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INSTRUMENTS AND METHODS

THE RESISTOGRAPH AND THE COMPRESSIVE STRENGTH OF SNOW

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Abstract. A recent field comparison of snow strength as measured by the snow resistograph and compressive strength as measured by direct loading to failure indicates good agreement in the range 25–400 g/cm².

Résumé. *Le résistographe et la force de compression de la neige*. Une récente comparaison sur le terrain de la force de cohésion de la neige mesurée à l'aide du résistographe, et de la force de compression mesurée par charge directe jusqu'à la rupture, donne un bon accord dans l'intervalle 25–400 g/cm².

Zusammenfassung. *Der Resistograph und die Druckfestikgeit des Schnees*. Die kürzlich im Freien vorgenommenen Vergleiche von Messungen der Druckfestigkeit des Schnees haben ergeben, dass die mit dem Schnee-Resistograph gewonnenen Werte mit jenen, wie sie durch unmittelbare Belastung bis zum Bruch ermittelt wurden, im Bereich von 25–400 g/cm² gut übereinstimmen.

Introduction

The snow resistograph (Fig. 1) is a field instrument designed for the rapid *in situ* measurement of snow strength. It consists of a probe with a horizontal bit at the bottom. The probe is pushed vertically down to the base of the snowpack, rotated 90 deg., and withdrawn. The resistance to upward movement encountered by the bit is balanced by a spring in the handle and thereby transmitted to a scribe. The rise and fall of the scribe is recorded on a roll of paper unwinding at a rate controlled by the rate of withdrawal of the probe. The graph (resistogram) thus produced shows resistance as a function of snow depth. On the assumption that the force necessary to move the bit upward is essentially the same as the force required to break the snow at that depth, the graph becomes a strength profile (except in the 10 cm disturbed portion at the base of the pack). The working scale for the resistograms is derived by dividing the force in grams by the area of the top silhouette of the bit in cm².

Variations in the rate of withdrawal, of course produce variations in the resistogram. Too rapid a rate introduces a momentum error, while too slow a rate allows compaction of snow ahead of the blade which in turn introduces spurious oscillations and the recording of "false crusts". Trial and error indicates that a withdrawal rate of 10 cm/s is about optimum. Consistency of withdrawal at this rate produces quite consistent results (Bradley, 1966).

The success of the snow resistograph used in conjunction with the Federal snow sampling tube to evaluate collapsing conditions in the snow-pack (Bradley and Bowles, 1967) suggests that either both instruments are delivering reasonably accurate measurements, or that consistent errors in the two instruments tend to cancel each other.

Work (1964) shows that the standard Federal snow sampler tends to overmeasure on the average 7 per cent and up to 12 per cent in very deep snow. Keeler and Weeks (1967) concluded that the resistograph, when compared to the torque shear vane, is responsible for inconsistencies up to a factor ten in its normal working range of 50–1 400 g/cm². These discrepancies underline the need for testing resistograms against some more direct measurements of snow strength. However, this is not an easy matter. The instrument is designed to measure snow so weak that a sample cannot be detached and stressed in the usual way.

LaChapelle (personal communication in 1965) suggested a field test which looked promising:

1. Select a site with a snow-pack which possesses a weak basal layer.
2. Place a plywood template of suitable area flat on the snow surface and with a thin blade cut the snow vertically down to the ground around the template.

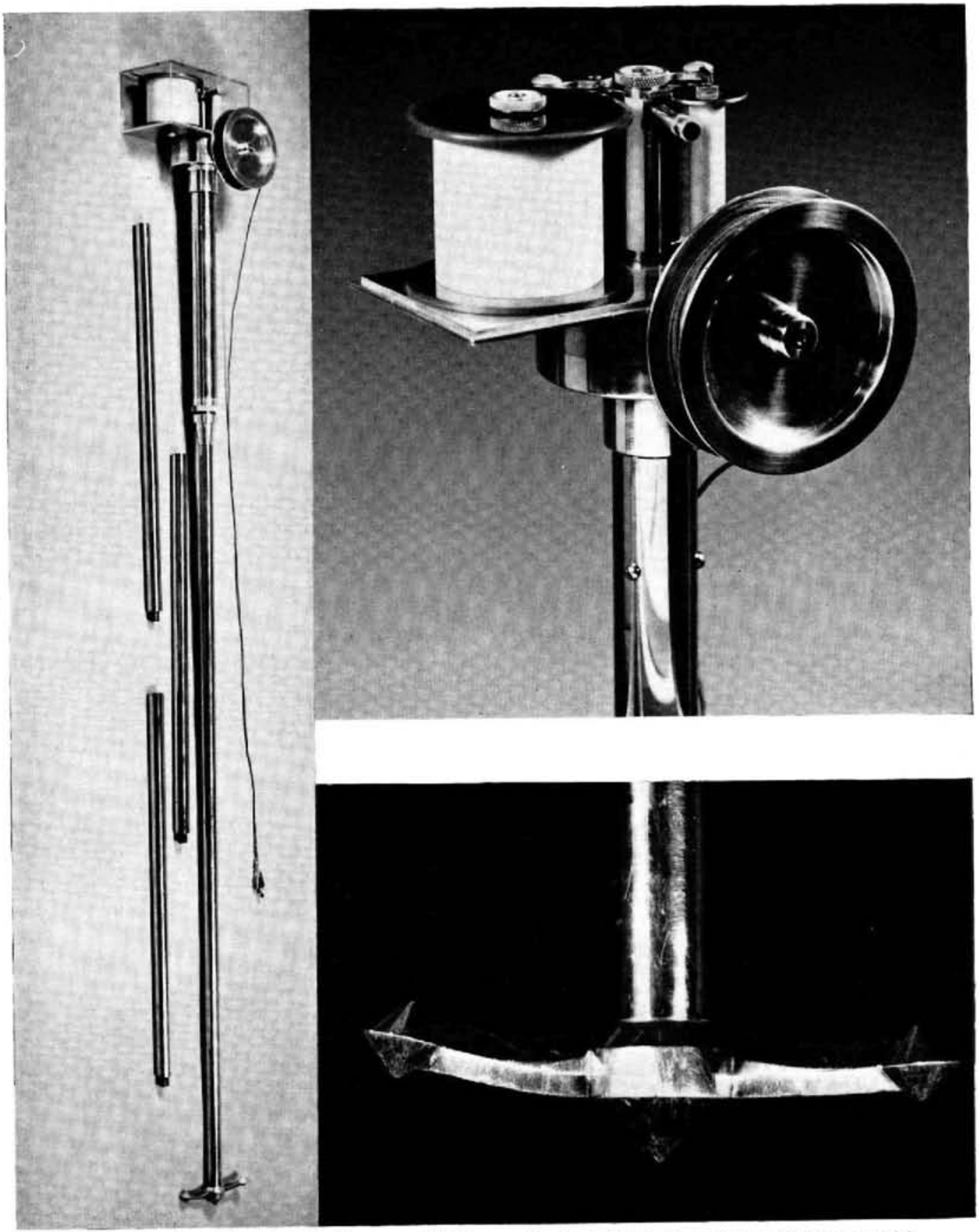

Fig. 1. The snow resistograph. Assembled instrument (left); recording head (top right); resistance bit (bottom right).

3. Leaving the template in place as a platform, apply load to it until the basal snow collapses.
4. Calculate compressive strength from the total load applied and area of the template according to the equation

$$\sigma_C = L/A.$$

GENERAL PLAN

On 15 April 1967 ideal conditions for such a test were discovered in meadows along the Gallatin River in Yellowstone Park. Preliminary resistograms showed a very weak basal layer in an otherwise strong snow-pack having depths ranging from 50–150 cm. Snow columns cut with a saw to a cross-sectional area of approximately 1 000 cm² generally collapsed under the weight of a man.

Two tests were conducted—one on 16 April and the other on 23 April—in a snow-pack essentially isothermal at 0°C. General procedure followed LaChapelle's suggestion. After the column was cut, an initial dead load was placed on the template. The top element of this dead load was a Borg household scale on which human weight was gradually added to produce the collapse within the limit of the scale (250 lb = 114 kg). If the column did not collapse within this limit, more dead weight was added and a new trial was made on the column.

For this procedure the working equation thus becomes

$$\sigma_C = (i+x)\,A^{-1}+\lambda$$

where σ_C is the compressive strength (g/cm²), λ the existing snow load on the basal layer as determined by a snow sampling tube (g/cm²), i the initial dead weight (g), x the added weight recorded on the household scale at the time collapse (converted to g), and A the area of the template (cm²). For comparison σ_R is the minimum basal snow strength as taken from resistograms (Fig. 2).

DISCUSSION

The resistograph is strictly a field instrument. The intent of this *in situ* test was, of course, to duplicate as nearly as possible the standard laboratory test for compressional strength without disturbing or abandoning the field situation. In addition, the method is apropos in that it tests very directly the theory of snow-pack collapse which lies back of our deep slab avalanche investigations at Montana State University.

Basic to standard compressive strength tests is a standard ratio of cross-sectional area to length of the block to be tested. This aspect was disregarded here in part because of the practical problem of load transport and application and in part because the weak layer to be tested is nearly impossible to define in terms of length. Almost surely when the load exceeds the strength of the weakest zone snow collapse is initiated and thereafter cascades dynamically of its own momentum involving more and more of the column until equilibrium is restored. The "weakest zone" may have essentially no depth or at best a highly variable depth (see Fig. 2).

Three assumptions are associated with the purpose of the saw cut which detaches the snow column:

1. The strong upper part of the snow column will be free to move vertically like a piston along frictionless planes.
2. The saw does not disturb the weak zone.
3. The confining forces on the very friable porous weak layer are essentially zero and the test is hence for *unconfined* compressive strength.

Obviously, these assumptions are not entirely valid. However, under the actual working conditions which were encountered it is probable that error from these sources was no greater than errors from other sources.

Test 1, 15 April, Meadow near Specimen Creek Junction (Table I)

The template used was a nearly square piece of plywood selected at random from a scrap pile. Its area was 1 320 cm². Since the snow was only about 65 cm deep, a carpenter's saw was satisfactory for cutting the snow. After the saw cut, the household scale was placed on the template. My assistant (Mrs Bradley) eased her weight onto the scale while I watched the dial up to the moment of collapse. Because of unsteadiness the method contained a probable error of ±2 kg.

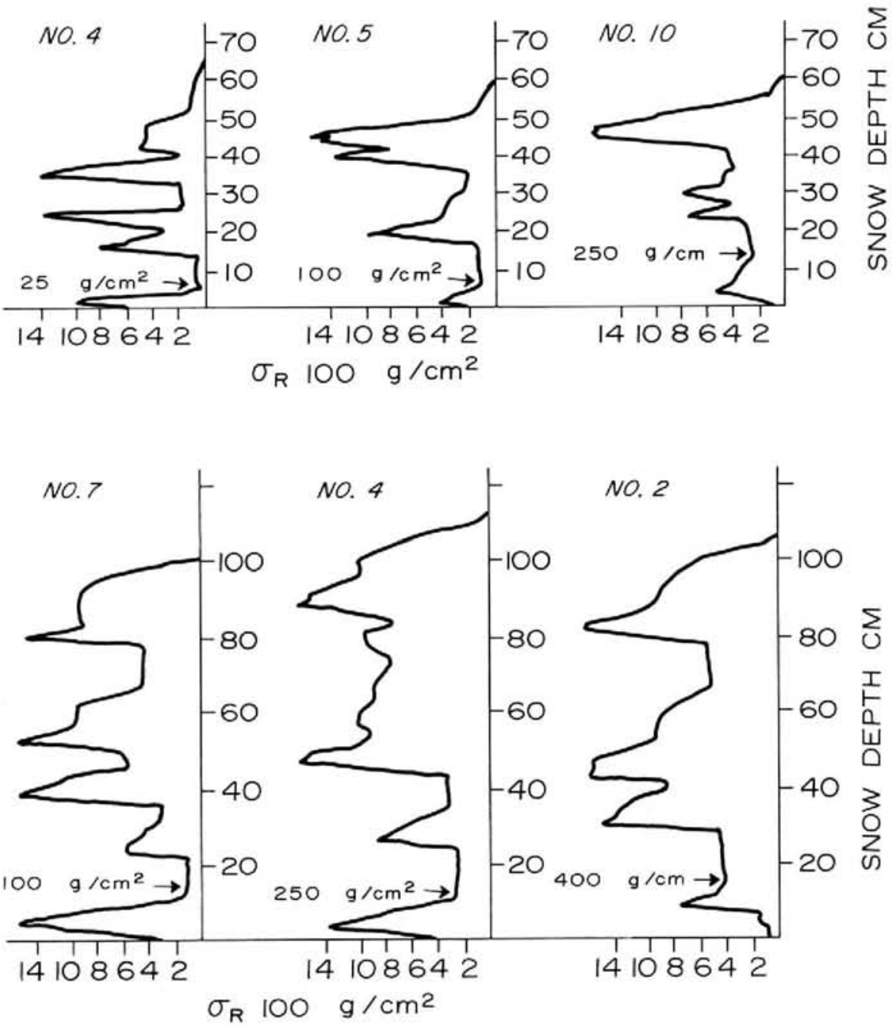

Fig. 2. Representative resistograms from Test 1 (top) and Test 2 (bottom).

Collapse when it came was very sudden and amounted to a drop of 10–20 cm.

Fourteen resistograms (Fig. 2) were also taken randomly in the same general area of the meadow. Resistograms carry a hysteresis variability of about ±15 g/cm². Except in the very lowest range the resistograms were usually read to the nearest 50 g/cm².

Snow load λ for the test was calculated at 20 g/cm² from the average of six sampling tube cores to the nearest 0.5 g/cm². These ranged from 16.5 g/cm² to 21.5 g/cm².

Initial dead weight i consisted of the combined weight of the scales and template and was approximately 3 kg. All figures for Table I were taken to the nearest whole number. In the last three test blocks, collapse occurred after the maximum reading on the scale was passed. In these x is estimated by extrapolation.

Table I. Comparative Snow Strength Measurements for Test 1 at Specimen Creek, Yellowstone Park, 16 April 1967. $\sigma_C = (i+x)\,A^{-1}+\lambda$ where $\lambda = 20$ g/cm², $i = 3$ kg, x is the Weight Added to Produce Collapse, $A = 1\,320$ cm², σ_C is Minimum Compressive Snow Strength, and σ_R Minimum Snow Strength as Measured by the Resistograph

Block no.	x kg	σ_C g/cm²	σ_R g/cm²
1	100	98	25
2	57	65	25
3	34	48	100
4	27	43	25
5	91	91	100
6	73	78	25
7	91	91	50
8	104	101	100
9	77	81	200
10	77	81	250
11	59	67	50
12	120 (estimate)	113	150
13	120 (estimate)	113	50
14	120 (estimate)	113	50
Average		85	86

Results

The fourteen compressive tests showed a minimum basal snow strength ranging between 43–100 g/cm² with an average of 85 g/cm². The resistograms showed a range of from 25–250 g/cm² with an average of 86 g/cm². The wider range of resistograms is to be expected since the blade area of the instrument (6.5 cm² as compared to the template area of 1 320 cm²) would be much more sensitive to small-scale variations of the snow-pack. The very close agreement of the two averages is, of course, somewhat fortuitous.

Test 2, 23 April, Meadows near Grayling Pass (Table III)

Certain refinements over Test 1 were introduced into Test 2:

1. By way of simplification a template was constructed with an area of 453 cm² which permits direct numerical conversion from pounds of weight to load in g/cm².
2. The individual blocks were spaced one meter apart in a straight east–west line across the meadow with each resistogram taken 50 cm south of each compression test (Fig. 3). The intent here was to get a more direct comparison of each test block with adjacent resistograph measurement.
3. Snow load λ was obtained by coring the center of each collapsed block thereby giving λ specific to that block.

The area was selected because preliminary resistograms showed that the snow-pack possessed a basal snow strength in a higher range but overlapping with that of Test Site 1. Snow depth was about 100 cm which necessitated the use of a one-man woodcutter's cross-cut saw. In addition, the deeper snow required a double cut to be made on each side of the block because preliminary testing revealed that friction on the sides of the snow block tended to impart significant spurious resistance to collapse.

Initial dead weights *i* were developed from local materials organized into the units as shown in Table II and applied in the sequence indicated. The household scale, of course, was placed on top of the load and body weight *x* added to produce collapse.

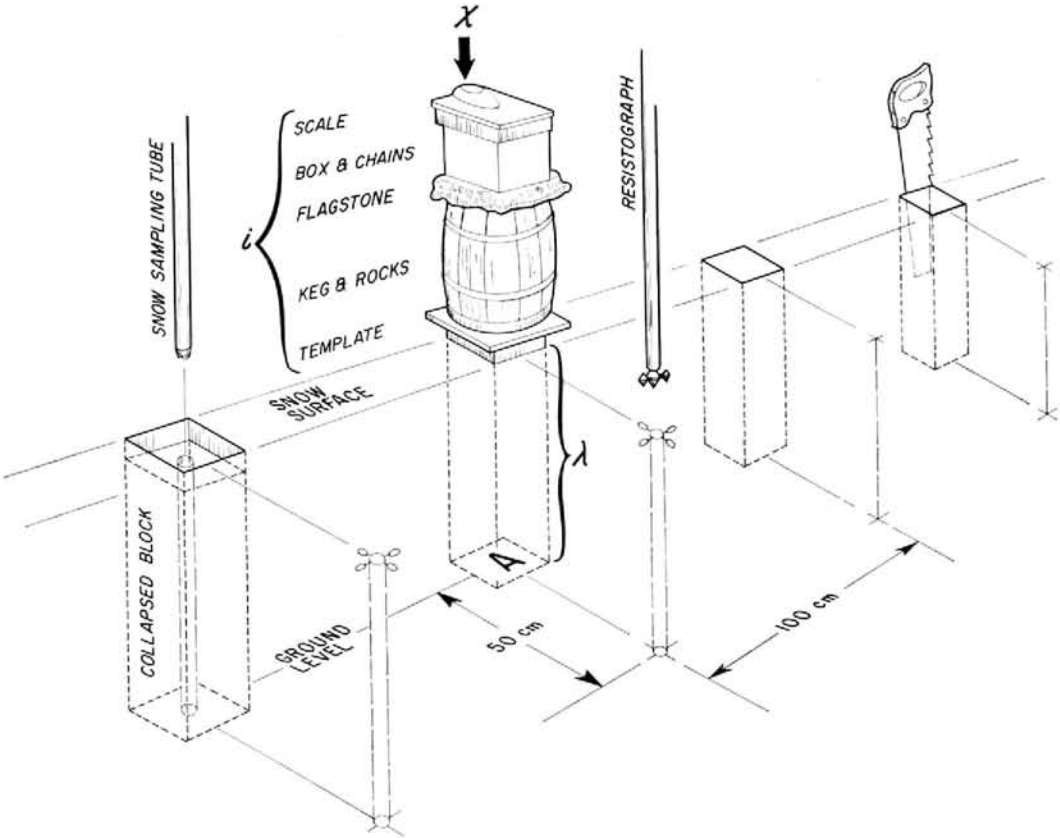

Fig. 3. Perspective diagram illustrating schematic arrangement for Test 2.

TABLE II. DEAD LOADS *i* USED IN TEST 2. WEIGHT IN lb ON TEMPLATE WITH AN AREA OF 453 cm² IS NUMERICALLY EQUAL TO LOAD IN g/cm²

	Weight lb	*Cumulative dead load* g/cm²
Borg scale and template	11	11
Keg of rocks	75	86
Flagstone	50	136
Box of chains	47	183

Thirteen blocks were tested. In blocks 4 and 5 the snow collapsed just after *x* reached scale limit (114 kg). Block 8 collapsed as the flagstone was being deposited and before the scale had been added. The loads in these three cases, of course, are estimated by interpolation. Also, resistogram 5 did not reach bottom. The blade hit sagebrush and therefore the basal measurement may not show true minimum strength. Table III details the results of measurement and calculation. Figure 4 compares the two methods. Figure 2 shows three typical resistograms.

TABLE III. COMPARISON OF SNOW STRENGTH MEASUREMENTS FOR TEST II AT GRAYLING PASS, YELLOWSTONE PARK, 23 APRIL 1967. COMPRESSIVE STRENGTH $\sigma_C = (i+x)\,A^{-1} + \lambda$ WHERE $A = 453$ cm² (SEE TABLE I)

Block no.	iA^{-1}	xA^{-1}	λ	σ_C	σ_R
1	86	195	45	326	275
2	86	150	44	280	400
3	86	185	44	325	350
4	136	260 (estimate)	41	437	250
5	183	260 (estimate)	41	484	150
6	183	80	44	307	300
7	183	50	41	274	100
8	121 (estimate)	0	45	166	300
9	183	125	43	351	300
10	136	65	45	246	200
11	136	115	45	296	300
12	183	135	42	360	275
13	183	115	42	340	350
Average				322	273

Results

1. The thirteen compressive tests revealed a basal snow strength which ranged from 166–484 g/cm² and had an average strength of 322 g/cm². The thirteen resistograms showed the range to be from 100–400 g/cm² with an average of 273 g/cm². Both methods gave about the same general spread with the resistograph recording somewhat lower strength values. It should be recalled here that in comparison with Test 1 the blocks of Test 2 are much longer and narrower. In spite of the double saw cuts it is likely that this discrepancy can be explained in part by additional friction on the sides of the test blocks which had to be overcome by additional load.

2. The lack of systematic strength trends in either the compressive tests or the resistograms (Fig. 4) indicates that the variability in basal snow strength exists at some scale less than the one meter spacing between the blocks, and rules out any meaningful correlation between each σ_C and adjacent σ_R.

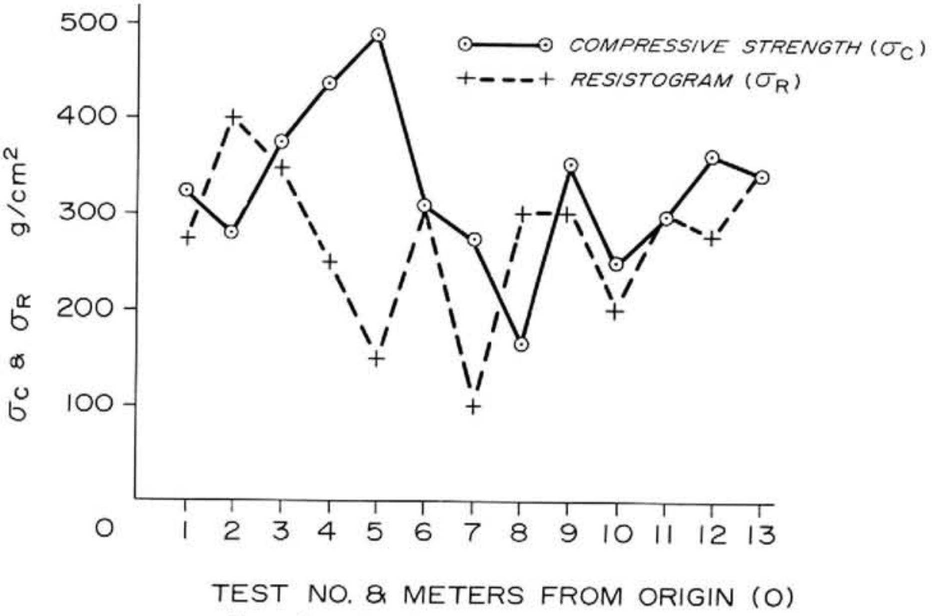

Fig. 4. Comparison of σ_C and σ_R with respect to position.

CONCLUSION

On the basis of these two comparative tests it appears that the resistograph provides *in situ* measurements roughly equivalent to the crushing strength of snow in the range 25–400 g/cm^2 at temperatures close to 0°C.

Though desirable, from a practical standpoint it would be quite difficult to continue the LaChapelle test into the upper ranges of the resistograph (400–14 00 g/cm^2). It is doubtful if the area of the template should be reduced any further. This makes for very difficult load manipulation. It can be said here that with instruments like the resistograph and the torque shear vane, of necessity, a certain amount of "art" goes into measurement taking. The operator's actions will, to a certain extent, depend upon the "feel" of things. The whole feel of the resistograph as it comes up through the snow-pack suggests to this operator that readings in excess of 1 000 g/cm^2 may carry considerable error. Up to approximately this point the blade moves through the snow quite smoothly. In these upper ranges, however, the blade, as designed, tends to stop and then break through setting up oscillations very difficult to control by hand. However, in terms of the avalanche problem for which the resistograph was designed we have already reached a practical limit.

Our original hypothesis (Bradley, 1966) states that deep slab avalanches may be initiated by collapse of the weak basal layer under the weight of the overlying snowpack. The strength–load ratio at the base of the pack is used as an index of systemic weakness with a ratio of 1.0 being the theoretical minimum.

The resistograph is used to measure the strength and the snow sampling tube is used to obtain load. In four years of study with these instruments, collapse has been observed only when the basal strength load ratio was less than 2.0 and greater than 1.0. When the ratio is greater than 4.0 the snow-pack appears to be very stable even when explosive charges are used.

Assuming a basal snow strength of 400 g/cm^2 and a greater than average snow density (0.4 g/cm^3) it would take at least 5 m of snow to produce collapsing conditions. 2.5 m of snow is about the normal maximum for the Bridger Range of Montana and is the current maximum length of the resistograph shaft. Within the above limits, then, we conclude at this time that the general usefulness and accuracy of the snow resistograph has for practical purposes been demonstrated.

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REFERENCES

Bradley, C. C. 1966. The snow resistograph and slab avalanche investigations. *Union de Géodésie et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique. Commission pour la Neige et la Glace. Division Neige Saisonnière et Avalanches. Symposium international sur les aspects scientifiques des avalanches de neige, 5–10 avril 1965, Davos, Suisse*, p. 251–60.

Bradley, C. C., *and* Bowles, D. 1967. Strength-load ratio: an index of deep slab avalanches. (*In* Ōura, H., *ed. Physics of snow and ice: international conference on low temperature science. ... 1966. ... Proceedings*, Vol. 1, Pt. 2. [Sapporo]. Institute of Low Temperature Science, Hokkaido University, p. 1243–53.)

Keeler, C. M., *and* Weeks, W. F. 1967. Some mechanical properties of alpine snow, Montana 1964–66. *U.S. Cold Regions Research and Engineering Laboratory. Research Report* 227, p. 22–23.

Work, R. A. 1964. Fidelity of snow sampling tube results. *Transactions. American Geophysical Union*, Vol. 45, No. 4, p. 609.