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Direct Shear Tests on Geological Fractures and Sawcut Samples from an Open Pit Mine in Northern Manitoba

by

75-3

P. Miles and G. Herget

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January 1975

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by

P. Miles* and G. Herget**

SUMMARY

Direct shear tests on samples of quartz-chlorite gneiss were carried out to determine the shear resistance along geological fractures and sawcuts for open pit design. Shear tests were performed at both low (10 to 36 psi) and high (150 to 1430 psi) normal stresses. It was found that the peak angle of friction varied between 30° and 63° with a mean of 44°. The peak shear stress/normal stress data was best represented by the power curve $\tau = a\sigma_n^{\ b}$. As a comparison, a straight line interpretation ($\tau = a + b\sigma_n$) is also given, which yields, however, a poorer fit of the data. The standard errors from regression were used to calculate the cumulative distributions of τ at a given normal stress of 15 psi. The large discrepancy of the standard errors has a profound effect on the cumulative distributions at low normal stresses.

A mean residual angle of friction of 29.3° was found which agreed well with the angle of friction from flat sawcuts (28.9°). A calculation of the angle of friction at zero dilatancy from measurements of horizontal and vertical displacements at peak yielded a value of 33°.

Direct Shear Tests: Geological Fractures: Sawcuts: Angles of Friction: Mohr-Coulomb: Power Curve: Dilatancy.

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LIST OF SYMBOLS

- T Shear stress [psi]
- σ_n Normal stress [psi]
- r Correlation coefficient
- N Number of observations
- $S_{T/\sigma_{\mathbf{n}}}$ -Standard error of estimate
 - s Shear displacement [in.]
 - n Dilatancy [in.]
 - ie Geometric component of angle of friction [degrees]
 - ϕ Angle of internal friction
 - A Amplitude [in.]
 - L Wavelength [in.]

1. INTRODUCTION

Direct shear tests were performed on samples of quartz-chlorite gneiss to determine the shear resistance along sawcuts and geological fractures of known in-situ orientation. The samples were obtained as diamond drill core from the slopes of an open pit in Northern Manitoba.

In the following, sample descriptions, testing procedures, results and analysis are presented.

2. SAMPLE DESCRIPTION

Jointed diamond drill core (4 in. diameter) was obtained from the wall of an open pit for the purposes of direct shear testing. The orientations of the geological fractures were known and testing was to simulate failure of the pit slopes.

The samples were of a quartz-chlorite gneiss with varying amounts of biotite and garnet. Almost 80% of the shear surfaces were at least 50% slickensided and were characteristically black, shiny, striated, and soft. Many slickensided surfaces were partially coated with a thin, soft layer of calcite. Several very rough, interlocking surfaces were formed by the intersection of the gneissosity with the shear plane. The individual shear surfaces are described in more detail in Appendix A.

3. TESTING PROCEDURES

3.1 Sample Preparation and Testing Arrangement

Most fractures were marked in terms of desired shear direction. Some directions were changed so that shearing took place along the slickensides. The directions of shear movement are given in Appendix A as angles to the left or right of vertical, as shown in Figure 1. All jointed samples were sheared top down except for No. 17. Six samples were provided with sawcuts, three from sample No. 7 and three from sample No. 22, to obtain a check on the residual shear resistance.

Blocks of rock containing the fractures or sawcuts were cut so that they could be moulded into forms suitable for the direct shear testing rig. The samples were moulded in a portland cement-sand mixture of 1:3 and left to cure for at least three days.

Direct shear tests were made with a Hoek shear box. For the initial tests at low normal stresses (10 to 36 psi) the shear box was modified so that the normal load was applied by lead weights and the shear force was applied by a hand screw via a proving ring. For these tests, shear force and shear and normal displacement were plotted by an x, y, y recorder.

High normal stress tests were made with the direct shear box using hydraulic hand pumps to apply the normal and shear loads. Shear force and shear displacement were recorded by an x, y recorder.

4. RESULTS AND ANALYSIS

Objectives of the shear tests were to define the peak shear resistance and its variation at different normal stresses and to obtain a value of the residual angle of friction.

4.1 Results

To allow interpretation of the continuous records obtained by measuring shear force/shear displacement, three phases were distinguished as shown in Figure 2 and described below.

a) Peak Shear Resistance

This reflects the maximum shear resistance obtained for a given normal stress which appears shortly after onset of shear displacement.

b) Post Peak Shear Resistance

Shear resistance reduces with displacement after the peak to a relatively constant value. The lowest average value is recorded.

c) Residual Shear Resistance

This is a value of shear resistance after considerable sliding which is constant with displacement.

In most cases the third phase could not be determined with confidence. Also, in many of the high normal stress tests a peak shear resistance did not exist. This indicates that the interlocking asperities causing the peak at low normal stresses are not effective (too weak) at the higher normal stresses. The presence of small rock chips and a large amount of rock powder on the shear surfaces after testing shows the effect of continuous wear on the surfaces. Even the sawcut samples showed these effects after testing at high normal stresses.

Necessary data to quantify shear and displacement data in these phases are given in Appendix A. If phase three was obtained, it is given in the table in the post peak column and is marked with an asterisk.

4.2 Peak Shear Resistance at Various Normal Stresses

Two sets of data are presented. Figure 3 shows a peak shear stress/normal stress diagram representing only low normal pressure tests. Figure 4 represents all tests. In each case the straight line Mohr-Coulomb function and a power curve were fitted to the data. A power curve showed a better fit in both instances. The relationships for both cases are presented below.

Low normal stresses (Figure 3):

straight lin	е: Т	Ξ	a + bσ _n
	Т	Ξ	$(2.5 \pm 2.45) + (0.954 \pm 0.11) \sigma_n$
	\mathbf{r}	Ξ	0.727
	N	Ξ	69
	s _{T/on}	Ξ	7.46
power law:	log T	=	$\log a + b \log \sigma_n$
	log T	=	$(0.155 \pm 0.105) + (0.895 \pm 0.081) \log \sigma_n$
	r	Ξ	0.803
	\mathbb{N}	Ξ	69
	S _{T∕σn}	=	0. 129

Low and high normal stresses (Figure 4):

straight line:
$$T = a + b \sigma_n$$

 $T = (10.0 \pm 5.8) + (0.970 \pm 0.033) \sigma_n$
 $r = 0.949$
 $N = 97$
 $S_T / \sigma_n = 47.6$

power law:
$$\log \tau = \log a + b \log \sigma_n$$

 $\log \tau = (0.031 \pm 0.039) + (0.998 \pm 0.023) \log \sigma_n$
 $r = 0.975$
 $N = 97$
 $S_T/\sigma_n = 0.125$

The peak angle of friction of 43.7° (arc tan 0.954) for the low normal stress cases agrees very closely with the angle 44.1° (arc tan 0.970) obtained for all tests combined. The power relationship representing all tests, which is very nearly linear, yields an angle of friction of 44.9° (arc tan 0.998).

A calculated example for a normal stress of 15 psi using the relationships for all tests gives the following results:

straight line	e: T	=	10.0 + 14.55
· .	ቸ	=	24.55 psi
	S _T /σ _n	=	47.6
	T.	=	24.55 <u>+</u> 47.6 psi
power law:	log T	Ξ	0.031 + 1.174
	log T	Ξ	1.205
	S_{τ}/σ_n	Ξ	0.125

 $\log \bar{\tau} = 1.205 \pm 0.125$

 $\vec{\tau} = 16.02 + 5.34$ $\vec{\tau} = 16.02 + 5.34$ psi

A comparison of the mean values of τ at 15 psi normal stress and the correlation coefficients indicates some agreement between the straight line and the power curve; however, a considerable difference exists for the standard errors and indicates that the power curve provides a far superior relationship between shear resistance and normal stresses.

4.3 Shear Resistance Due to Dilatancy

Measurements of shear displacement (s) and dilatancy (n) during shearing at low normal pressures allowed determination of the geometric component affecting shear resistance. This geometric component is defined as:

angle $i_e = arc tan (dn/ds)$.

Since the residual angle of friction could not reliably be determined, an attempt was made to obtain the angle of friction at zero dilatancy using the equation,

$$T = \sigma_n \tan(\phi + i_e).$$

This was obtained by running a regression analysis of arc tan (T/σ_n) on arc tan (dn/ds) which is shown in Figure 5. The angle of friction at zero dilatancy was found to be 33°. This compares well with the mean residual angle of friction for the geological fractures of 29.3°,

[arc tan (T/σ_n) - arc tan (dn/ds)] and the mean post peak value for the sawcuts of 28.9°.

5. REFERENCES

1.

Herget, G. and Miles, P., "Shear Resistance of Geological Fractures in Weathered and Fresh Rock", Mining Research Centre Divisional Report, 1974.







FIGURE 2: Direct Shear Test on Geological Fracture in Quartz-Chlorite Gneiss at a Normal Stress of 20 psi.



FIGURE 3: Peak Shear Resistance at Low Normal Stresses in Direct Shear Tests.

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FIGURE 4: Peak Shear Resistance at Low and High Normal Stresses in Direct Shear Tests.



FIGURE 5: Calculation of Angle of Friction at Zero Dilatancy for All Samples.

TEST DATA

APPENDIX A

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•		Results	s from D	irect Sh	ear Tes	Results from Direct Shear Tests										
Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ²)	Normal Stress,	Peak Shcar Stress, T (psi)	Peak arc tan (r/o _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Pcak arc tan (r/c _n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)							
Quartz-chlor	ite gneis	s	L		•			-I								
slickens	1des, vei 16 26 36 164	rtical, go 16.9 25.7 32.5 205	ood surfa 46.6 44.7 42.1 51.3	ace cont 24.0 26.6 20	act, 6.1 .035 .025 .035 .065	in. 29.0 23.2 28.7 43.83 43.53	22.6 18.1 22.1	1.0 1.0 1.0 1.005 1.0	300 300 300 180 248							
	328 492					41.13		1.0	252							
.2, contains h sided, tl few shar good sur	biotite, chin calcit p asperi	lean moc te coveri ties, she tact, 6.5	lerately ng $\approx 60\%$ eared alc in. ²	smooth %, irreg ong slick	geologic ular asp censides	41.13 al fractu perities u , 17° lef	tre, 100 to ≈ 100 t of ver	1.0 0% slich 05 in. tical, y	252 xen- hig very							
2, contains h sided, tl few shar good sur	$\begin{array}{c c} 528 \\ 492 \\ \hline 0 \\ 10 \\ 10 \\ 16 \\ 26 \\ 36 \\ 154 \\ 308 \\ 462 \\ \end{array}$	lean moc te coveri ties, she tact, 6.5 10.9 17.5 22.3	lerately ng $\approx 60\%$ eared alc in. ² 34.3 34.0 31.8	smooth 6, irreg ong slick 7.6 4.1 2.9	geologic ular asp censides .08 .07 .095	41.13 41.13 erities u , 17° lef 22.9 25.9 25.2 36.9 39.5 38.4	tre, 100 $t o \approx 100$ t of ver 26.7 29.9 28.9	1.0% slich 05 in. tical, v 1.0 1.0 1.0 1.01 .955 .975	252 xen- higl yery 190 227 271 187 210 210							

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Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ²)	Normal Stress, c _n (psi)	Peak Shear Stress, T (psi)	Peak arc tan (T/ơ _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (r/ơ _n)	CalculatedRosidual arc tan (T/o _n)	Total Displacement (in.)	Time (seconds)
				L				I	
4, contains h slickens $\approx .15$ in 8° left o	biotite an ided, ca n. high, f vertica 10 20 30 238	d garnets lcite cove undulatic l, poor s 6.9 16.2 23.3	s, clean ering < 1 on $A \approx .$ 34.6 39.0 37.9	very ro 0%, sha 153 in contact, 20.0 14.0 12.5	ugh geol rp inter , shear 4.2 in.* .225 .240 .235	ogical fr locking a red along 19.7 30.8 32.4 45.6	acture, asperiti g slicker 14.6 25.0 25.4	80% es up t nsides, 1.0 1.0 1.0 .905	o 223 300 300 220
	476					44.6		.755	184
	714					42.0		.895	210
5, contains h sided, s protrudi surface	biotite an everal in ng garne contact, 10 20 30 156 313 469	nd garnet nterlockin ets, shea: 6.4 in. ² 9.4 9.4 19.5 25.8	s, clean ng asper red alon 43.2 44.3 40.7	rough g ities up g slicken 13.2 20.0 10.3	eologicz to \approx . 1 nsides, . 025 . 015 . 025	1 fractur 5 in. hig 35° left 31.4 29.4 30.5 41.9 39.9 37.2	re, 50% h, seve: of vertic 30.0 24.3 30.4	slicker ral cal, go .77 .54 .73 1.0 1.0 .995	od 155 110 145 210 270 240
6-1, contain	s biotite	and garn	ets, clea	an mode	rately r	ough geo	logical	fractui	e,
100% sli	ckenside	ed, minor	calcite	, severa	al interle	ocking as	speritie	s up to	-
$\approx .12$ i	n. high,	undulatio	on A \approx .	15 in.,	sheared	along sl	ickensid	les, 25	°left
of vertic	cal, very	good su	rface co	ntact, 5	.9 in. ²			F .	
	10	9.4	43.2	6.0	.035	26.6*	37.2 35 1	.945	214
	30	25.8	40.7	10 3	0425	27 5	30 1	03	210
	170	150 0	11 6	10.5	20	31 6		1 015	205
	220	201 5	40 7		20	26 2	,	1.015	205
	559	671.5	40.1		. 255	27 2	· · ·	. 995	300
	509					51.6		1.900	220
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l			L		L	1			<u> </u>

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Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ²)	Normal Stress, G _n (psi)	Peak Shcar Stress, T (psi)	Peak arc tan (t/c _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak are tan (T/c _n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Timc (scconds)
6-2, contains of calcit $A \approx .15$ is	s biotite, e coveri in., shea	clean rong $\approx 30\%$ ared alon	ough geo , dull as g slicker	logical f sperities nsides,	racture up to≈ 27° left	, 95% sli .08 in., of vertic	ckensid smooth al, poo	led, pa undul r surfa	tches lation lce
contact,	5. 1 in. 10 20 30 196 392 588	7.8 19.1 24.5	38.0 43.7 39.2	12.5 14.0 12.5	.025 .0125 .03	25.7* 32.9* 32.1* 41.7 41.8 39.5	25.5 29.7 26.7	.97 .915 .955 1.01 .840 1.0	210 201 210 245 260 240
7, contains h sided, p sheared	oiotite, c atches o along sl:	lean mod f calcite ickenside	lerately covering s, 15° l	smooth $g \approx 15\%$, eft of ve	geologic dull asp rtical,	al fractu perities u good sur:	re, 95% p to \approx face con	6 slick 08 in. htact,	en- high,
6.0 in. ²	10 20 30 167 333 500	8.0 15.5 23.8 177.5	38.7 37.8 38.4 46.8	8. 1 7. 4 8. 7	. 125 . 11 . 115 . 150	26.6* 25.8* 25.5* 43.4 40.2 39.1	30.6 30.4 29.7	.98 1.05 1.0 1.0 .985 1.0	192 229 265 190 205 215
8, contains b calcite, sheared	oiotite, c no sharr along sl	lean smo interloc ickenside	ooth geol king asp s 15° le	ogical fi perities, ft of ver	racture, smooth tical, g	100% sl: undulati ood surfa	ickensie ons A ≈ ace cont	ded, m z.04 i: tact,	inor n.,
5.0 m.	10 20 30 172 345 517					20.8* 21.8* 22.5* 35.0 34.4 37.0		1.05 1.0 1.0 .960 1.0 1.005	223 267 330 190 175 200

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Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ³)	Normal Stress, G _n (psi)	Peak Shear Stress, T (psi)	Peak arc tan (T/o _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (T/o _n)	Calculated Residual are tan (τ/σ _n)	Total Displacement (in.)	Time (seconds)
9, contains the calcite of $A \approx .12$ vertical	oiotite, c covering in., L = , poor su	clean rou $\approx 10\%$, a 1.6 in urface co	gh geolo speritie to shea ntact, 2	gical fra s up to a ar direct .5 in. ²	cture, ° ≿.12 in. ;ion, she	95% slick high, la ared alc	censidec arge und ong slic	l, patcl lulatior kenside	hes of a s,
	14.8 20 30 400 800 1200	13.2 17.2 23.0	41.7 40.7 37.5	7.6 9.5 5.9	.22 .08 .10	31.3 25.6 28.1 41.7 42.8 38.9	34.1 31.2 31.6	.485 .525 .485 1.0 .995 .995	102 120 175 185 190 165
9-A, contai $\approx 10\%$, high for troughs vertical	ns biotit calcite med by i parallel , very g	e, clean covering ntersecti to direct ood surfa	very rou 5-10%, on of gn ion of sl .ce conta	gh geold sharp in eissosity nearing, .ct, 6.0	gical fr terlocki y with sl sheared in. ²	acture, ang asper near plar d top dow	iron oxi ities up ne, ridg vn, 20°	de cov $to \approx .$ to $\approx .$ es and left of	ering 25 in.
	10 20 30 167 333 500	20.2 34.0 44.7 250.0 413.3 503.3	53.6 59.5 56.1 56.3 51.1 45.2	33.7 29.7 24.0	.01 .015 .03 .025 .065 .115	30.3* 33.7* 35.0* 43.5 42.1 41.3	29.9 29.8 32.1	1.05 1.01 1.0 1.0 1.0 1.0	236 240 195 230 220 210
10, contains patches high, la along sl	biotite, of iron o rge undu ickensid 17.6 20 30 476 952	clean ve oxide cov lations A es, 15° r 11.2 16.2 24.0	ry rough ering \approx \approx .15 in ighi of v 32.4 39.0 38.7	$e geologi 10%, irr L \approx .8ertical,11.38.78.4$	cal frac egular : in to poor su . 12 . 145 . 12	ture, 95 asperitie o shear co 22.1 34.2 33.4 42.0 41.8	% slicke s up to lirection ntact, 2 21.1 30.3 30.3	ensided $\approx .12$ n, shea 2.1 in. 1.01 1.45 .96 .96 .995	, in. 159 190 176 180 190
11, no test.	1429					40.7		1.005	180

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ²)	Normal Stress, a _n (psi)	Pcak Shcar Stress, T (psi)	Peak arc tan (1/0 _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (scconds)
12, clean ve troughs locking surface	ry rough formed l asperitie contact.	geologic by interse s up to \approx 5.1 in. ²	al fractu ection of .3 in. h	re, no s gneissc igh, she	slickens sity wit ared top	iding, di h shear j down, v	agonal : plane, s vertical,	ridges sharp i good	and nter-
	10	17.1	59.6	45.0	.0075	42.4	14.6	.94	200
	20	29.0	55.4	29.7	.03	39.5	25.7	1.005	171
	30	52.9	60.5	38.7	.005	40.8	21.8	1.01	189
	196	388.2	63.2		.020	47.7		1.0	180
	392 500	535.3	53.8		.060	49.0		.94	220
	200	080.4	47.2		.10	45.9		1.0	225
13, clean ro asperiti A≈.4 ir slickens	ugh geold es up to 2 n., L = 6 ides, ve 10 20 30 196 392 588	pgical fra \approx .08 in. .2 in., s rtical, go 13.4 29.6 37.6	high, 1 high, 1 sample g bod surf 53.3 56.0 51.4	50% slich arge into lued tog ace cont 18.4 24.0 17.1	kensided erlockin ether fo act, 5.1 .08 .06 .095	l, thin ca g diagona r testing 43.6 42.4 42.5 48.5 45.0 42.0	lcite co al undul , shear 34.9 32.0 34.3	vering ation ed alor .995 .97 .91 1.0 .895 1.0	rg 231 180 143 210 230 192
14, contains locking	biotite, asperitie	clean rous up to \approx	igh geol .25 in.	ogical fr high, m	acture, ainly \approx .	30% slic 1 in. hig	kenside h, shea	ed, inte red al	er- Ong
slickens	ides, 32 10 20 30 159 318 476	<pre>* left of v 11.6 18.4 26.8 193.7</pre>	vertical, 49.2 42.6 41.8 50.7	very go 26.6 18.4 18.4	od surf .005 .055 .025 .010	ace cont: 20.1* 22.4* 22.2* 41.0 41.4 40.4	act, 6.3 22.6 24.2 23.4	in. ² .85 .985 1.005 1.01 1.0 1.005	150 191 190 168 185 190

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Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ² ,	Normal Stress, d _n (psi)	Peak Shcar Strcss, T (psi)	Peak arc tan (T/o _n)	Pcak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (r/ơ _n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
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16-1, contai calcite undulati slickens	ns biotit covering on $A \approx \cdot$ sides, 15 10 20 30 164 328 492	e, clean ≈ 35%, s 12 in., I ° right o 11.0 21.6 30.2 213.1	rough ge several i ≈ 3 in. f vertica 47.7 47.3 45.2 52.4	ological interlock parallel 1, good 14.0 12.5 10.8	fractur to shea surfact . 12 . 08 . 135 . 095	e, 95% s erities up r directi contact, 37.9 36.4 38.0 48.6 46.7 45.0	lickens: o to ≈ . on, she 6.1 in. 33.7 34.8 34.4	ided, t. 15 in. ared a. 1.005 1.005 1.005 .635 .995 1.0	hin high, long 217 219 235 150 185 195
16-2, contai locking with she sheared	ns biotit asperitie ar plane top dow 10 20 30 154 308 462	e, clean es up to ≈ , undulat n, vertic 29.7 39.1 243.1 547.7	rough ge ∴ 15 in. ion A≈ . al, very 50.6 56.0 52.5 57.6 49.9	eological high fo: 4 in., I good su 24.0 29.7 26.6	fractur rmed by _ = 2 in. rfact co . 04 . 03 . 01 . 020 . 46	e, no sli intersec to sho ntact, 6. 32.2 32.6 35.3 52.2 49.1 47.0	ckensid tion of 2 in. ² 26.6 26.3 25.9	ing, in gnciss ection, 1.01 1.015 1.015 1.015 1.015	243 210 195 180 190

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ²)	Normal Stress, G _n (psi)	Peak Shear Stress, T (psi)	Peak arc tan (T/ơ _n)	Pcak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak are tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
17, contains sided, ca $\approx .04$ in. movemen 23° right	biotite, alcite co high, l nt, shea: of verti	clean mo vering ce arge step red along ical, goog	derately ntre 60% across slicken d surface	smooth %, smoo sample sides, b e contac	geologi th undul $\approx .2$ in ottom do t, 5.4 in	cal fract ations ar high re own due f	ure, 95 nd aspen strictin to large	% slick tities u g shea step,	cen- p to r
	10 20 30 152 303 455	8.1 16.7 24.2 153.5 286.4 398.5	39.0 39.8 38.9 45.2 43.4 41.2	5.4 6.3 6.7	.045 .12 .025 .070 .100 .115	31.2* 27.9 31.2* 43.2 41.8 39.4	33.6 33.5 32.2	1.01 1.055 1.005 1.015 1.005 1.005	212 220 188 170 155 200
18-1, contain sided, pa undulatic pieces gl surface o	as biotite atches of ons $A \approx$ ued toge contact, 10 20 30	e, clean r f calcite 45 in., L f ther, sho 5.4 in. ²	noderate covering , > 3.4 in eared ale	ely rough $z \approx 20\%$, n. \perp to song slich	n geolog asperit hear din censides	ical frac ies up to ection, s, 16° les	ture, 6 $\approx .04$ is sample ft of ver	0% slic n. high, has se rtical, . 41 . 405 38	ken- large veral good 95 99
19.2 contain	185 370 556				fractur	47. 2 41. 7	changid	1.01 1.005 1.0	240 240 175
of calcite undulatio contact,	e coverin ons $A \approx .$ 5.4 in. ²	$r_{g} \approx 10\%$, 2 in., L	sharp a = 2.7 in	.speritie .sheare	s up to x od top do	\approx . 15 in. \approx . vert	high, tical, g	diagona ood suu	al rface
	10 20 30 185 370 556	14.3 28.5 60.9 314.8 356 466.7	55.0 54.9 63.8 59.6 43.9 40.0	24.0 26.6 26.6	.065 .04 .02 .01 .075 .185	34. 4 37. 5 41. 2 41. 4 38. 7 37. 9	31.0 28.3 37.2	1.025 1.005 1.025 1.005 1.0 1.02	150 183 180 190 170 180

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Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ³) Normal Stress, σ_n (psi)	Peak Shcar Stress, T (psi)	Peak arc tan (T/ơ _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (T/ơ _n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (scconds)
19, contains biotite sided, patches high, sample h poor surface co	, clean mo of calcite as pieces ontact, 4.5	oderately covering glued tog 5 in. ²	smooth $\approx 20\%$, gether, s	geologi smooth sheared	ical fract asperitie along sli	ure, 95 es up to ckensid	$\approx .08$	ken- in. rtical,
10 20 30 222 444 667	375.6	29.4		.070	20.7* 29.3* 22.2* 31.0 31.0 28.1	•	.75 .705 .70 .60 .70 .64	149 171 142 95 120
20-1, contains biot patches of calc sheared along 10	ite, clean ite, sharp slickenside 19.3	rough ge interloc es, 30°1 62.7	ological king asp eft of ve 24.0	fractur erities rtical, .015	e, 95% s up to \approx . good sur 38.7	lickens 12 in. 1 face con 38.7	 	ninor 5.0 in ² 144
20 30 167 333 500	27.3 34.0 209.2 321.7	53.8 48.6 51.4 44.0	21.8 17.1	.015 .025 .030 .070	32.335.444.741.040.5	32.0 31.5	1.005 1.005 1.0 1.01 .9005	236 213 230 185 200
20-2, contains biot: sided, asperiti along slickensi	ite, clean : es up to \approx des, 35° 1	moderate .08 in. eft of ver	ely smoo high, fe tical, g	oth geol w interl good sur	ogical fra ocking as face cont	acture, speritie act, 6.	95% sl s, she: 3 in. ²	icken- ared
10 20 30 159 318 476	$ \begin{array}{c c} 14.8\\ 24.6\\ 34.0\\ 175.4 \end{array} $	55.9 50.9 48.5 47.7	26.6 24.0 18.4	.035 .0275 .05 .030	27. 3* $29. 4*$ $31. 1*$ $40. 5$ $40. 7$ $39. 4$	29.3 26.9 30.1	1.005 1.0 1.005 1.01 .960 1.0	213 217 242 180 200 200

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Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ²)	Normal Stress, G _n (psi)	Peak Shear Stress, T (psi)	Peak arc tan (T/o _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Pcak arc tan (T/o _n)	Calculated Residual arc tan (τ/σ_n)	TotalDisplacement (in.)	Time (seconds)
21, contains sided, d slickens	s biotite, ull inter ides, 20 10 20 30 152 303 455	clean m locking a ° left of 11.5 36.1 30.0 154.5	oderatel speritie vertical, 49.0 61.0 45.0 45.6	y smoot s up to≈ very g 20.0 21.8 15.9	h geolog 0.8 in. ood surf .02 .01 .015 .045	gical frac high, sh ace conta 31.2* 31.2* 31.6* 40.4 40.9 39.5	eture, 9 eared a act, 6.6 29.0 39.2 29.1	5% slic long in. ² 1.005 1.00 .975 1.0 1.0	261 196 211 195 190
22-1, contai sided, t up to ≈ surface	ns biotite hin patch . 12 in. h contact, 10 20 30 154 308 462	e, clean 1 les of cal ligh, shea 6.5 in. ² 8.0 17.2 36.0 156.9	moderat cite cov ared alo 38.7 40.7 50.2 45.6	ely roug ering≈ ng slick 14.0 11.3 20.0	h geolog 40%, sn ensides, .025 .03 .01 .03	gical frac nooth inte 20° left 25.9 29.6 31.6 42.0 41.2 38.3	eture, 9 erlockin of vert 24.7 29.4 30.4	0% slic g aspe ical, g 1.005 1.015 1.005 1.0 1.0 1.0	cken- rities ood 257 216 218 180 195 195
22-2, contai sulphide asperiti good su:	 ns biotito e mineral es, undu rface con 20 30 154 308 462	 e, clean lization, lations A ntact, 6.9 8.6 16.9 25.8 158.5	 rough ge asperiti > :. 15 i 5 in. ² 40. 7 40. 2 40. 7 45. 7	es up to n., shea 8.7 17.1 7.4	\approx . 15 i ared alo . 17 . 0225 . 325 . 055	e, 85% s n. high, ng slicke 30.3 30.3 29.4 39.2 36.5 34.7	lickens some in nsides, 32.0 23.1 33.3	ided, n nterloci 1.01 1.015 1.01 1.01 1.01 1.01	hinor king al, 192 198 220 185 195 175

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Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ²)	Normal Stress, O _n (psi)	Peak Shear Stress, T (psi)	Peak arc tan (T/o _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (T/ơ _n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (scconds)
S-7-1 Sawcu	t, 6.0 ir 10 20 30 166.7 333.3 500.0	2				25.8* 27.9* 28.6* 36.5 37.8 37.7		1.01 1.005 1.005 1.0 1.0 .98	209 228 253 170 195 170
S-7-2 Sawcu	t, 6.0 in 10 20 30 166.7 333.3 500.0					22.6 23.2 26.1 40,4 40.7 40.7		1.005 1.005 1.0 1.0 1.0 1.0	150 177 175 170 200 215
S-7-3 Sawcu	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	4.6 8.2 13.8	24.6 22.2 24.8		.195 .215 .155	19.3 15.8 21.0 31.8 32.4 33.2		1.005 1.005 1.005 1.0 1.0 1.0	178 162 165 170 210 200
S-22-1 Sawc	cut, 5.8 10 20 30 172.4 344.8 517.2	in. ²				16.3 20.3 19.0 31.8 35.9 36.0		1.005 1.01 1.005 1.0 1.0 1.0	132 158 137 155 205 195

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Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in. ²)	Normal Stress, G _n (psi)	Peak Shcar Stress, ^T (psi)	Peak arc tan (r/ơ _n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak are tan (T/ơ _n)	Calculated Residual arc tan (τ/σ_n)	TotalDisplacement (in.)	Time (seconds)
5-22-2, Saw	cut, 5.9 10 20 30 169.5 339.0 508.5	in. ² 3.6 7.2 11.9	20.0 19.8 21.6		. 165 . 12 . 085	16.1 14.9 16.8 31.0 36.9 35.5		1.005 1.005 1.005 1.0 1.015 1.025	229 252 277 180 165 205
S-22-3 Sawc	ut, 6.0 i: 10 20 30 166.7 333.3 500.0					25.0 27.1 24.4 36.9 38.1 37.2		1.01 1.01 1.01 1.0 1.005 1.0	135 141 227 180 180 185
	Rock Type Rock Type Sample No. Fracture Description S-55-25 Samo Size Shear Direction Size Shear Surf. (in. ²)	 U (i) 	u (°, ui) (°, ui) (°, ui) u (°, ui) (°, ui) (°, ui) (°, ui) (°, ui) (°, ui) <	.	S-22-2, Sawcut, 5.9 in.2 S-22-3 Sawcut, 6.0 in.3 S-22-3 Sawcut, 7.0 in.3 S-22-3 Sawcut,	u (a) u<	S-22-2, Sawcut, 6.0 in.2 $S-22-3 Sawcut, 6.0 in.2$ $S-22-3 Sawcut, 7.0 in.2$	S-22-2, Sawcut, 5.9 in.2 $S-22-2, Sawcut, 6.0 in.3$ $S-22-3 Sawcut, 6.0 in.3$ $Sawcut, 6.0 in.3$ $Sawcut, 6.0 in.3$ $Sawcut, 6.0$	S-22-2, Sawcut, 5.9 in * S-22-2, Sawcut, 5.9 in * S-22-3 Sawcut, 6.0 in * S-22-3 Sawcut, 7.0 in * S-22-3 Sawcut,

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