

## Slab avalanche measurements<sup>1</sup>

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From a study of 205 slab avalanches it is concluded that failure initiates where the slope is 25° or steeper, that slab failure stress is in the range  $10^2$ – $10^4$  N/m<sup>2</sup>, and that the slab failure plane is most commonly at a temperature of –5°C or warmer.

The *in situ* measurement of shear strength is still an unresolved problem. A statistical analysis of a shear-frame device shows that the device is sensitive to the rate of pull and to the frame area. The larger the frame area, the smaller the measured shear strength. Approximately 10 measurements are required to sample a mean shear strength of a slab failure plane to within 15% accuracy at 90% confidence.

Après une étude de 205 avalanches de plaques de neige il se conclut que la rupture commence quand la pente est 25° ou plus raide, que la traction de la rupture de plaque de neige se trouve de  $10^2$  à  $10^4$  N/m<sup>2</sup> et que le plan de la rupture de plaque de neige se produit le plus souvent à une température de –5°C ou plus chaude.

Le mesurage *in situ* de la résistance au cisaillement reste toujours un problème à résoudre. Une analyse statistique d'un cadre de cisaillement montre que cet appareil est sensible au degré de traction et à la surface du cadre. Plus la surface du cadre est grande, plus la résistance mesurée est faible. Il faut approximativement 10 mesures pour prendre des prélevements d'une moyenne résistance au cisaillement d'un plan de la rupture de plaques de neige pour arriver à une précision de 15% à une confiance de 90%.

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### Introduction

Recent studies of snow slope stability were reviewed by Scheidegger (1975) and Perla (1975, 1976a). From the viewpoint of release mechanisms, it is conventional to divide snow slope failure into two categories: loose-snow avalanches and slab avalanches. Loose-snow avalanches initiate in a surface layer that lacks cohesion, either in a layer of dry and unsintered snow or in a very wet layer. Initial failure is similar to the rotational slip of cohesionless soils, but occurs within a smaller volume (of the order of 1 m<sup>3</sup>) by comparison to the initiation volume of soil slides. From a distance, it appears that a loose-snow avalanche initiates and spreads downward from a point; thus, loose-snow avalanches are sometimes called point avalanches.

The other type of avalanche is the snow-slab. This involves the release of a cohesive layer over a stratigraphic plane of weakness, and has some similarity to planar failures of rock slopes, e.g. rock slides observed in the tilted strata of the Canadian Rockies (Cruden

1976). Area of the shear fracture of snow slabs ranges from  $10^2$ – $10^4$  m<sup>2</sup>. The initial slab volume ranges up to about 10<sup>4</sup> m<sup>3</sup>. Once set in motion, the avalanche may entrain additional mass (Schaerer 1971).

Based on nomenclature illustrated in Fig. 1, slab failure is considered as a first approximation due to shear stress at the bed surface exceeding the shear strength. Loss of shear support leads to rapid buildup of tensile stress in the crown, followed by rapid tensile fractures (of the order of 10<sup>2</sup> m/s). The details of progressive failure are presently speculative, but are thought to involve an interaction where-

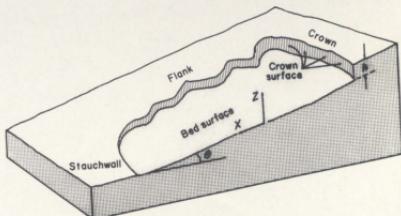


FIG. 1. Slab avalanche nomenclature and coordinate system.

<sup>1</sup>Paper presented at the 29th Canadian Geotechnical Conference, Vancouver, B.C. October, 1976.

TABLE 1. Sources of slab measurements

Source (Perla 1976b)	Reference	Location of Study
A	Bader <i>et al.</i> 1939	Switzerland
B	Roch 1966a	Switzerland
C	LaChapelle 1964	Utah
D	A. Judson (personal communications)	Colorado
E	Wakabayashi and Yamamura 1968	Japan
F	Keefer 1969	Utah
G	Perla 1971	Utah
H	Ives <i>et al.</i> 1973	Colorado
I	Armstrong <i>et al.</i> 1974	Colorado
J	LaChapelle <i>et al.</i> 1975	Colorado
K	Perla (unpublished)	Washington State, Utah, Colorado, Alberta, and British Columbia
L	Swiss Institute for Snow and Avalanche Research 1947-1973	Switzerland

TABLE 2. Summary of slab measurements

(No. of cases)	Parameter	Range			Standard deviation
		Maximum	Minimum	Mean	
(194)	Slope angle $\theta$ (deg.)	55	25	38.3	4.79
(193)	Slab thickness $h$ (m)	4.2	0.08	0.67	0.43
(121)	Mean density $\bar{\rho}$ ( $\text{kg}/\text{m}^3$ )	461	60	206	77.2
(121)	Shear stress at bed surface $B_{xz}$ ( $\text{N}/\text{m}^2$ )	9050	65	964	1049
(72)	Density at bed surface $\rho_B$ ( $\text{kg}/\text{m}^3$ )	400	90	231	75.9
(111)	Temperature at bed surface $T_B$ ( $^\circ\text{C}$ )	0	-13	-4.58	3.08
(80)	Shear frame index at bed surface ( $\text{N}/\text{m}^2$ ) SFI	8159	200	1536	1461
(80)	Ratio SFI/ $B_{xz}$	6.4	0.19	1.66	0.98

by shear failure produces tension fractures which in turn reinforce further shear failure.

Using a coordinate system fixed to the bed surface as shown in Fig. 1, and assuming an infinitely extended planar slab, the shear stress  $B_{xz}$  and normal stress  $B_{zz}$  on the bed surface prior to failure are

$$[1] \quad B_{xz} = \bar{\rho}gh \sin \theta$$

$$[2] \quad B_{zz} = -\bar{\rho}gh \cos \theta$$

where  $\bar{\rho}$  is the average density of the slab,  $g$  is the acceleration due to gravity,  $h$  is the slab thickness, and  $\theta$  is the inclination of the bed surface. Equations 1 and 2 are approximations that do not account for boundary effects due to slope curvature, terrain protrusions, etc., nor

for the effects of snow inhomogeneity in the  $x$  direction. However, [1] and [2] suffice for purposes of this paper to describe presently available data, as discussed below.

#### Measurements at Slab Fracture Lines

Measurements taken at 205 slab crowns are compiled in the work by Perla (1976b) and were obtained from the sources shown in Table 1.

A statistical summary of these data is given in Table 2. The data are biased toward measurements of larger and more spectacular slabs, especially those that caused accidents or damage, as opposed to measurements of smaller, more innocuous slabs. Measurements were

## APPENDIX. SLAB DATA

See  
Table  
1

			$h$ (m)	$\bar{\rho}$ (kg/m <sup>3</sup> )	$\rho_B$ (N/m <sup>2</sup> )	$\rho_B$ (kg/m <sup>3</sup> )	T <sub>B</sub> °C	SFI (N/m <sup>2</sup> )	SFI/B <sub>xz</sub>
1	A	9JAN37	36	1.00	140	807	- 7.5	M	M
2	A	15FEB37	33	1.60	320	2735	- 4.0	M	M
3	A	16MAR37	40	1.20	M	M	M	M	M
4	A	30MAR37	38	2.00	210	2536	- 3.0	M	M
5	A	19MAY37	33	1.80	M	M	M	M	M
6	B	7DEC49	44	0.36	115	282	M	588	2.09
7	B	18DEC49	36	0.72	312	1294	M	245	0.19
8	B	5JAN50	45	1.10	109	834	M	1177	1.41
9	B	27DEC50	45	0.30	264	549	M	1814	3.30
10	B	17JAN51	41	0.74	268	1274	M	490	0.38
11	B	23DEC52	34	0.65	176	628	M	4021	6.40
12	B	30DEC52	37	0.60	285	1010	M	1471	1.46
13	B	5JAN53	45	0.90	396	2471	M	4903	1.98
14	B	5FEB53	37	0.63	227	843	M	1765	2.09
15	B	27FEB53	34	0.80	346	1520	M	2059	1.35
16	B	3MAR54	38	0.63	232	883	M	1500	1.70
17	B	3MAR54	38	0.57	208	716	M	588	0.82
18	B	8DEC54	37	0.50	180	530	M	490	0.92
19	B	13DEC54	42	0.90	151	892	M	1177	1.32
20	B	16DEC54	38	0.70	260	1098	M	981	0.89
21	B	30DEC55	38	0.35	108	228	M	294	1.29
22	B	31DEC55	45	0.80	182	1010	M	490	0.49
23	B	2JAN56	42	0.45	140	412	M	785	1.91
24	B	5JAN56	38	0.90	269	1461	M	3236	2.21
25	B	28JAN56	44	0.45	147	451	M	490	1.09
26	B	7FEB56	42	0.80	286	1500	M	1373	0.92
27	B	15FEB56	40	0.47	204	603	M	932	1.55
28	B	20FEB56	44	0.40	229	623	M	883	1.42
29	B	4DEC56	34	0.48	231	608	M	245	0.40
30	B	7JAN57	47	0.42	238	716	M	1569	2.19
31	B	10JAN57	38	0.36	212	461	M	883	1.92
32	B	29JAN57	34	0.42	141	324	M	343	1.06
33	B	29JAN57	37	0.38	153	343	M	363	1.06
34	B	18FEB57	37	0.70	316	1304	M	1177	0.90
35	B	22FEB57	34	0.85	284	1324	M	588	0.44
36	B	14MAR58	39	0.85	170	892	M	785	0.88
37	B	16MAR58	42	0.32	182	382	M	588	1.54
38	B	7JAN59	30	0.80	200	785	M	490	0.62
39	B	29JAN59	55	1.43	461	5296	M	3432	0.65
40	B	5JAN65	33	0.53	114	324	M	353	1.09
41	C	20JAN63	40	0.33	170	354	M	M	M
42	C	20JAN63	35	0.39	150	329	M	M	M
43	C	28FEB61	39	0.99	270	1650	M	M	M
44	C	28FEB61	36	0.67	250	965	M	M	M
45	C	20JAN62	32	1.02	230	1219	M	M	M
46	C	25JAN64	35	0.95	220	1176	M	M	M
47	C	8JAN64	45	0.65	M	M	M	M	M
48	C	4FEB63	40	0.76	M	M	M	M	M
49	D	29JAN65	39	M	M	M	M	M	M
50	D	3FEB65	39	M	M	M	M	M	M
51	D	15MAR65	41	M	M	M	M	M	M
52	D	21DEC67	44	M	M	M	M	M	M
53	E	20FEB66	40	M	M	M	M	M	M
54	E	25FEB66	32	M	M	M	M	M	M
55	E	25FEB67	36	M	M	M	M	M	M

## APPENDIX. Cont'd.

See Table 1	Date	$\theta$	h (m)	$\bar{\rho}$ (kg/m <sup>3</sup> )	B <sub>xz</sub> (N/m <sup>2</sup> )	$\rho_B$ (kg/m <sup>3</sup> )	T <sub>B</sub> °C	SFI (N/m <sup>2</sup> )	SFI/B <sub>xz</sub>	
56	E	1MAR67	32	M	M	M	M	M	M	
57	E	28JAN67	33	M	M	M	M	M	M	
58	F	67	28	0.78	130	467	M	M	M	
59	F	67	31	1.03	210	1092	M	M	M	
60	F	67	35	0.56	110	347	M	M	M	
61	F	66	27	0.61	200	543	M	M	M	
62	F	67	33	0.30	180	288	M	M	M	
63	G	22DEC69	33	0.5	260	860	300	- 5.0	1600	1.86
64	G	22DEC69	35	0.3	250	430	300	- 5.0	950	2.21
65	G	22DEC69	35	0.85	240	1120	290	- 6.0	1100	0.98
66	G	22DEC69	36	0.7	250	1100	280	- 1.0	1200	1.09
67	G	25DEC69	40	0.65	230	880	220	- 2.0	2200	2.50
68	G	25DEC69	35	0.8	220	735	280	- 2.0	1400	1.90
69	G	27DEC69	40	1.0	240	1430	310	- 1.0	1900	1.33
70	G	27DEC69	40	0.9	210	1250	140	- 3.0	2000	1.60
71	G	29DEC69	39	0.6	220	745	240	- 3.0	2800	3.76
72	G	18JAN70	33	0.77	250	1040	220	- 1.0	2550	2.45
73	G	18JAN70	34	1.36	260	2010	300	M	2800	1.39
74	G	18JAN70	38	1.43	240	2080	280	- 5.0	3270	1.57
75	G	22JAN70	35	1.08	240	1480	300	- 1.0	2910	1.97
76	G	22JAN70	42	1.6	300	3220	300	- 1.0	1500	0.47
77	G	24JAN70	36	1.3	250	1900	300	- 3.0	1400	0.74
78	G	25JAN70	40	0.91	370	2200	320	- 5.0	2910	1.32
79	G	25JAN70	38	4.2	350	9050	400	- 5.0	7300	0.81
80	G	30JAN70	47	0.8	170	908	230	- 5.0	1900	2.09
81	G	20FEB70	40	0.5	230	708	185	-13.0	600	0.85
82	G	6MART0	35	0.49	140	396	170	-10.0	1000	2.53
83	G	9MART0	40	0.18	110	124	100	- 7.0	200	1.61
84	G	9MART0	42	0.18	90	112	100	- 5.0	240	2.14
85	G	18MART0	38	0.48	140	460	220	- 3.0	800	1.74
86	H	26NOV72	40	0.18	160	182	180	- 7.0	M	M
87	H	6DEC72	42	0.54	134	475	180	- 4.0	M	M
88	H	6DEC72	47	0.42	170	512	150	-10.0	M	M
89	H	26DEC72	37	0.64	224	846	250	M	M	M
90	H	6JAN73	36	0.32	87	160	130	- 4.0	M	M
91	H	13FEB73	40	0.64	101	407	180	M	M	M
92	H	13FEB73	41	0.78	120	602	175	M	M	M
93	H	14FEB73	41	0.57	150	550	225	- 4.0	M	M
94	H	14FEB73	37	0.36	122	259	190	- 5.3	M	M
95	H	7MART3	40	0.20	M	M	220	- 5.0	M	M
96	H	13MART3	30	0.65	126	402	215	- 1.0	M	M
97	H	14MART3	48	0.51	154	572	230	- 2.5	M	M
98	H	15MART3	32	0.55	M	M	- 2.5	M	M	M
99	H	20MART3	41	0.78	130	346	180	M	M	M
100	H	14APR73	36	0.44	450	1141	430	0.0	M	M
101	H	12MAY73	40	0.81	370	1889	330	0.0	M	M
102	I	28DEC73	43	0.26	150	261	200	M	M	M
103	I	31DEC73	40	0.50	150	473	200	- 5.7	M	M
104	I	3JAN74	41	0.78	180	903	250	- 6.5	M	M
105	I	7JAN74	31	0.83	175	734	250	- 3.3	M	M
106	I	8JAN74	42	0.92	220	1328	310	- 4.0	M	M
107	I	9JAN74	26	0.81	140	488	220	- 3.0	M	M
108	I	10JAN74	34	1.29	220	1556	300	M	M	M
109	I	21JAN74	25	1.27	240	1263	300	- 3.0	M	M
110	I	9FEB74	36	0.31	310	554	300	-12.2	M	M

## APPENDIX. Cont'd.

See Table 1		Date	h (m)	$\bar{\rho}$ (kg/m <sup>3</sup> )	$B_{xz}$ (N/m <sup>2</sup> )	$\rho_B$ (kg/m <sup>3</sup> )	T <sub>B</sub> °C	SFI (N/m <sup>2</sup> )	SFI/B <sub>xz</sub>
111	I	22FEB74	38	0.55	220	731	340	- 9.0	M M
112	I	2MAR74	38	1.18	350	2494	365	M M	M M
113	I	2MAR74	41	0.89	240	1374	310	M M	M M
114	I	10MAR74	39	0.08	M	M	340	M M	M M
115	I	10MAR74	39	0.21	182	236	190	- 2.0	M M
116	I	16MAR74	38	0.99	300	1793	240	- 0.0	M M
117	I	16MAR74	37	0.26	223	342	215	- 1.0	M M
118	J	15JAN75	38	0.18	60	65	90	- 11.2	M M
119	J	15JAN75	32	0.47	130	318	110	- 3.3	M M
120	J	25JAN75	32	0.15	100	78	100	- 4.5	M M
121	J	7FEB75	44	0.18	106	130	140	- 8.5	M M
122	J	14FEB75	46	0.64	210	948	270	- 7.5	M M
123	J	15FEB75	50	1.11	175	1459	250	- 4.0	M M
124	J	20FEB75	47	0.25	200	359	90	- 3.0	M M
125	J	22FEB75	42	0.56	160	588	220	- 8.0	M M
126	J	13MAR75	48	0.31	110	248	170	- 3.0	M M
127	K	2DEC71	36	0.85	191	937	260	- 4.0	1400 1.49
128	K	9DEC72	40	0.70	123	541	205	M	1206 2.23
129	K	13DEC72	38	0.57	140	483	M	M	1334 2.76
130	K	30DEC72	42	1.08	310	2197	368	M	8159 3.70
131	K	13JAN73	38	0.39	273	643	300	M	2187 3.40
132	K	13JAN73	39	0.32	220	434	240	M	1317 3.03
133	K	20JAN73	37	0.75	110	486	225	M	703 1.45
134	K	10DEC74	39	0.32	248	490	179	- 8.0	1040 2.12
135	K	17DEC74	42	0.35	136	312	M	- 7.5	610 1.96
136	K	4DEC75	38	0.30	153	277	M	- 4.5	493 1.78
137	K	24FEB76	42	0.27	119	211	M	- 7.2	430 2.04
138	L	1JAN47	M	0.25	M	M	M	- 6.5	M M
139	L	9FEB47	M	1.20	M	M	M	M	M M
140	L	13MAR47	37	0.60	M	M	M	0.0	M M
141	L	18DEC48	37	0.82	M	M	M	M	M M
142	L	3JAN49	M	0.47	M	M	M	- 4.5	M M
143	L	3JAN49	M	0.62	M	M	M	- 1.0	M M
144	L	3JAN49	M	M	M	M	M	- 2.0	M M
145	L	3JAN49	M	M	M	M	M	- 3.0	M M
146	L	18JAN49	M	0.73	M	M	M	M	M M
147	L	18JAN49	M	0.38	M	M	M	- 9.3	M M
148	L	20MAR49	M	1.40	M	M	M	- 6.5	M M
149	L	7APR50	45	0.36	M	M	M	M	M M
150	L	26JAN51	32	0.60	M	M	M	M	M M
151	L	23JAN52	42	1.18	M	M	M	M	M M
152	L	24MAR52	36	0.53	M	M	M	M	M M
153	L	20APR52	36	1.18	M	M	M	M	M M
154	L	12JAN52	38	0.43	M	M	M	M	M M
155	L	4FEB53	36	0.61	M	M	M	- 6.5	M M
156	L	9FEB53	M	1.05	M	M	M	M	M M
157	L	27FEB55	40	0.80	M	M	M	M	M M
158	L	11DEC54	42	0.85	M	M	M	M	M M
159	L	2DEC56	37	0.61	M	M	M	- 1.5	M M
160	L	9JAN57	31	0.35	M	M	M	M	M M
161	L	15MAR58	35	0.70	M	M	M	- 6.0	M M
162	L	17MAR58	30	0.47	M	M	M	M	M M
163	L	14DEC58	40	0.35	M	M	M	- 4.0	M M
164	L	17DEC58	39	0.50	M	M	M	- 2.0	M M
165	L	30DEC59	37	1.60	M	M	M	- 1.0	M M

## APPENDIX. Cont'd

See Table 1		Date	$\theta$	$h$ (m)	$\bar{\rho}$ (kg/m <sup>3</sup> )	$B_{xz}$ (N/m <sup>2</sup> )	$\rho_B$ (kg/m <sup>3</sup> )	T <sub>B</sub> °C	SFI (N/m <sup>2</sup> )	SFI/B <sub>xz</sub>
166	L	8JAN61	50	0.30	M	M	M	- 3.5	M	M
167	L	1FEB61	37	0.33	M	M	M	- 3.0	M	M
168	L	29JAN62	34	0.50	M	M	M	- 5.0	M	M
169	L	10FEB62	39	1.00	M	M	M	- 2.0	M	M
170	L	8JAN63	43	0.90	M	M	M	- 8.0	M	M
171	L	15JAN63	M	M	M	M	M	- 4.0	M	M
172	L	3APR63	38	0.48	M	M	M	- 2.0	M	M
173	L	27JAN63	37	0.56	M	M	M	- 13.0	M	M
174	L	19MAR63	44	0.30	M	M	M	- 1.5	M	M
175	L	19MAR63	45	0.30	M	M	M	- 2.5	M	M
176	L	26MAR63	37	0.38	M	M	M	- 2.0	M	M
177	L	12APR64	36	0.50	M	M	M	0.0	M	M
178	L	8FEB64	45	0.25	M	M	M	- 5.0	M	M
179	L	13FEB64	35	0.41	M	M	M	- 7.0	M	M
180	L	14FEB64	35	0.48	M	M	M	- 7.0	M	M
181	L	2MAR64	37	0.36	M	M	M	- 2.5	M	M
182	L	8JAN65	31	0.20	M	M	M	- 5.0	M	M
183	L	18FEB65	30	0.35	M	M	M	- 4.0	M	M
184	L	5JAN65	32	1.02	M	M	M	- 7.5	M	M
185	L	5JAN65	40	0.34	M	M	M	- 6.0	M	M
186	L	7MAR65	37	0.60	M	M	M	- 3.0	M	M
187	L	24FEB66	37	0.48	M	M	M	- 5.0	M	M
188	L	23FEH67	38	0.24	M	M	M	- 4.0	M	M
189	L	13MAR68	38	0.24	M	M	M	- 6.0	M	M
190	L	8JAN68	37	0.65	M	M	M	M	M	M
191	L	13FEB69	35	0.57	M	M	M	- 9.0	M	M
192	L	21FEB69	40	1.07	M	M	M	M	M	M
193	L	28FEB69	35	0.34	M	M	M	M	M	M
194	L	10MAR69	36	1.08	M	M	M	M	M	M
195	L	22MAR69	47	0.21	M	M	H	0.0	M	M
196	L	25FEB70	40	1.38	M	M	H	M	M	M
197	L	18JAN70	39	0.74	M	M	M	- 2.0	M	M
198	L	2FEB71	40	0.51	M	M	M	- 2.5	M	M
199	L	11APR71	32	0.85	M	M	M	0.0	M	M
200	L	3JAN71	42	0.47	M	M	M	-11.0	M	M
201	L	9MAR71	49	0.48	M	M	M	- 3.0	M	M
202	L	17FEB72	38	0.33	M	M	M	- 7.0	M	M
203	L	18FEB72	30	1.26	M	M	M	- 2.5	M	M
204	L	21FEB72	40	0.67	M	M	M	- 6.0	M	M
205	L	3FEB73	47	0.28	M	M	M	- 4.0	M	M