips)	Init. Normal Stress (psi) *	Const. Stiffness (kips/in)
R5F2	0.6	40	0
R2F2	3.0	200	0
R3F2	5.9	400	0
R4F2	11.8	800	0
KR6F2	3.0	200	14.8
KR7F2	3.0	200	44.3
KR8F2	3.0	200	147.8

* Area = 14.77 in²

Table 1c
Experimental schedule for F3 specimens.

Sample	Normal Load (kips)	Init. Normal Stress (psi)*	Const. Stiffness (kips/in)
R1F3	0.8	40	0
R6F3	3.8	200	0
R4F3	7.5	400	0
R5F3	15.0	800	0
KR7F3	3.8	200	18.8
KR8F3	3.8	200	56.3
KR9F3	3.8	200	187.5
KR10F3	7.5	400	56.3
KR11F3	7.5	400	187.5

* Area = 18.75 in²

Table 1d
Experimental schedule for F4 specimens.

Sample	Normal Load (kips)	Init. Normal Stress (psi)*	Const. Stiffness (kips/in)
R1F4	0.7	40	0
R2F4	3.6	200	0
R3F4	7.2	400	0
R4F4	10.8	600	0
R5F4	14.4	800	0
R6F4	10.8	600	0
R8F4	10.8	600	0
R13F4	3.6	200	0
KR7F4	3.6	200	18.0
KR9F4	3.6	200	54.0
KR10F4	3.6	200	179.9
KR11F4	7.2	400	54.0
KR12F4	7.2	400	179.9

* Area = 18.0 in²

shear test responses can be found in the report by Wibowo et al. (1993b).

In this report, the results of the shear tests conducted under constant normal load are analyzed using several constitutive models proposed in the rock mechanics literature for joint shear strength, dilatancy, and joint surface damage (models of Goodman, Ladanyi and Archambault, Barton, Schneider, and Jing). Some of the existing models have limitations. New constitutive models are proposed and are included in a mathematical analysis tool that can be used to predict joint behavior under various boundary conditions.

2.0 DEFINITIONS AND ASSUMPTIONS

In the report of Wibowo et al. (1993a), the results of the cyclic direct shear experiments and the normal compression tests are presented in terms of normal or shear loads and displacements. On the other hand, most constitutive models of rock joints available in the literature use normal or shear stresses and displacements. The normal and shear stresses mentioned in this report are all nominal stresses and are calculated using the normal and shear loads divided by the initial cross-sectional areas of the joints: i.e., 32, 14.8, 18.7, and 18.0 in² (206.5, 95.5, 120.6, and 116.1 cm²) for joint samples G2, F2, F3, and F4, respectively. The error in neglecting the change in joint area during shear was investigated. An example is shown in Figure 2 for sample R1F4, where two shear stress versus shear displacement response curves have been plotted for the same shear test under a constant normal load of 0.72 kips (3.2 kN). One curve assumes a constant area during shear whereas the other has been obtained after area correction. The difference in shear stress at 0.6 in. (1.5 cm) of shear displacement is 0.004 ksi (27.6 kN/m²) or about 10% of the value of shear stress for constant area.

In this report, the shear stress versus shear displacement response curves obtained by Wibowo et al. (1993a) under constant normal load

Figure 2. Comparison between shear stress versus shear displacement curves using initial and corrected areas for sample R1F4 and forward shear motion.

are idealized, as shown in Figure 3(a), and consist of three regions: prepeak, peak and postpeak. The slope of the prepeak region for data ranging between 25% and 75% of the peak shear load is defined as the *joint shear stiffness* k_j . It is only defined for the forward part of the first shear cycle. The shear stresses and displacements for the peak and residual conditions are defined as (τ_p, u_p) and (τ_r, u_r) , respectively. In this data analysis, the residual shear displacement is assumed to be independent of the normal load and equal to the maximum forward or reverse shear displacement of 0.5 in. (1.3 cm) for samples F2, F3, and F4, and 0.6 in. (1.5 cm) for sample G2. Thus, the shear stresses observed at 0.5 in. (1.3 cm) or 0.6 in. (1.5 cm) of shear displacement are assumed to represent the residual shear strengths.

From the normal displacement, v , versus shear displacement, u , response curves measured during the constant normal load direct

Figure 3. (a) Idealized shear stress versus shear displacement curve. (b) Idealized normal displacement (dilatancy) versus shear displacement curve.

shear tests, three angles of dilatancy are defined as shown in Figure 3(b): (1) an average dilation angle, i_w , between 0.1 and 0.4 in. (0.25 and 1.0 cm) of shear displacement, (2) a peak secant dilation angle, i_s , at the peak shear stress, and (3) a peak tangent dilation angle, i_p , at the peak shear stress.

3.0 VARIATION OF PEAK SHEAR DISPLACEMENT AND SHEAR STIFFNESS WITH NORMAL STRESS

Goodman (1976) recommended two models shown in Figure 4 to represent the variation of joint shear stress with shear displacement under constant normal stress. One model [Figure 4(a)] assumes that the joint shear stiffness, k_s , is independent of the normal stress (constant stiffness model), whereas the second model [Figure 4(b)] assumes that the peak and residual shear displacements u_p and u_r are constant (constant displacement model). Both models show an increase in peak and residual shear strengths with normal stress. Based on the shape of the shear load vs. shear displacement response curves in the data report by Wibowo et al (1993a), it is shown below that neither constant stiffness model nor constant displacement model, by itself, fits the observed behavior.

3.1 Peak shear displacement

The peak shear displacement measured in the experiments by Wibowo et al. (1993a) was found to increase with the normal load or stress. A linear relation was used to describe the variation of the peak displacement, u_p , with the applied normal stress, σ_n , as follows:

$$u_p = a + b\sigma_n \quad (1)$$

Figure 4. Constant stiffness and constant peak displacement models
(adapted from Goodman, 1976)

As an example, Figures 5(a) and 5(b) show the variation of the peak displacement with the normal stress for samples F3 and for the forward and reverse parts of the first shear cycle, respectively. Similar variations for samples F4, F2, and G2 can be found in Appendix A1. Coefficients a and b in equation (1) were determined by linear regression analysis. Their values are listed in Table 2. In general, peak shear displacement increases with the normal stress.

Table 2

Variation of coefficients a and b for samples F4, F3, F2, and G2.
Forward and reverse parts of the first shear cycle.

Sample	1st cycle Forward Motion			1st cycle Reverse Motion		
	Coeff. a (in.)	Coeff. b (in/ksi)	Coeff. of Corr.	Coeff. a (in.)	Coeff. b (in/ksi)	Coeff. of Corr.
F4	0.025	0.079	0.93	0.051	0.004	0.31
F3	0.000	0.099	0.98	0.016	0.095	0.97
F2	0.016	0.038	0.86	0.025	0.023	0.56
G2	0.045	0.136	0.99	0.241	0.195	0.88

It is noteworthy that equation (1) was used to describe the variation of the peak displacement with the normal stress for the first shear cycle only. For the other four cycles, the peak displacement was sometimes poorly defined and it was difficult to separate the peak and residual displacements because of accumulated joint surface damage. This resulted in more scatter in the plots of peak shear displacement vs. normal stress. An example of such a plot is shown in Figure 6 for forward shear of samples F4.

(a)

(b)

Figure 5. Peak shear displacement versus normal stress for samples F3, (a) forward shear motion, and (b) reverse shear motion.

In general, the peak shear displacements were found to be small. The ratio u_p/L between the peak displacement, u_p , and the length of each test sample, L , was found to vary between 0.001 and 0.047 (Table 3). This indicates that the peak shear stress is mobilized after a small amount of shear displacement.

Table 3
Range of u_p/L for samples F4, F3, F2, and G2.

Sample	Range of u_p/L
F4	0.003 - 0.014
F3	0.001 - 0.016
F2	0.003 - 0.009
G2	0.006 - 0.047

Figure 6. Peak shear displacement versus normal stress for samples F4, forward shear motion (all cycles).

3.2 Shear stiffness

A linear relation was used to describe the variation the shear stiffness, k , with the applied normal stress, σ_n , as follows

$$k_s = c + d\sigma_n \quad (2)$$

Figure 7 shows an example of the variation of the shear stiffness with the normal stress for samples F4. Similar variations for samples F3, F2, and G2 can be found in Appendix A2. Coefficients c and d in equation (2) were determined by linear regression analysis. Their values are listed in Table 4. In general, the shear stiffness increases with the normal stress.

Figure 7. Shear stiffness versus normal stress for samples F4.

Table 4

Variation of coefficients c and d for samples F4, F3, F2 and G2.
Forward part of the first shear cycle.

Sample	1st cycle Forward Motion		
	Coeff. c (ksi/in)	Coeff. d (1/in.)	Coeff. of Corr.
F4	75.67	16.69	0.84
F3	61.68	18.04	0.87
F2	59.91	12.56	0.98
G2	35.14	6.53	0.67

4.0 VARIATION OF THE RATIO OF RESIDUAL TO PEAK SHEAR STRENGTHS WITH NORMAL STRESS

Goodman (1976) proposed the following equation describing the variation of the ratio between the residual shear strength, τ_r , and the peak shear strength, τ_p , of a rock joint with the normal stress σ_n

$$\frac{\tau_r}{\tau_p} = B_0 + (1 - B_0) \frac{\sigma_n}{\sigma_T} \quad (3)$$

when $\sigma_n < \sigma_T$ and

$$\tau_r = \tau_p \quad (4)$$

when $\sigma_n \geq \sigma_T$. In equation (3), B_0 ($0 \leq B_0 \leq 1$) is the ratio of residual to peak shear strengths at zero normal stress and σ_T (N_T divided by the initial joint area) is a transitional stress beyond which the peak shear strength is always equal to the residual shear strength.

The peak and residual shear loads obtained from the constant normal load direct shear tests on samples F4, F3, F2, and G2 were used to determine the values of B_0 and σ_T for the forward and reverse parts of each shear cycle. Linear regression analyses were carried out between the ratios of residual to peak shear loads (also equal to τ_r/τ_p) and the applied constant normal loads.

As an example, Figures 8(a) and 8(b) show the variation of τ_r/τ_p with the normal stress σ_n for samples F4 for the forward and reverse parts of the five shear cycles, respectively. The corresponding values of B_0 and σ_T for each one of the five shear cycles are given in Tables 5a and 5b. Using a similar analysis, the values B_0 and σ_T for the various test series conducted on samples F3, F2, and G2 are given in Tables 6, 7, and 8, respectively. The corresponding plots of variation of τ_r/τ_p with the normal stress σ_n can be found in Appendix B.

Figures 8(a) and 8(b) and the plots presented in Appendix B show that the linear model of Goodman defined in equation (3) gives a fair representation of the observed increase in τ_r/τ_p with the normal stress σ_n . Tables 5-8 indicate that for a given joint sample, B_0 and σ_T are not constant, but vary from one shear cycle to another and have different values for forward and reverse motions. It appears that B_0 approaches unity as the number of cycles increases, that is, the peak shear strength approaches its residual value as more damage occurs along the joint surfaces during shear. For a given joint sample, the smallest values of B_0 are always obtained for the first shear cycle for which the difference between peak and residual shear loads is the largest.

Goodman (1976) suggested that the uniaxial compressive strength of the intact material q_u in the joint walls can be used as an estimate of σ_T . Here q_u for the gypsum cement is equal to 4.0 ksi (27.6 MN/m²). From the test results shown in Tables 5-8, the value of σ_T/q_u is not equal to one but varies between 0.22 and 0.47 for samples F4, 0.23 and 0.34 for samples F3, 0.23 and 0.61 for samples

(a)

(b)

Figure 8. Ratio of residual to peak shear stress versus normal stress for samples F4, (a) forward shear motion, and (b) reverse shear motion.

Table 5a
Value of B_o , N_T , σ_T , and σ_T/q_u for samples F4.
Forward part of the five shear cycles.

Sample F4	Forward Motion				
Cycle #	B_o	N_T (kips)	σ_T (ksi)	σ_T/q_u	Coeff. of Correlation.
1st	0.48	33.6	1.86	0.47	0.95
2nd	0.66	16.0	0.88	0.22	0.90
3rd	0.81	16.8	0.93	0.23	0.81
4th	0.87	19.6	1.08	0.27	0.63
5th	0.90	21.1	1.17	0.29	0.59

Table 5b
Value of B_o , N_T , σ_T , and σ_T/q_u for samples F4.
Reverse part of the five shear cycles.

Sample F4	Reverse Motion				
Cycle #	B_o	N_T (kips)	σ_T (ksi)	σ_T/q_u	Coeff. of Correlation
1st	0.57	32.9	1.83	0.46	0.94
2nd	0.80	22.1	1.23	0.31	0.79
3rd	0.84	23.4	1.28	0.32	0.80
4th	0.81	16.0	0.89	0.22	0.83
5th	0.89	20.4	1.13	0.28	0.90

Table 6a
Value of B_o , N_T , σ_T , and σ_T/q_u for samples F3.
Forward part of the five shear cycles.

Sample F3	Forward Motion				
Cycle #	B_o	N_T (kips)	σ_T (ksi)	σ_T/q_u	Coeff. of Correlation.
1st	0.45	22.1	1.17	0.29	0.81
2nd	0.59	19.5	1.04	0.26	0.85
3rd	0.63	25.4	1.35	0.34	0.75
4th	0.56	20.9	1.11	0.28	0.79
5th	0.62	24.3	1.29	0.32	0.81

Table 6b
Value of B_o , N_T , σ_T , and σ_T/q_u for samples F3.
Reverse part of the five shear cycles.

Sample F3	Reverse Motion				
Cycle #	B_o	N_T (kips)	σ_T (ksi)	σ_T/q_u	Coeff. of Correlation
1st	0.39	24.0	1.28	0.32	0.93
2nd	0.57	24.6	1.31	0.33	0.90
3rd	0.62	21.1	1.12	0.26	0.96
4th	0.58	17.1	0.91	0.23	0.87
5th	0.64	17.1	0.91	0.23	0.85

Table 7a

Value of B_o , N_T , σ_T , and σ_T/q_u for samples F2.
Forward part of the five shear cycles.

Sample F2	Forward Motion				
Cycle #	B_o	N_T (kips)	σ_T (ksi)	σ_T/q_u	Coeff. of Correlation.
1st	0.51	33.0	2.23	0.56	0.72
2nd	0.72	19.9	1.34	0.34	0.92
3rd	0.84	33.4	2.26	0.57	0.46
4th	0.73	13.8	0.94	0.24	0.79
5th	0.74	21.3	1.44	0.36	0.67

Table 7b

Value of B_o , N_T , σ_T , and σ_T/q_u for samples F2.
Reverse part of the five shear cycles.

Sample F2	Reverse Motion				
Cycle #	B_o	N_T (kips)	σ_T (ksi)	σ_T/q_u	Coeff. of Correlation
1st	0.46	26.5	1.79	0.45	0.84
2nd	0.67	14.4	0.97	0.24	0.97
3rd	0.77	36.2	2.45	0.61	0.38
4th	-	-	-	-	-
5th	-	-	-	-	-

Table 8a
Value of B_o , N_T , σ_T , and σ_T/q_u for samples G2.
Forward part of the five shear cycles.

Sample G2	Forward Motion				
Cycle #	B_o	N_T (kips)	σ_T (ksi)	σ_T/q_u	Coeff. of Correlation.
1st	0.69	79.3	2.48	0.47	0.51
2nd	0.83	130.3	4.10	1.03	0.88
3rd	-	-	-	-	-
4th	-	-	-	-	-
5th	-	-	-	-	-

Table 8b
Value of B_o , N_T , σ_T , and σ_T/q_u for samples G2.
Reverse part of the five shear cycles.

Sample G2	Reverse Motion				
Cycle #	B_o	N_T (kips)	σ_T (ksi)	σ_T/q_u	Coeff. of Correlation
1st	0.75	27.0	0.84	0.22	0.81
2nd	0.92	143.1	4.47	1.12	0.42
3rd	-	-	-	-	-
4th	-	-	-	-	-
5th	-	-	-	-	-

F2, and 0.21 and 1.12 for samples G2. The value of σ_T/q_u varies and depends on the joint profile and the number of cycles.

5.0 VARIATION OF DILATANCY WITH NORMAL STRESS

The models of Ladanyi and Archambault (1970), Schneider (1976), Barton and Choubey (1977) and Jing (1990) were used to analyze the variation of joint dilatancy with normal load (stress). In these models, different dilation angles are defined as shown in Figure 3(b). Barton and Choubey (1977) used the peak secant dilation angle, i_s , (also called initial dilation angle), and the peak tangent dilation angle, i_p . Based on their experimental tests, Barton and Choubey found that the peak secant dilation angle is about one-third of the peak tangent dilation angle. Ladanyi and Archambault (1970), Schneider (1976), and Jing (1990) considered the peak tangent dilation angle only.

Based on the present experimental results, values of the three dilatancy rates $\tan(i_s)$, $\tan(i_p)$, and $\tan(i_v)$ were determined for samples F2, F3, F4, and G2 and can be found in Appendix C1. As an example, Table 9 gives the values of the three rates of dilatancy for the forward and reverse parts of the first shear cycle for samples F4. Under relatively small normal stresses of 0.04 and 0.20 ksi (0.28 and 1.38 MN/m²), the three dilatancy rates differ with larger values for the peak tangent dilatancy rate. Under larger normal stresses between 0.40 and 0.80 ksi (2.76 and 5.52 MN/m²) the three dilatancy rates are about the same.

Figure 9 shows the variation of $\tan(i_v)$ with the applied constant normal load for the forward and reverse parts of each one of the five shear cycles for samples F4. Due to the anisotropic behavior of joint surfaces, joint dilatancy is not the same in the forward and reverse directions, and varies from one cycle to another and decreases as the applied normal load increases. Plots similar to

Table 9
 Secant, tangential, and average rates of dilatancy for
 samples F4. Forward and reverse motions of the first cycle.

Normal Stress (ksi)	$\tan(i_s)$	$\tan(i_p)$	$\tan(i_{av})$
Forward			
0.04	0.12	0.19	0.14
0.20	0.16	0.16	0.14
0.40	0.12	0.11	0.11
0.60	0.09	0.11	0.10
0.80	0.09	0.08	0.08
Reverse			
0.04	0.16	0.19	0.14
0.20	0.10	0.15	0.11
0.40	0.06	0.08	0.08
0.60	0.07	0.07	0.09
0.80	0.06	0.06	0.07

Figure 9. Average dilatancy versus normal load for samples F4.

those presented in Figure 9 for samples F3, F2, and G2 can be found in Appendix C2.

The models of Ladanyi and Archambault (1970), Barton and Choubey (1977), Schneider (1976), and Jing (1990) were used to fit the observed variation of the peak tangent dilatancy rate, $\tan(i_p)$, with the normal stress σ_n .

5.1 Model of Ladanyi and Archambault

Ladanyi and Archambault (1970) proposed the following expression between the peak tangent dilatancy rate and the applied normal stress σ_n

$$\tan(i_p) = (1 - \frac{\sigma_n}{\sigma_T})^{k_2} \tan(i_{p0}) \quad (5)$$

where k_2 is an empirical coefficient, σ_T is a transitional stress beyond which no further dilatancy takes place and $\tan(i_{p0})$ is the peak rate of dilatancy at zero normal stress. Using the values of σ_T defined in Tables 5-8, the values of k_2 and $\tan(i_{p0})$ were determined by linear regression analysis between $\log(\tan(i_p))$ and $\log(1 - \sigma_n/\sigma_T)$. Tables 10a-10d give the values of k_2 and $\tan(i_{p0})$ for the forward and reverse parts of each shear cycle for joint samples F4, F3, F2, and G2, respectively. In general, $\tan(i_{p0})$ decreases as the number of cycles increases, with most or all of the decrease following the first cycle. The value of k_2 decreases as the number of cycles increases for joint samples F4, F2, and G2 and increases with the number of cycles for samples F3. The values of k_2 range between 0.25 to 3.55 and are less than the value of 4 initially suggested by Ladanyi and Archambault (1970). The value of k_2 was found to be influenced by joint surface roughness.

5.2 Model of Barton and Choubey

Barton and Choubey (1977) proposed the following expression between the peak tangent dilatancy rate and the applied normal stress σ_n

Table 10a
Coefficients k_2 and $\tan(i_{p0})$
in Ladanyi and Archambault's equation, samples F4.

Sample F4	Forward Motion		Reverse Motion	
Cycle #	k_2	$\tan(i_{p0})$	k_2	$\tan(i_{p0})$
1st	0.81	0.18	1.14	0.17
2nd	0.73	0.12	0.65	0.10
3rd	0.40	0.10	0.39	0.10
4th	0.25	0.10	0.39	0.10
5th	0.38	0.10	0.49	0.11

Table 10b
Coefficients k_2 and $\tan(i_{p0})$
in Ladanyi and Archambault's equation, samples F3.

Sample F3	Forward Motion		Reverse Motion	
Cycle #	k_2	$\tan(i_{p0})$	k_2	$\tan(i_{p0})$
1st	0.63	0.23	0.93	0.27
2nd	0.86	0.19	1.23	0.23
3rd	1.15	0.18	1.13	0.19
4th	1.12	0.17	1.13	0.19
5th	1.12	0.17	1.07	0.18

Table 10c
Coefficients k_2 and $\tan(i_{po})$
in Ladanyi and Archambault's equation, samples F2.

Sample F2	Forward Motion		Reverse Motion	
Cycle #	k_2	$\tan(i_{po})$	k_2	$\tan(i_{po})$
1st	1.98	0.24	8.2	0.16
2nd	1.25	0.10	11.9	0.13
3rd	1.02	0.10	12.9	0.13
4th	0.36	0.09	15.8	0.15
5th	-	-	-	-

Table 10d
Coefficients k_2 and $\tan(i_{po})$
in Ladanyi and Archambault's equation, samples G2.

Sample G2	Forward Motion		Reverse Motion	
Cycle #	k_2	$\tan(i_{po})$	k_2	$\tan(i_{po})$
1st	3.55	0.23	10.7	0.11
2nd	2.26	0.11	-	-
3rd	-	-	-	-
4th	-	-	-	-
5th	-	-	-	-

$$\tan(i_p) = \tan(JRC \log_{10} \frac{JCS}{\sigma_n}) \quad (6)$$

where JRC is the *Joint Roughness Coefficient* and JCS is the *Joint Wall Compressive Strength* (equal to q_u for unweathered rock surface i.e., 4.0 ksi (27.6 MN/m²) for gypsum cement). According to Barton and Choubey (1977), equation (6) is valid as long as $\sigma_n < JCS$.

Knowing the values of JCS, the applied normal stress and the peak tangent dilatancy rate, JRC was back-calculated directly from equation (6) for each joint sample and for the forward and reverse parts of each shear cycle. For clarity, JRC determined from the peak dilatancy rates is defined here as JRC_{pd} .

The values of JRC_{pd} for the first shear cycle are plotted as a function of normal stress in Figures 10(a) and 10(b) for forward and reverse shear motion, respectively. These two figures show that JRC_{pd} is not constant for a given joint sample, but is relatively independent of normal stress (except for sample G2 at a normal stress of 0.8 ksi (5.52 MN/m²) in Figure 10(a) and sample F2 in Figure 10b). The average values of JRC_{pd} for the forward and reverse parts of the five shear cycles are given in Table 11 for joint samples F4, with similar tables for joint samples F2, F3, and G2 in Appendix C3. These tables show that the average value of JRC_{pd} back-calculated from the dilatancy curves decreases significantly between the first and second cycles and remains essentially constant for the other three cycles, indicating a major degradation in the joint surface asperities during the first shear cycle.

Using the initial and final joint surface roughness profiles X2 and X3 reported by Wibowo et al (1993a), the values of JRC at the beginning of the first shear cycle and at the end of the fifth shear cycle were determined for all joint samples using the methods of Tse and Cruden (1979) and modified by Yu and Vayssade (1991). These authors proposed an empirical regression equation between the

(a)

(b)

Figure 10. Joint Roughness Coefficient versus normal stress, (a) first cycle forward motion, and (b) first cycle reverse motion.

Table 11

Comparison between average JRC_{pd} back-calculated from the dilatancy curves and average JRC_{pr} determined from roughness profiles on samples F4.

	Cycle Motion	JRC_{pd} (back-calculated from dilatancy curves)	JRC_{pr} (from profiles)
Forward Motion	1st	6.6	6.7
	2nd	4.6	
	3rd	4.6	
	4th	4.6	
	5th	4.6	
Reverse Motion	1st	5.4	1.5
	2nd	4.0	
	3rd	4.5	
	4th	4.7	
	5th	4.6	

joint roughness coefficient, defined here as JRC_{pr} , and the root-mean-square (RMS) of the first derivative of the profile, Z_2 . Yu and Vayssade (1991) recommended the following equation

$$JRC_{pro} = 60.32 * (Z_2) - 4.51 \quad (7)$$

for profiles with a sampling interval of 0.25 mm. The value of Z_2 is defined as follows

$$Z_2 = \sqrt{\frac{1}{M(Dx)^2} \sum (y_{i+1} - y_i)^2} \quad (8)$$

where M is the number of sampling intervals, Dx is the interval size, and y_i is the asperity height along the profile. The value of JRC_{pr} is then corrected for scale effect as suggested by Barton and Bandis (1990) using the following equation

$$JRC_{pr} = JRC_{pro} \left(\frac{L_n}{L_o} \right)^{-0.02JRC_{pro}} \quad (9)$$

where JRC_{pro} is the value of JRC before correction corresponding to a joint sample length L_o of 100 mm, and JRC_{pr} is the value of JRC after correction for the actual length L_n of the joint profiles. The average values of JRC_{pr} calculated using that method are reported in Table 11 and other tables in Appendix C3. These tables reveal that the average values of JRC_{pr} determined from the initial profiles at the beginning of the direct shear tests are similar to those back-calculated from the dilatancy curves. However, the average values of JRC_{pr} determined from the final profiles at the end of the shear tests are much smaller. Additional discussion about JRC is presented in Section 6.2.

5.3 Model of Schneider

Schneider (1976) proposed the following relationship between the peak tangent dilation angle and the normal stress σ_n

$$i_p = i_{po} e^{-k\sigma_n} \quad (10)$$

where k is an empirical coefficient and i_{po} is the peak tangent dilation angle at zero normal stress. The values of k and i_{po} were determined by linear regression analysis between $\log(i_p)$ and $\log(\sigma_n)$ and are given in Tables 12a-12d for the forward and reverse parts of each shear cycle for all joint samples. Schneider (1976) found that the value of coefficient k depends on the joint surface roughness and material type. In Schneider's experiments on limestone, sandstone and granite the coefficient k was found to range between 0.002 and 0.013 in²/lb. In our experiments, with a much weaker material (gypsum), coefficient k varies between 0.05 and 0.11 in²/lb for all samples (first shear cycle forward motion).

Table 12a
Coefficients k and i_{po} in Schneider's equation, for samples F4.

Sample F4	Forward Motion		Reverse Motion	
Cycle #	k (in ² /lb)	i_{po} (degrees)	k (in ² /lb)	i_{po} (degrees)
1st	0.060	10.8	0.088	10.8
2nd	0.055	7.4	0.053	6.4
3rd	0.033	6.2	0.030	6.0
4th	0.020	5.7	0.032	6.3
5th	0.029	6.0	0.037	6.3

Table 12b
Coefficients k and i_{po} in Schneider's equation, for samples F3.

Sample F3	Forward Motion		Reverse Motion	
Cycle #	k (in ² /lb)	i_{po} (degrees)	k (in ² /lb)	i_{po} (degrees)
1st	0.052	13.7	0.080	17.3
2nd	0.072	11.2	0.106	15.0
3rd	0.098	11.6	0.102	12.6
4th	0.097	10.9	0.102	12.6
5th	0.096	10.9	0.096	11.9

Table 12c

Coefficients k and i_{po} in Schneider's equation, for samples F2.

Sample F2	Forward Motion		Reverse Motion	
Cycle #	k (in ² /lb)	i_{po} (degrees)	k (in ² /lb)	i_{po} (degrees)
1st	0.111	14.3	0.390	9.8
2nd	0.072	6.1	0.560	8.2
3rd	0.060	6.2	0.600	7.8
4th	0.020	5.1	0.740	9.4
5th	-	-	-	-

Table 12d

Coefficients k and i_{po} in Schneider's equation, for samples G2.

Sample G2	Forward Motion		Reverse Motion	
Cycle #	k (in ² /lb)	i_{po} (degrees)	k (in ² /lb)	i_{po} (degrees)
1st	0.091	14.2	0.23	6.8
2nd	0.038	2.8	-	-
3rd	-	-	-	-
4th	-	-	-	-
5th	-	-	-	-

5.4 Model of Jing

Jing (1990) proposed another relationship between the peak tangent dilation angle and the normal stress σ_n as follows

$$i_p = i_{p0} \left(1 - \frac{\sigma_n}{q_u}\right)^k \quad (11)$$

where k is another empirical coefficient, i_{p0} is the peak tangent dilation angle at zero normal stress and q_u is the uniaxial compressive strength of the intact material in the joint walls. Using the values of σ_T defined in Tables 5-8 instead of q_u , the values of k and i_{p0} were determined by linear regression analysis between $\log(i_p)$ and $\log(\sigma_n)$ and are given in Tables 13a-13d for the forward and reverse parts of each shear cycle for all joint samples. Jing et. al. (1992) suggested values of k ranging between 0.2 and 5. In our experiments, the coefficient k varies between 0.65 and 3.52 for all samples (first shear cycle forward motion).

5.5 Summary

An overall comparison between the peak dilatancy rates measured on all joint samples and those predicted using the models of Ladanyi and Archambault, Barton and Choubey, Schneider, and Jing can be found in Appendix C4. An example of such comparison is shown in Figures 11(a) and 11(b) for samples F4 and for the forward and reverse parts of the first shear cycle, respectively. In general, good agreement is found between predictions and observations. In particular, the dilatancy model of Schneider was found to fit the experimental results the best. The second best fit was obtained with Barton and Choubey's model using the average values of JRC_{pd} in Table 11 and in the tables in Appendix C3.

Table 13a
Coefficients k and i_{po} in Jing's equation, for samples F4.

Sample F4	Forward Motion		Reverse Motion	
Cycle #	k	i_{po} (degrees)	k	i_{po} (degrees)
1st	0.80	10.3	1.14	9.6
2nd	0.73	6.9	0.66	5.9
3rd	0.39	5.8	0.38	5.8
4th	0.24	5.4	0.40	6.0
5th	0.38	5.8	0.50	6.1

Table 13b
Coefficients k and i_{po} in Jing's equation, for samples F3.

Sample F3	Forward Motion		Reverse Motion	
Cycle #	k	i_{po} (degrees)	k	i_{po} (degrees)
1st	0.65	12.8	0.97	15.4
2nd	0.89	10.1	1.29	12.9
3rd	1.20	10.1	1.19	10.7
4th	1.17	9.4	1.19	10.7
5th	1.16	9.5	1.13	10.2

Table 13c
Coefficients k and i_{po} in Jing's equation, for samples F2.

Sample F2	Forward Motion		Reverse Motion	
Cycle #	k	i_{po} (degrees)	k	i_{po} (degrees)
1st	1.95	13.3	8.2	9.2
2nd	1.22	5.8	11.9	7.5
3rd	1.02	5.9	12.9	7.1
4th	0.35	5.0	15.8	8.6
5th	-	-	-	-

Table 13d
Coefficients k and i_{po} in Jing's equation, for samples G2.

Sample G2	Forward Motion		Reverse Motion	
Cycle #	k	i_{po} (degrees)	k	i_{po} (degrees)
1st	3.52	12.9	12.7	5.2
2nd	10.7	6.4	-	-
3rd	-	-	-	-
4th	-	-	-	-
5th	-	-	-	-

Figure 11. Comparison between the different dilatancy models for samples F4, (a) first cycle forward shear motion, and (b) first cycle reverse shear motion.

5.6 Proposed Model

The variation of the average dilatancy rate $\tan(i_{av})$ with the normal stress was analyzed using the following equation similar to equation (5),

$$\tan(i_{av}) = (1 - \frac{\sigma_n}{\sigma_T})^{k_3} \tan(i_{av0}) \quad (12)$$

where k_3 is an empirical coefficient, σ_T is a transitional stress beyond which no further dilatancy takes place and $\tan(i_{av0})$ is the average rate of dilatancy at zero normal stress. Using the values of σ_T defined in Tables 5-8, the values of k_3 and $\tan(i_{av0})$ were determined by linear regression analysis between $\log(\tan(i_{av}))$ and $\log(1 - \sigma_n/\sigma_T)$. Tables 14a-14d give the values of k_3 and $\tan(i_{av0})$ for the forward and reverse parts of each shear cycle for joint samples F4, F3, F2, and G2, respectively. Comparison between model and actual test results for samples F4 are shown in Figure 12(a) and 12(b), for forward and reverse shear motion respectively. Similar comparison for the other samples can be found in Appendix C5.

6.0 PEAK SHEAR STRENGTH ENVELOPE

The joint failure criteria of Saeb (1990) and Barton (1976) were used to determine the variation of the peak shear strength τ_p with the normal stress σ_n for the direct shear tests conducted under constant normal load.

6.1 Modified Ladanyi and Archambault Criterion

Saeb (1990) modified the failure criterion of Ladanyi and Archambault (1970) which is now expressed as follows

$$\tau_p = \sigma_n \tan(\phi_u + i) (1 - a_s) + a_s s_r \quad (13)$$

Table 14a
Coefficients k_3 and $\tan(i_{sv0})$
in the proposed dilatancy model for samples F4.

Sample F4	Forward Motion		Reverse Motion	
Cycle #	k_3	$\tan(i_{sv0})$	k_3	$\tan(i_{sv0})$
1st	0.58	0.15	0.59	0.12
2nd	0.56	0.13	0.76	0.13
3rd	0.59	0.13	0.76	0.13
4th	0.52	0.12	0.91	0.13
5th	0.69	0.13	0.95	0.13

Table 14b
Coefficients k_3 and $\tan(i_{sv0})$
in the proposed dilatancy model for samples F3.

Sample F3	Forward Motion		Reverse Motion	
Cycle #	k_3	$\tan(i_{sv0})$	k_3	$\tan(i_{sv0})$
1st	0.54	0.19	0.85	0.23
2nd	0.64	0.19	1.10	0.24
3rd	0.71	0.19	1.10	0.24
4th	0.69	0.18	1.22	0.24
5th	0.69	0.18	1.22	0.23

Table 14c
Coefficients k_3 and $\tan(i_{avo})$
in the proposed dilatancy model for samples F2.

Sample F2	Forward Motion		Reverse Motion	
Cycle #	k_3	$\tan(i_{avo})$	k_3	$\tan(i_{avo})$
1st	1.40	0.17	11.13	0.19
2nd	0.92	0.14	11.01	0.17
3rd	1.59	0.14	10.33	0.13
4th	0.43	0.10	8.20	0.08
5th	-	-	-	-

Table 14d
Coefficients k_3 and $\tan(i_{avo})$
in the proposed dilatancy model for samples G2.

Sample G2	Forward Motion		Reverse Motion	
No. of Cycle	k_3	$\tan(i_{avo})$	k_3	$\tan(i_{avo})$
1st	2.36	0.19	16.88	0.15
2nd	2.41	0.07	-	-
3rd	-	-	-	-
4th	-	-	-	-
5th	-	-	-	-

Figure 12. Comparison between average dilatancy model and actual test results for samples F4, (a) first cycle forward shear motion, and (b) first cycle reverse shear motion.

where a_s is the proportion of total joint area sheared through the asperities and $1-a_s$ is the proportion on which sliding takes place. ϕ_u is the angle of friction for sliding along the asperities. The angle, i , is the peak tangent dilation angle, i_p , of Figure 3. s_r represents the shear strength of the intact rock in the asperities. As suggested by Ladanyi and Archambault (1970), s_r can be approximated by the Mohr-Coulomb criterion:

$$s_r = s_o + \sigma_n \tan \phi_o \quad (14)$$

or Fairhurst's parabolic criterion (Fairhurst, 1964):

$$s_r = q_u \frac{\sqrt{(1+n)} - 1}{n} \left(1 + n \frac{\sigma_n}{q_u}\right) \quad (15)$$

In equation (14), s_o and ϕ_o are the intact rock cohesion and internal friction angle, respectively. In equation (15), q_u is the intact rock compressive strength and n is the ratio between the rock compressive and tensile strengths.

According to Ladanyi and Archambault (1970), a_s and $\tan(i)$ are normal stress dependent such that

$$a_s = 1 - \left(1 - \frac{\sigma_n}{\sigma_T}\right)^{k_1} \quad (16)$$

$$\tan(i) = \left(1 - \frac{\sigma_n}{\sigma_T}\right)^{k_2} \tan(i_{po}) \quad (17)$$

In addition to unconfined compression experiments, triaxial tests were conducted on two cylindrical samples of gypsum cement at confining stresses of 500 and 1,000 psi (3.45 and 6.9 MN/m²). The test results are represented in Figure 13 using Mohr circles along with the best fit Mohr-Coulomb and Fairhurst failure envelopes. Using the Mohr-Coulomb criterion, it was found that $s_0 = 1.11$ ksi (7.7 MN/m²) and $\phi_0 = 31.5$ degrees. Fairhurst failure envelope was obtained with $q_u = 4.0$ ksi (28 MN/m²) and $n = 10$. The value of ϕ_u was determined from four shear tests conducted on smooth gypsum cement surfaces under normal stresses ranging between 0.04 and 0.8 ksi (0.28 and 5.6 MN/m²). As shown in Figure 14, ϕ_u was found to be approximately 30 degrees. The values of k_2 and $\tan(i_{p0})$ in equation (17) were taken directly from Tables 10a-10d.

Because it was not possible to determine the proportion of total joint area, a_i , sheared at the end of the forward and reverse parts of each shear cycle (except at the end of the fifth shear cycles), coefficient k_1 in equation (16) was varied until equation (13) would fit the experimental results. As an example, Figure 15 shows that for samples F4, $k_1=0.25$ gives the best fit for the forward part of the first shear cycle. The values of k_1 for the five shear cycles for samples F2, F3, F4, and G2 can be found in Tables 15a-15d. The actual failure envelopes can be found in Appendix D1.

Tables 15a-15d indicate that for the forward part of the first shear cycle, k_1 varies between 0.05 and 0.3 which is much smaller than the value of 1.5 initially suggested by Ladanyi and Archambault (1970). For the other four cycles, k_1 is equal to 0 except for the reverse part of the second and third shear cycles for samples F4. According to equation (16), if $k_1=0$ then $a_i=0$, and the second term in equation (13) vanishes. This means that, in most cases, starting on the second shear cycle, sliding (and not shearing) is dominant along the joint surfaces.

Figure 13. Mohr-Coulomb and Fairhurst strength criteria.

Figure 14. Peak shear stress versus normal stress for smooth joints.

Figure 15. Trial values of k_1 for samples F4 and first shear cycle.

6.2 Barton Failure Criterion

Barton (1976) proposed the following joint failure criterion

$$\tau_p = \sigma_n \tan(\phi_u + JRC \log_{10} \frac{JCS}{\sigma_n}) \quad (18)$$

where JRC is the *Joint Roughness Coefficient* and JCS is the *Joint Wall Compressive Strength* (for an unweathered joint this is equal to 4.0 ksi for gypsum cement). ϕ_u is the basic friction angle which is equal to 30 degrees for all cases.

The peak shear strength envelope was predicted for the forward and reverse parts of each shear cycle and for each joint sample using the average JRC_{pd} values determined from the dilatancy curves reported in Table 11 and the tables in Appendix C3. The peak shear strength was also predicted for the forward part of the first shear cycle only using the average values of JRC_{pr} determined from the

Table 15a
Coefficients k_1 in Ladanyi and Archambault's equation
for samples F4, forward and reverse shear motions.

Cycle #	k_1 (forward)	k_1 (reverse)
1st	0.25	0.30
2nd	0.00	0.10
3rd	0.00	0.05
4th	0.00	0.00
5th	0.00	0.00

Table 15b
Coefficients k_1 in Ladanyi and Archambault's equation
for samples F3, forward and reverse shear motions.

Cycle #	k_1 (forward)	k_1 (reverse)
1st	0.05	0.20
2nd	0.00	0.00
3rd	0.00	0.00
4th	0.00	0.00
5th	0.00	0.00

Table 15c
Coefficients k_1 in Ladanyi and Archambault's equation
for samples F2, forward and reverse shear motions.

Cycle #	k_1 (forward)	k_1 (reverse)
1st	0.10	0.05
2nd	0.00	0.00
3rd	0.00	0.00
4th	0.00	0.00
5th	-	-

Table 15d
Coefficients k_1 in Ladanyi and Archambault's equation
for samples G2, forward and reverse shear motions.

Cycle #	k_1 (forward)	k_1 (reverse)
1st	0.10	0.05
2nd	0.00	0.00
3rd	0.00	0.00
4th	0.00	0.00
5th	-	-

initial joint surface profiles. Figures 16(a) and 16(b) show two examples of comparison between predicted and measured shear strengths for forward and reverse motions for the first cycle of shear on samples F4 and F3, respectively. Comparison between predicted and observed peak shear strengths for the other shear cycles and for joint samples F2 and G2 can be found in Appendix D2. For samples F4, the predicted shear strengths are less than the measured ones. However, for samples F3, measured and predicted shear strengths are similar for forward motion, but slightly different for reverse motion.

Because of some of the discrepancies between the measured and predicted shear strengths, JRC in equation (18) was also back-calculated from the measured peak shear strengths. Its values are reported as JRC_p in Tables 16a and 16b for the forward part of the first shear cycle for samples F4 and F3 and in other tables in Appendix D3 for the other shear cycles and joint samples. In Figure 17, JRC_p has been plotted versus JRC_{pm} back-calculated from the dilatancy curves (see Table 11 and tables in Appendix C3) for all joint samples and shear cycles. This figure shows that the values of JRC_p are, in general, higher than the values of JRC_{pm} .

JRC at the beginning of the first shear cycle for each test was also determined from tilt tests following the methodology recommended by Barton and Choubey (1977). The measured values are reported as JRC_t in Tables 16a through 16d. In Figure 18, JRC_t has been plotted versus JRC_p determined from the initial joint surface profiles (see Table 10 and tables in Appendix C3). Figure 18 shows that the values of JRC calculated from the profiles are higher than those determined from the tilt tests.

The JRC values reported in Tables 11, 15a, and 15b, and the tables in Appendices C3 and D3 show that when using the model of Barton

Figure 16. Comparison between Barton's peak shear strengths and observed peak shear strengths, (a) for samples F4 first cycle, and (b) for samples F3 first cycle.

Figure 17. JRC_{pd} (back-calculated from dilatancy angle) versus JRC_{ps} (back-calculated from measured peak shear strengths). All samples.

Figure 18. JRC_{pr} (calculated from profiles) versus JRC_t (determined from tilt tests).

Table 16a

JRC values for samples F4. Forward motion for first shear cycle.

N Load (kips)	JRC _{ps} (τ_p)	JRC _{psd} (i_p)	JRC _{pr} (profile)	JRC _t (tilt test)
0.72	13.9	5.4	6.7	4.7
3.60	12.7	7.0		
7.20	14.4	6.3		
10.80	18.3	7.6		
14.40	19.4	6.5		
	(av = 15.5)	(av = 6.6)		

Table 16b

JRC values for samples F3. Forward motion for first shear cycle.

N Load (kips)	JRC _{ps} (τ_p)	JRC _{psd} (i_p)	JRC _{pr} (profile)	JRC _t (tilt test)
0.75	10.9	7.0	9.6	8.3
3.75	9.0	7.8		
7.50	18.0	9.6		
15.00	8.6	9.0		
	(av = 9.8)	(av = 8.4)		

Table 16c
JRC values for samples F2.
Forward motion for first shear cycle.

N Load (kips)	JRC _{ps} (τ_p)	JRC _{pd} (i_p)	JRC _{pr} (profile)	JRC _t (tilt test)
0.60	7.9	7.0	15.3	7.1
2.95	11.1	7.8		
5.90	9.8	6.8		
11.80	10.9 (av = 9.9)	5.7 (av = 6.8)		

Table 16d
JRC values for samples G2.
Forward motion for first shear cycle.

N Load (kips)	JRC _{ps} (τ_p)	JRC _{pd} (i_p)	JRC _{pr} (profile)	JRC _t (tilt test)
1.28	11.3	5.7	24.4	5.5
6.40	11.9	5.2		
12.80	16.3	6.8		
25.60	19.1 (av = 14.6)	1.6 (av = 4.8)		

and Choubey (1977), significantly different values of the Joint Roughness Coefficient JRC can be obtained for a same rock joint with different methods.

7.0 CORRELATION BETWEEN JRC AND FRACTAL DIMENSION

Another way of quantifying joint surface roughness is by using the self affine fractal dimension (FD). Figure 19 shows how FD varies with JRC_{pr} for samples F2, F3, F4 and G2. Both quantities are average values determined on two initial joint surface profiles X2 and X3 (see Wibowo et al., 1993a). Using a linear regression analysis, FD is related to JRC_{pr} as follows

$$FD = 0.005JRC_{pr} + 1.081 \quad (19)$$

The variation of FD with JRC_{pr} was also investigated for each joint sample using the profiles X2 and X3 at the end of the fifth cycle in each direct shear test. This is shown in Figure 20 for joint samples F4 and in Appendix E for joint samples F2, F3, and G2.

The plots in Figures 19 and 20 and those in Appendix E show that JRC_{pr} varies over a much wider range than the fractal dimension. Thus, a slight change in fractal dimension results in a much larger change in JRC_{pr} .

8.0 A MATHEMATICAL MODEL FOR JOINT BEHAVIOR

Based on the test results presented in the report by Wibowo et al. (1993a) and the data analysis presented above, a non-linear joint mathematical model was developed to predict joint behavior under various boundary conditions. The model is an extension of that proposed by Saeb (1989) and Amadei and Saeb (1990) and incorporates the different constitutive models presented in this report.

Figure 19. Fractal dimension FD versus JRC_{pr} calculated from pre-test profiles.

Figure 20. Fractal dimension FD versus JRC_{pr} determined on profiles after shear on samples F4.

8.1 Assumptions

8.1.1 Joint Normal Behavior

The hyperbolic model of Bandis et al. (1983) shown as curve 1 in Figure 21 is used to describe joint behavior under increasing normal load (stress). The normal stress σ_n and joint normal displacement, v , are related as follows

$$\sigma_n = \frac{vk_{ni}V_m}{V_m + v} \quad (20)$$

or

$$v = \frac{\sigma_n V_m}{k_{ni} V_m - \sigma_n} \quad (21)$$

In equations (20) and (21), compressive stresses and joint opening are assumed to be positive, V_m is the maximum joint closure and k_{ni} is the initial normal stiffness of the joint which is negative for the sign convention adopted here. At any other normal stress level, the joint tangent normal stiffness is equal to

$$k_{nn} = \frac{\partial \sigma_n}{\partial v} = k_{ni} \left(\frac{k_{ni} V_m - \sigma_n}{k_{ni} V_m} \right)^2 \quad (22)$$

Also, the joint is assumed to have zero tensile strength.

8.1.2 Joint Shear and Dilatant Behavior

For the geometry of Figures 3(a), the shear stress and shear displacement are related as follows

Figure 21. Normal stress versus normal displacement curves for zero shear displacement (curve 1) and for shear displacement $u < u_r$ (curve 2).

$$\tau = \frac{u}{\frac{u_p}{\tau_p} + B(u - u_p)} \quad \text{for } u < u_p \quad (23)$$

$$\tau = \left(\frac{\tau_p - \tau_r}{u_p - u_r} \right) u + \left(\frac{\tau_r u_p - \tau_p u_r}{u_p - u_r} \right) \quad \text{for } u_p \leq u \leq u_r \quad (24)$$

$$\tau = \tau_r \quad \text{for } u > u_r \quad (25)$$

The variation of u_p with the normal stress is defined by equation (1). The residual displacement is assumed to be independent of the normal stress. The variation of peak shear strength, τ_p , with the normal stress is defined by the modified Ladanyi and Archambault's failure criterion [equation (13)] or Barton's failure criterion [equation (18)]. The variation of the ratio between the residual and peak shear strengths with the normal stress is defined by equations (3) and (4). The coefficient B in equation (23) is the positive root of the following second-degree polynomial

$$\frac{3}{16} B^2 \tau_p^2 - B(\tau_p - u_p k_s) + \left(1 - \frac{u_p}{\tau_p} k_s\right) = 0 \quad (26)$$

The variation of k_s with the normal stress is defined by equation (2). Note that B in equation (26) depends on the normal stress.

Using an approach similar to that of Goodman and St. John (1977), the dilatancy rate $\tan(i) = \partial v / \partial u$ is assumed to be independent of the shear displacement for $0 \leq u \leq u_p$ and to vanish for $u > u_p$. It depends on the normal stress only according to equations (5), (6), or (12).

8.2 Formulation

Consider a rock joint undergoing first normal compression followed

by shear. Combining equations (5) or (6) and equation (21), the total normal displacement of the joint is then equal to

$$v = u(1 - \frac{\sigma_n}{\sigma_T})^{k_2} \tan(i_{po}) + \frac{\sigma_n V_m}{k_{ni} V_m - \sigma_n} \quad (27)$$

or

$$v = u \tan(JRC \log_{10} \frac{JCS}{\sigma_n}) + \frac{\sigma_n V_m}{k_{ni} V_m - \sigma_n} \quad (28)$$

If equation (12) is used instead of (5), then k_2 and $\tan(i_{po})$ in equation (27) must be replaced by k_3 and $\tan(i_{svo})$, respectively.

Equations (27) and (28) are valid as long as $u \leq u_r$. When $u > u_r$ and $\sigma_n < \sigma_T$ or $\sigma_n < JCS$, the joint ceases to dilate and v is equal to its value obtained by substituting $u = u_r$ in equations (27) or (28). When $\sigma_n \geq \sigma_T$ or $\sigma_n \geq JCS$, the first term in equation (27) or (28) vanishes and no dilation is possible during shearing.

If the first term on the right-hand side of equations (27) and (28) is called, w , then after rearrangement, those equations take the more general form

$$\sigma_n = \frac{(v-w) k_{ni} V_m}{V_m + (v-w)} \quad (29)$$

Comparing equations (29) and (20), it appears that $v-w$ has now been substituted for v . In other words, equation (29) models the normal stress-displacement behavior of the joint after having been sheared by an amount equal to u . Equation (29) has been plotted as curve 2 in Figure 21 for a value of u less than or equal to u_r . Curves 1 and 2 are a distance w apart as long as $\sigma_n < \sigma_T$ or $\sigma_n < JCS$ and coincide

when $\sigma_n \geq \sigma_T$ or $\sigma_n \geq JCS$. Figure 21 shows that as more shear develops, the joint becomes more deformable in the normal direction.

An incremental formulation can be obtained by differentiating equations (27) and (28) which, after rearrangement, can be written in a more compact form as follows

$$d\sigma_n = k_{nn}dv + k_{nt}du \quad (30)$$

where $k_{nn} = \partial\sigma_n/\partial v$ and $k_{nt} = \partial\sigma_n/\partial u$ are two normal stiffness coefficients equal to

$$k_{nn} = \frac{1}{-\frac{uk_2}{\sigma_T} \left(1 - \frac{\sigma_n}{\sigma_T}\right)^{k_2-1} \tan(i_{po}) + \frac{V_m^2 k_{ni}}{(k_{ni} V_m - \sigma_n)^2}} \quad (31)$$

and

$$k_{nt} = \frac{-(1 - \frac{\sigma_n}{\sigma_T})^{k_2} \tan(i_{po})}{-\frac{uk_2}{\sigma_T} \left(1 - \frac{\sigma_n}{\sigma_T}\right)^{k_2-1} \tan(i_{po}) + \frac{V_m^2 k_{ni}}{(k_{ni} V_m - \sigma_n)^2}} \quad (32)$$

when using the modified Ladanyi and Archambault's criterion. If Barton's criterion is used instead, equations (31) and (32) are replaced by

$$k_{nn} = \frac{1}{-\frac{u}{\sigma_n} \frac{JRC}{\ln(10)} [1 + \tan^2(JRC \log_{10} \frac{JCS}{\sigma_n})] + \frac{V_m^2 \cdot k_{ni}}{(k_{ni} V_m - \sigma_n)^2}} \quad (33)$$

and

$$k_{nt} = \frac{-\tan(JRC \log_{10} \frac{JCS}{\sigma_n})}{-\frac{u}{\sigma_n} \frac{JRC}{\ln(10)} [1 + \tan^2(JRC \log_{10} \frac{JCS}{\sigma_n})] + \frac{V_m^2 k_{ni}}{(k_{ni} V_m - \sigma_n)^2}} \quad (34)$$

Note that equations (31) and (33) provide an analytical expression for the joint tangent normal stiffness (slope of curve 2 in Figure 21) when the joint has been sheared by an amount equal to u . Both equations reduce to equation (22) when $u=0$. Also equations (31) - (34) are valid as long as $u \leq u_r$ and $\sigma_n < \sigma_T$ or $\sigma_n < JCS$. When $u > u_r$ or $\sigma_n \geq \sigma_T$ or $\sigma_n \geq JCS$, k_m vanishes.

Because the shear stress τ depends on u and v , increments of shear stress are related to increments of normal and shear displacements, as follows

$$d\tau = k_{tn}dv + k_{tt}du \quad (35)$$

where $k_m = \partial\tau/\partial v$ and $k_u = \partial\tau/\partial u$ are two shear stiffness coefficients that are equal to

(i) for $u < u_p$

$$k_{tn} = -\frac{u}{Den} [k_{nn} \frac{d}{d\sigma_n} (\frac{u_p}{\tau_p}) + k_{nn}(u-u_p) \frac{dB}{d\sigma_n}] \quad (36)$$

$$k_{tt} = \frac{1}{Den} [\frac{u_p}{\tau_p} - Bu_p - uk_{nt} \frac{d}{d\sigma_n} (\frac{u_p}{\tau_p}) - uk_{nt}(u-u_p) \frac{dB}{d\sigma_n}] \quad (37)$$

with $Den = ((u_p/\tau_p) + B(u-u_p))^2$.

(ii) for $u_p \leq u \leq u_r$

$$k_{tt} = k_{ss} + k_{nt} \left[(u - u_p) \frac{dk_{ss}}{d\sigma_n} + \frac{d\tau_p}{d\sigma_n} - k_{ss} \frac{du_p}{d\sigma_n} \right] \quad (38)$$

$$k_{tn} = k_{nn} \left[(u - u_p) \frac{dk_{ss}}{d\sigma_n} + \frac{d\tau_p}{d\sigma_n} - k_{ss} \frac{du_p}{d\sigma_n} \right] \quad (39)$$

with $k_{ss} = (\tau_p - \tau_r) / (u_p - u_r)$.

(iii) for $u > u_r$

$$k_{tt} = k_{nt} \left[(1 - B_o) \frac{\tau_p}{\sigma_T} + (B_o + (1 - B_o) \frac{\sigma_n}{\sigma_T}) \frac{d\tau_p}{d\sigma_n} \right] = 0 \quad (40)$$

$$k_{tn} = k_{nn} \left[(1 - B_o) \frac{\tau_p}{\sigma_T} + (B_o + (1 - B_o) \frac{\sigma_n}{\sigma_T}) \frac{d\tau_p}{d\sigma_n} \right] \quad (41)$$

When $\sigma_n \geq \sigma_T$ or $\sigma_n \geq \text{JCS}$, $k_u = \tau_p / u_p$ when $u < u_p$ and k_u vanishes when $u \geq u_p$.

In equations (36)-(41), the derivative $du_p/d\sigma_n$ is equal to the coefficient b in equation (1). The expression of the derivative $d\tau_p/d\sigma_n$ depends on the selected peak shear strength criterion. For instance, for the modified Ladanyi and Archambault's criterion [equation (13)] with a Mohr Coulomb's criterion for the intact rock shear strength (equation (14)), $d\tau_p/d\sigma_n$ is equal to

$$\begin{aligned}
\frac{d\tau_p}{d\sigma_n} = & (1-a_s) \tan(\phi_u+i) - \frac{\sigma_n}{\sigma_T} \frac{(1-a_s) k_2}{\cos^2(\phi_u+i)} \\
& \frac{1}{1 + (1 - \frac{\sigma_n}{\sigma_T})^{2k_2} \tan^2(i_{po})} \tan(i_{po}) (1 - \frac{\sigma_n}{\sigma_T})^{k_2-1} \\
& - \frac{\sigma_n}{\sigma_T} k_1 \tan(\phi_u+i) (1 - \frac{\sigma_n}{\sigma_T})^{k_1-1} + \frac{s_r}{\sigma_T} k_1 (1 - \frac{\sigma_n}{\sigma_T})^{k_1-1} + a_s \tan\phi_o
\end{aligned} \tag{42}$$

For Barton's criterion (equation (18)), $d\tau_p/d\sigma_n$ is now equal to

$$\frac{d\tau_p}{d\sigma_n} = \tan(\phi_u + JRC \log_{10} \frac{JCS}{\sigma_n}) - \frac{JRC}{\ln(10)} [1 + \tan^2(\phi_u + JRC \log_{10} \frac{JCS}{\sigma_n})] \tag{43}$$

Combining equations (29) and (35), an incremental formulation can be written relating the increments of normal and shear stresses to the increments of normal and shear displacements.

8.3 Joint Response Under Applied Stiffness Boundary Conditions

As a direct application of the formulation in section 8.2, the shear response of a rock joint under applied stiffness boundary conditions can be predicted. This can be done by writing that $d\sigma_n$ and dv must be related as follows

$$d\sigma_n = K dv \tag{44}$$

where K is the applied stiffness that can be constant or vary with u or σ_n . Substituting equation (44) into (29), gives two relationships between the increments of normal stress and normal displacement and the increment of shear displacement, e.g.

$$d\sigma_n = \frac{Kk_{nt}}{K-k_{nn}} du \quad (45)$$

and

$$dv = \frac{k_{nt}}{K-k_{nn}} du \quad (46)$$

Similarly, using equation (35), the increments of shear stress are related to the increments of shear displacement as follows

$$d\tau = \left[\frac{k_{tn}k_{nt}}{K-k_{nn}} + k_{tt} \right] du \quad (47)$$

As a special case, consider the case when the applied stiffness K is equal to zero, corresponding to a constant normal stress condition ($d\sigma_n = 0$). Then, equation (46) reduces to $dv = -(k_{nn}/k_{nn})du$. Using equations (36)-(41) and equation (47), it follows that $d\tau = [u_p/\tau_p - Bu_p] / [(u_p/\tau_p) + B(u - u_p)]^2 du$ when $u < u_p$, $d\tau = k_{nn}du$ when $u_p < u < u_r$, and $d\tau = 0$ when $u > u_r$. If K is now equal to infinity, corresponding to a constant normal displacement boundary condition ($dv=0$), it follows from equation (45) that $d\sigma_n = k_{nn}du$ and $d\tau = k_{tt}du$.

In general, knowing the initial stress across a dilatant joint and its shear displacement and dilatancy curves at different normal stress levels, equations (45)-(47) can be used to predict the joint shear response under various boundary conditions.

8.4 Illustrative Examples

As illustrative examples, it is proposed to predict the shear response of samples F4 under constant normal stiffness from the results of the constant normal load direct shear tests for the forward part of the first shear cycle. In order to use the present

model, some of the experimental data reported by Wibowo et al. (1993a) and analyzed in this report were selected, e.g:

- joint maximum closure $V_m = 0.029$ in.,
- joint initial stiffness $k_{ni} = -50000$ psi/in.,
- joint basic friction angle $\phi_u = 30$ degrees,
- ratio of residual to peak shear strengths $B_o = 0.48$,
- transitional stress $\sigma_T = 1860$ psi,
- $a = 0.025$ in. in equation (1),
- $b = 7.9 \times 10^{-5}$ in./psi in equation (1),
- $c = 75.67 \times 10^3$ psi/in. in equation (2),
- $d = 16.69$ in⁻¹ in equation (2),
- residual displacement of 0.5 in.

Further, if the modified Ladanyi and Archambault's criterion is used for the peak shear strength and dilatancy, the following data must also be input:

- $k_1 = 0.25$ in equation (16),
- $k_2 = 0.81$ in equation (17) or $k_3 = 0.58$ in equation (12),
- initial dilatancy rate $\tan(i_{po}) = 0.18$ or $\tan(i_{svo}) = 0.15$,
- intact rock cohesion $s_o = 1110$ psi,
- intact rock friction angle $\phi_o = 31.5$ degrees.

If on the other hand, Barton's criterion is used, the following data must be input:

- joint roughness coefficient JRC = 15.5 (back calculated from peak shear equation), or JRC = 6.6 (back calculated from dilatancy equation),
- joint wall compressive strength JCS = 4000 psi.

Figures 22a, 22b and 22c show respectively, the predicted and observed shear load versus shear displacement curves, the dilatancy curves and the shear load versus normal load paths for the F4 samples tested under an initial normal load of 3.6 kips (initial

nominal normal stress of 200 psi) with constant applied stiffness, K , equal to 0, 1, 3 and 10 ksi/in, $k_3 = 0.58$ and $\tan(i_{avo}) = 0.15$. Figures 23(a), 23(b), and 23(c) show similar predicted and observed response curves for the samples tested under an initial normal load of 7.2 kips (initial nominal normal stress of 400 psi). In Figures 22 and 23, the modified Ladanyi and Archambault's criterion was used in the predictions. These figures show that the predicted curves agree relatively well with the experimental observations. In particular, the mathematical model is able to predict postpeak softening at low applied stiffnesses and hardening as the applied stiffness increases. Comparison between observed and predicted response curves for samples F3, F2, and G2 can be found in Appendix F1.

Figures 24(a), 24(b), and 24(c) show, respectively, the predicted and observed shear load versus shear displacement curves, the dilatancy curves and the shear load versus normal load paths for the F4 samples tested under an initial normal load of 3.6 kips (initial nominal normal stress of 200 psi) with constant applied stiffness equal to 0, 1, 3, and 10 ksi/in, and $JRC = 15.5$. Figures 25(a), 25(b), and 25(c) show similar predicted and observed response curves for the samples tested under the same conditions, except that JRC is now equal to 6.6. In both Figures 24 and 25, Barton's criterion was used in the predictions.

Figures 24(a)-(c) indicate that using Barton's criterion with $JRC = 15.5$ (back calculated from peak shear equation) overestimates joint shear strength and dilatancy. On the other hand, for $JRC = 6.6$ (back calculated from dilatancy equation), Figures 25(a)-(c) show that the predicted joint shear strengths are lower than the actual test results, but the predicted joint dilatancy agrees quite well with the experimental observations. Figures 24 and 25 show that the mathematical predictions using Barton's model are very sensitive to the input value of JRC . Comparison between observed and predicted response curves for samples F3, F2, and G2 can be found in Appendix F2.

(a)

(b)

Figure 22. Predicted and observed shear load vs. shear displacement curves, dilatancy curves and shear load vs. normal load paths in (a)-(c), respectively, for $K = 0, 1, 3$, and 10 ksi/in, $k_s = 0.58$ and $\tan(i_{av0}) = 0.15$. Samples F4, first shear cycle forward motion with initial normal stress = 200 psi. The mathematical model is based on Ladanyi and Archambault's criterion.

Figure 22. (Continued) (c)

Figure 23. Predicted and observed shear load vs. shear displacement curves, dilatancy curves and shear load vs. normal load paths in (a)-(c), respectively, for $K = 0, 1, 3$, and 10 ksi/in, $k_s = 0.58$ and $\tan(i_{avo}) = 0.15$. Samples F4, first shear cycle forward motion with initial normal stress = 400 psi. The mathematical model is based on Ladanyi and Archambault's criterion.

(b)

(c)

Figure 23. (Continued)

Figure 24. Predicted and observed shear load vs. shear displacement curves, dilatancy curves and shear load vs. normal load paths in (a)-(c), respectively, for $K = 0, 1, 3$, and 10 ksi/in and $\text{JRC} = 15.5$. Samples F4, first shear cycle forward motion with initial normal stress = 200 psi . The mathematical model is based on Barton's criterion.

Figure 24. (Continued)

(c)

(a)

Figure 25. Predicted and observed shear load vs. shear displacement curves, dilatancy curves and shear load vs. normal load paths in (a)-(c), respectively, for $K = 0, 1, 3$, and 10 ksi/in and JRC = 6.6. Samples F4, first shear cycle forward motion with initial normal stress = 200 psi. The mathematical model is based on Barton's criterion.

Figure 25. (Continued).

9.0 CONCLUSIONS

In this report, several existing constitutive models were used to describe the constant normal load cyclic direct shear test results obtained by Wibowo et al. (1993a). The analysis of the test results was done for the forward and reverse part of each shear cycle.

For the forward part of the first shear cycle, the shear load vs. shear displacement response curves show an increase in peak shear displacement and shear stiffness with the applied normal load (stress). Thus, the constant displacement and stiffness models initially proposed by Goodman (1976) are inadequate to describe the observed behavior. Note that in this report, and contrary to existing models in the literature, the prepeak region of the shear load versus shear displacement curves was assumed to be nonlinear and the shear stiffness was defined for data ranging from 25 to 75% of the peak shear load. The increase in peak shear displacement and shear stiffness with normal load was observed for the forward part of the first shear cycle only. For the other four cycles, the peak displacement was found to be poorly defined. It was difficult to separate the peak and residual displacements because of accumulated joint surface damage.

The model of Goodman (1976) predicting a linear increase of the ratio between the residual and peak shear strengths with normal load (or stress) was found to describe the experimental observations relatively well for forward and shear motions and all shear cycles. As the number of cycles increases and joint surface damage accumulates, the peak shear strength rapidly approaches its residual value.

Joint dilatancy decreases with increasing normal load (stress). For a given normal load, it decreases rapidly as the number of cycles increases. The models of Ladanyi and Archambault (1970), Schneider (1976), Barton and Choubey (1977), and Jing (1990) were found to fit the observed variation of joint dilatancy with normal load (stress). The model of Schneider was found to fit the experimental

results the best. The second best fit was found using Barton and Choubey's model.

The modified Ladanyi and Archambault's failure criterion proposed by Saeb (1990) and that of Barton (1976) were used to model the variation of peak shear strength with normal load (stress) for the forward and reverse parts of each shear cycle. The modified Ladanyi and Archambault's criterion fits the experimental data quite well. This criterion implies that both shear and sliding occurs simultaneously along joint surfaces during shear [(Ladanyi and Archambault (1970))]. It was found that starting with the second shear cycle, sliding is dominant along the joint surfaces.

Barton's failure criterion requires knowledge of the joint roughness coefficient JRC. Several methods were explored in this report to determine JRC, e.g., (1) from the tangent dilatancy rate at the peak shear stress, (2) from initial joint surface profiles, (3) from measured peak shear strengths, and (4) from tilt tests. It was found that those methods lead to different values of JRC. A value of JRC determined with one of those methods may give a good prediction of dilatancy, but a poor prediction of shear strength and vice versa.

The JRC values determined from initial joint surface profiles were found to be linearly related to the self affine fractal dimension of those profiles. The JRC was found to vary over a much wider range than the fractal dimension. Thus, a slight change in fractal dimension may result in a much larger change in JRC.

A mathematical model for joint shear response under various boundary conditions was proposed. In this model, joint normal behavior is represented by the hyperbolic formulation of Bandis et al. (1983). Joint shear behavior is represented by the modified Ladanyi and Archambault's criterion or Barton's criterion and joint dilatant behavior is represented using the model of Goodman and St. John (1977). Comparison between predicted joint response under constant normal stiffness and test results revealed that Ladanyi

and Archambault's criterion can model relatively well the gain in shear strength of rock joints during shear and their dilatant response under constant applied normal stiffness. On the other hand, the mathematical predictions using Barton's model were found to be very sensitive to the input value of JRC and not as good as the predictions with Ladanyi and Archambault's criterion.

The mathematical model assumes that, regardless of the path followed by a joint, its final shear strength is controlled by the same failure envelope. Also, the model is limited to monotonic loading. The effect of loading and unloading and cyclic loading could however be incorporated in a future version.

10. REFERENCES

- Amadei, B. and Saeb, S. 1990. Constitutive Model of Rock Joints. Proc. Int. Conf. on Rock Joints, pp. 581-594. Loen, Norway. (NNA.920610.0033)
- Archambault, G., Fortin, M., Gill, D. E., Aubertin, M., and Ladanyi, B. 1990. Experimental Investigation for an Algorithm Simulating the Effect of Variable Normal Stiffness on Discontinuities Shear Strength. Proc. Int. Conf. on Rock Joints, pp. 141-148. Loen, Norway. (NNA.920610.0034)
- Bandis, S. C., Lumsden, A. C., and Barton, N. R. 1983. Fundamentals of Rock Joint Deformation. Int. J. Rock Mech. Min. Sci & Geomech. Abstr., Vol. 20, No. 6 pp. 249-268. (NNA.890928.0106)
- Bandis, S. C. 1990. Mechanical Properties of Rock Joints. Proc. Int. Conf. on Rock Joints, pp. 125-140. Loen, Norway. (NNA.920610.0035)
- Barton, N. 1976. Rock Mechanics Review, The Shear Strength of Rock and Rock Joints. Int. J. Rock Mech. Min. Sci & Geomech. Abstr., Vol. 13 pp. 255-279. (NNA.920427.0046)
- Barton, N. and Choubey, V. 1977. The Shear Strength of Rock Joints in Theory and Practice. Rock Mechanics, 10, pp. 1-54. (NNA.890713.0161)
- Barton, N. and Bandis, S. C. 1990. Review of Predictive Capabilities of JRC-JCS Model in Engineering Practice. Proc. Int. Conf. on Rock Joints, pp. 603-610. Loen, Norway. (NNA.931221.0054)
- Benmokrane, B., Bouraoui, M., and Mouchaorab, K. S. 1991. Shearing Behavior of Rock Discontinuities Under Constant or Variable Normal Stiffness Conditions. Addendum to Proc. of the 32nd U.S. Sym. in Rock Mech. Norman, Oklahoma. (NNA.930914.0072)
- Fairhurst, C., 1964. On the Validity of Brazilian Test for Brittle Materials. Int. J. Rock Mech. Min. Sci & Geomech. Abstr., Vol. 1 pp. 535-546. (NNA.931012.0018)
- Goodman, R.E., 1976. Methods of Geological Engineering in Discontinuous Rocks. West Publ. Company. 472pp. (NNA.900403.0002)
- Goodman, R. E., and St. John, C., 1977. Finite Element Analysis for Discontinuous Rocks. Numerical Methods in Geotechnical Engineering (Desai, C. S., and Christian, J. T. editors). McGraw-Hill, pp. 148-175. (NNA.931129.0080)
- Goodman, R. E. and Boyle, W. 1985. Non-linear Analysis for Calculating the Support of a Rock Block With Dilatant Joint Faces. Presented at the 34th Geomechanics Colloquy, Salzburg, Austria. (NNA.930802.0060)
- Hutson, R. W. 1987. Preparation of Duplicate Rock Joints and Their Changing Dilatancy Under Cyclic Shear. Ph.D. dissertation, Northwestern University. (NNA.920427.0048)

- Jing, L., 1990. Numerical Modelling of Jointed Rock Masses by Distinct Element Method for Two, and Three Dimensional Problems. Ph.D. Thesis, Division of Rock Mechanics, Lulea University of Technology, Lulea, Sweden. (NNA.940426.0001)
- Jing, L., Nordlund, E., and Stephanson, O. 1992. An Experimental Study on the Anisotropy and Stress-Dependency of the Strength and Deformability of Rock Joints. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 29, No. 6, pp. 535-542. (NNA.940502.0149)
- Ladanyi, B., and Archambault, G. 1970. Simulation of Shear Behavior of a Jointed Rock Mass, Proc. 11th Symp. on Rock Mech. Berkeley, California, pp. 105-125. (NNA.931129.0081)
- Leichnitz, W. 1985. Mechanical Properties of Rock Joints. Int. J. Rock Mech. Min. Sci. Vol. 22, pp. 313-321. (NNA.900308.0332)
- Obert, L., Brady, B. T., and Schmechel, F. H. 1976. The Effect of Normal Stiffness on the Shear Resistance of Rock. Rock Mechanics 8, pp. 57-72. (NNA.900403.0405)
- Ohnishi, Y. and Dharmaratne, P. G. R. 1990. Shear Behavior of Physical Models of Rock Joints Under Constant Normal Stiffness Conditions. Proc. Int. Conf. on Rock Joints, pp. 267-273. Loen, Norway. (NNA.920610.0036)
- Saeb, S. 1989. Effect of Boundary Conditions on the Behavior of a Dilatant Rock joint. Ph.D. dissertation, Univ. of Colorado at Boulder. (NNA.900515.0007)
- Saeb, S. 1990. A Variance on the Ladanyi and Archambault's Shear Strength Criterion. Proc. Int. Conf. on Rock Joints, pp. 701-705. Loen, Norway. (NNA.940426.0002)
- Schneider, H. J., 1976. The Friction and Deformation Behavior of Rock Joints. Rock Mech. 8, Springer-Verlag, pp.169-185. (NNA.931102.0069)
- Skinas, C. A., Bandis, S. C., and Demiris, C.A. 1990. Experimental Investigation and Modeling of Rock Joint Behavior under Constant Stiffness. Proc. Int. Conf. on Rock Joints, pp. 301-308. Loen, Norway. (NNA.920610.0037)
- Tse, R, and Cruden, D. M., 1979. Estimating Joint Roughness Coefficients. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 16, pp. 303-307. (NNA.900918.0023)
- Wibowo, J. T., Amadei, B., Sture, S., Robertson, A. B., Price, R. H. 1993a. Effect of Boundary Condition on the Strength and Deformability of Replicas of Natural Fractures in Welded Tuff: Data Report. SAND 92-1853. (NNA.930907.0001)
- Wibowo, J. T., Amadei, B., Sture, S., Robertson, A. B., Price, R. H. 1993b. Effect of Boundary Condition on the Strength and Deformability of Replicas of Natural Fractures in Welded Tuff: Comparison Between Predicted and Observed Shear Behavior. SAND 92-

2247. (NNA.930709.0002)

Yu, X., and Vayssade, B., 1991. Technical Note: Joint Profiles and Their Roughness Parameter. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 28, pp. 333-336. (NNA.931012.0019)

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U PEAK VS. NORMAL STRESS SAMPLES F4 REVERSE

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SAMPLES G2 REVERSE

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SHEAR STIFFNESS SAMPLES F3

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RES/PEAK SHEAR STRESS VS. NORMAL STRESS SAMPLES F2 REVERSE

RES/PEAK SHEAR STRESS VS. NORMAL STRESS SAMPLES G2 FORWARD

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Secant, tangent, and average rates of dilatancy for samples F4.
Forward and reverse motions of the first cycle.

Normal Stress (ksi)	$\tan i_s$	$\tan i_p$	$\tan i_{av}$
<u>Forward</u>			
0.04	0.12	0.19	0.14
0.20	0.16	0.16	0.14
0.40	0.12	0.11	0.11
0.60	0.09	0.11	0.10
0.80	0.09	0.08	0.08
<u>Reverse</u>			
0.04	0.16	0.19	0.14
0.20	0.10	0.15	0.11
0.40	0.06	0.08	0.08
0.60	0.07	0.07	0.09
0.80	0.06	0.06	0.07

Secant, tangent, and average rates of dilatancy for samples F3.
Forward and reverse motions of the first cycle.

Normal Stress (ksi)	$\tan i_s$	$\tan i_p$	$\tan i_{av}$
<u>Forward</u>			
0.04	0.38	0.25	0.18
0.20	0.10	0.18	0.18
0.40	0.15	0.17	0.16
0.80	0.10	0.11	0.10
<u>Reverse</u>			
0.04	0.13	0.33	0.26
0.20	0.09	0.22	0.19
0.40	0.09	0.14	0.14
0.80	0.07	0.10	0.09

Secant, tangent, and average rates of dilatancy for samples F2.
Forward and reverse motions of the first cycle.

Normal Stress (ksi)	$\tan i_s$	$\tan i_p$	$\tan i_{av}$
<u>Forward</u>			
0.04	0.16	0.25	0.17
0.20	0.12	0.18	0.14
0.40	0.06	0.12	0.11
0.80	0.10	0.07	0.10
<u>Reverse</u>			
0.04	0.07	0.16	0.16
0.20	0.02	0.04	0.04
0.40	0.03	0.02	0.01
0.80	0.02	0.01	-

Secant, tangent, and average rates of dilatancy for samples G2.
Forward and reverse motions of the first cycle.

Normal Stress (ksi)	$\tan i_s$	$\tan i_p$	$\tan i_{av}$
<u>Forward</u>			
0.04	0.10	0.20	0.21
0.20	0.08	0.12	0.10
0.40	0.12	0.12	0.11
0.80	0.01	0.02	-
<u>Reverse</u>			
0.04	0.04	0.07	0.06
0.20	0.03	0.04	0.04
0.40	-0.01	0.01	0.00
0.80	-	-	-

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DILATANCY VS. NORMAL STRESS

SAMPLES F4

DILATANCY VS. NORMAL STRESS

SAMPLES F3

DILATANCY VS. NORMAL STRESS

SAMPLES F2

DILATANCY VS. NORMAL STRESS

SAMPLES G2

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Comparison between average JRC_{pdd} back-calculated from the dilatancy curves and average JRC_{pr} determined from roughness profiles on samples F4.

	Cycle Motion	JRC_{pdd} (back-calculated from dilatancy curves)	JRC_{pr} (from profiles)
Forward Motion	1st	6.6	6.7
	2nd	4.6	
	3rd	4.6	
	4th	4.6	
	5th	4.6	
Reverse Motion	1st	5.4	1.5
	2nd	4.0	
	3rd	4.5	
	4th	4.7	
	5th	4.6	

Comparison between average JRC_{pkl} back-calculated from the dilatancy curves and average JRC_{pr} determined from roughness profiles on samples F3.

	Cycle Motion	JRC_{pkl} (back-calculated from dilatancy curves)	JRC_{pr} (from profiles)
Forward Motion	1st	8.4	10.0
	2nd	5.9	
	3rd	5.2	
	4th	5.0	
	5th	5.0	
Reverse Motion	1st	8.7	
	2nd	6.4	
	3rd	5.7	
	4th	5.7	
	5th	5.5	

Comparison between average JRC_{pdd} back-calculated from the dilatancy curves and average JRC_{pr} determined from roughness profiles on samples F2.

	Cycle Motion	JRC_{pdd} (back-calculated from dilatancy curves)	JRC_{pr} (from profiles)
Forward Motion	1st	6.8	15.3
	2nd	3.6	
	3rd	3.9	
	4th	4.1	
	5th	-	
Reverse Motion	1st	2.5	
	2nd	1.5	
	3rd	1.3	
	4th	1.3	
	5th	-	

Comparison between average JRC_{pd} back-calculated from the dilatancy curves and average JRC_{pr} determined from roughness profiles on samples G2.

	Cycle Motion	JRC_{pd} (back-calculated from dilatancy curves)	JRC_{pr} (from profiles)
Forward Motion	1st	4.8	24.3
	2nd	3.1	
	3rd	-	
	4th	-	
	5th	-	
Reverse Motion	1st	1.4	
	2nd	-	
	3rd	-	
	4th	-	
	5th	-	

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DILATANCY COMPARISON SAMPLES F41R

DILATANCY COMPARISON

SAMPLES F42F

DILATANCY COMPARISON

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DILATANCY COMPARISON

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AVERAGE DILATANCY SAMPLES F42R

AVERAGE DILATANCY SAMPLES F43F

AVERAGE DILATANCY SAMPLES F43R

AVERAGE DILATANCY SAMPLES F44F

AVERAGE DILATANCY SAMPLES F44R

AVERAGE DILATANCY SAMPLES F45F

AVERAGE DILATANCY SAMPLES F45R

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AVERAGE DILATANCY SAMPLES F32F

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AVERAGE DILATANCY SAMPLES F23F

AVERAGE DILATANCY SAMPLES F23R

AVERAGE DILATANCY SAMPLES F24F

AVERAGE DILATANCY SAMPLES F24R

AVERAGE DILATANCY SAMPLES G21F

(a)

AVERAGE DILATANCY SAMPLES G21R

(b)

AVERAGE DILATANCY

SAMPLES G22F

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PEAK SHEAR STRESS F41F

TRIAL VALUES OF K1

PEAK SHEAR STRESS F41R

TRIAL VALUES OF K1

PEAK SHEAR STRESS F42F

TRIAL VALUES OF K1

PEAK SHEAR STRESS F42R

TRIAL VALUES OF K1

PEAK SHEAR STRESS F43F

TRIAL VALUES OF K1

PEAK SHEAR STRESS F43R

TRIAL VALUES OF K1 PEAK SHEAR STRESS F44F

TRIAL VALUES OF K1 PEAK SHEAR STRESS F44R

TRIAL VALUES OF K1 PEAK SHEAR STRESS F45F

TRIAL VALUES OF K1 PEAK SHEAR STRESS F45R

TRIAL VALUES OF K1 PEAK SHEAR STRESS F31F

TRIAL VALUES OF K1 PEAK SHEAR STRESS F31R

TRIAL VALUES OF K1 PEAK SHEAR STRESS F32F

TRIAL VALUES OF K1 PEAK SHEAR STRESS F32R

TRIAL VALUES OF K1 PEAK SHEAR STRESS F33F

TRIAL VALUES OF K1 PEAK SHEAR STRESS F33R

TRIAL VALUES OF K1 PEAK SHEAR STRESS F34F

TRIAL VALUES OF K1 PEAK SHEAR STRESS F44R

TRIAL VALUES OF K1

PEAK SHEAR STRESS F35F

TRIAL VALUES OF K1

PEAK SHEAR STRESS F35R

TRIAL VALUES OF K1 PEAK SHEAR STRESS F21F

TRIAL VALUES OF K1 PEAK SHEAR STRESS F21R

TRIAL VALUES OF K1 PEAK SHEAR STRESS F22F

TRIAL VALUES OF K1 PEAK SHEAR STRESS F22R

TRIAL VALUE OF K1

PEAK SHEAR STRESS G21F

TRIAL VALUES OF K1

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BARTON'S PEAK SHEAR STRENGTH

SAMPLES F4 1ST CYCLE

BARTON'S PEAK SHEAR STRENGTH

SAMPLES F3 1ST CYCLE

BARTON'S PEAK SHEAR STRENGTH

SAMPLES F2 1ST CYCLE

BARTON'S PEAK SHEAR STRENGTH

SAMPLES G2 1ST CYCLE

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FRACTAL DIMENSION VS. JRC SAMPLES F4

FRACTAL DIMENSION VS. JRC SAMPLES F3

FRACTAL DIMENSION VS. JRC **SAMPLES F2**

FRACTAL DIMENSION VS. JRC **ALL SAMPLES**

APPENDIX F1

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CYCLIC SHEAR RF4

1ST CYCLE FORWARD

DILATANCY RF4

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 1ST CYCLE FORWARD

CYCLIC SHEAR RF4

1ST CYCLE FORWARD

DILATANCY RF4

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 1ST CYCLE FORWARD

CYCLIC SHEAR RF3

1ST CYCLE FORWARD

DILATANCY RF3

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 1ST CYCLE FORWARD

CYCLIC SHEAR RF3

1ST CYCLE FORWARD

DILATANCY RF3

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 1ST CYCLE FORWARD

CYCLIC SHEAR RF2

1ST CYCLE FORWARD

DILATANCY RF2

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF2 1ST CYCLE FORWARD

CYCLIC SHEAR RG2 1ST CYCLE FORWARD

DILATANCY RG2 1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RG2 1ST CYCLE FORWARD

APPENDIX F2

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- F2-C Predicted and observed shear load vs. shear displacement curves, dilatancy curves and shear load vs. normal load paths in (a)-(c), respectively, for $K = 0, 3$, and 10 ksi/in and $JRC = 15.5$. Samples F4, first shear cycle forward motion with initial normal stress = 400 psi . The mathematical model is based on Barton's criterion. F2-5&6
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CYCLIC SHEAR RF4

1ST CYCLE FORWARD

DILATANCY RF4

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 1ST CYCLE FORWARD

CYCLIC SHEAR RF4

1ST CYCLE FORWARD

DILATANCY RF4

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 1ST CYCLE FORWARD

CYCLIC SHEAR RF4

1ST CYCLE FORWARD

DILATANCY RF4

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 1ST CYCLE FORWARD

CYCLIC SHEAR RF4

1ST CYCLE FORWARD

DILATANCY RF4

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 1ST CYCLE FORWARD

CYCLIC SHEAR RF3

1ST CYCLE FORWARD

DILATANCY RF3

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 1ST CYCLE FORWARD

(c)

CYCLIC SHEAR RF3

1ST CYCLE FORWARD

DILATANCY RF3

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 1ST CYCLE FORWARD

CYCLIC SHEAR RF3

1ST CYCLE FORWARD

DILATANCY RF3

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 1ST CYCLE FORWARD

CYCLIC SHEAR RF3

1ST CYCLE FORWARD

DILATANCY RF3

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 1ST CYCLE FORWARD

CYCLIC SHEAR RF2

1ST CYCLE FORWARD

DILATANCY RF2

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF2 1ST CYCLE FORWARD

CYCLIC SHEAR RF2

1ST CYCLE FORWARD

DILATANCY RF2

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF2 1ST CYCLE FORWARD

CYCLIC SHEAR RG2

1ST CYCLE FORWARD

DILATANCY RG2

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RG2 1ST CYCLE FORWARD

CYCLIC SHEAR RG2

1ST CYCLE FORWARD

DILATANCY RG2

1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RG2 1ST CYCLE FORWARD

APPENDIX

Information from the Reference Information Base Used in this Report

This report contains no information from the Reference Information Base.

Candidate Information for the Reference Information Base

This report contains no candidate information for the Reference Information Base.

Candidate Information for the Geographic Nodal Information Study and Evaluation System

This report contains no candidate information for the Geographic Nodal Information Study and Evaluation System.

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