Journal of Glaciology, Vol. 12, No. 65, 1973

INSTRUMENTS AND METHODS

COMPARISON OF THE SNOW RESISTOGRAPH WITH THE RAM PENETROMETER

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ABSTRACT. Comparative tests of the snow resistograph with the ram penetrometer indicate that there is a high degree of correlation between the two instruments despite fundamental differences in operation. It is probable therefore that the two instruments are measuring essentially the same parameters and may be used interchangeably. The resistograph has a large advantage over the ram penetrometer, in terms of speed and ease of operation, and in its capacity to measure the strength of very weak snow.

RÉSUMÉ. *Comparaison entre le résistograph à neige et la sonde de battage.* Des tests comparatifs du résistographe à neige et de la sonde de battage montrent qu'il y a une excellente corrélation entre les deux instruments en dépit des différences fondamentales entre les modes opératoires. Il est donc probable que les deux instruments mesurent essentiellement les mêmes paramètres et peuvent être interchangeables. Le résistographe a un grand avantage sur la sonde de battage quant à la vitesse et la facilité d'opération et quant à sa capacité de mesurer la résistance de neiges très fragiles.

ZUSAMMENFASSUNG. *Vergleich zwischen dem Schnee-Resistographen und der Ramm-Sonde.* Vergleichende Versuche mit dem Schnee-Resistographen und der Ramm-Sonde zeigen, dass zwischen den beiden Geräten trotz grundsätzlicher Unterschiede in der Arbeitsweise sehr nahe Verwandtschaft besteht. Das kommt vermutlich daher, dass die beiden Geräte im Prinzip dieselben Parameter messen und wechselweise benutzt werden können. Die grossen Vorteile des Resistographen gegenüber der Ramm-Sonde liegen in der Schnelligkeit und Einfachheit seiner Arbeitsweise und in seiner Fähigkeit, die Festigkeit auch sehr weichen Schnees zu messen.

INTRODUCTION

The ram penetrometer has long been accepted as the standard instrument for measuring the relative strengths of various strata within the snowpack. The penetrometer, which is of uncomplicated design and operation, has its major deficiency in the large amount of data that must be recorded by hand and the subsequent time required for data reduction to produce a ram profile.

The snow resistograph was developed (Bradley, 1966) to aid in the investigation of the mechanism of avalanche release. This instrument has the capability of making a strength profile of the snowpack stratigraphy in a fraction of the time required with the ram penetrometer, and requires a minimum amount of time for data reduction.

THE RAM EQUATIONS

The ram penetrometer was developed by Haefeli (Bader and others, 1939) to fulfill a need for a simple field instrument which could be used to determine the relative strength properties of a stratified snowpack without resorting to the digging of pits.

The relation that governs the ram penetrometer is based on the principle of the conservation of energy and momentum, and in its most general form may be written (using Haefeli's notation) as:

$$W = \frac{L}{S} + (R+Q) \qquad (1)$$

where

$$L = Rh \, . \, \frac{R+\eta^2 Q}{R+Q} \qquad (2)$$

with the following definitions being given as: W = ram resistance, s = depth of penetration, R = weight of the ram, Q = weight of the cone assembly, h = height from which the ram was dropped, and η = coefficient of restitution.

The physical interpretation given to the ram resistance (or ram number as it is sometimes called) is the amount of resistive force required to dissipate the energy of the hammer and cone assembly over a measured depth of penetration for a given size and shape of cone.

Equation (1) can be reduced to three different forms, depending on the value of the coefficient of restitution (η). For $\eta = 1$ we have the case of perfectly elastic impact where all the impact energy of the ram and cone is recovered, and Equation (1) reduces to the familiar form

$$W = \frac{Rh}{S} + (R+Q) \tag{3}$$

when $\eta = 0$ we have perfectly plastic impact between the ram and cone assembly which indicates that the total energy of the impact is dissipated. In this case Equation (1) becomes

$$W = \frac{R^2h}{(R+Q)S} + (R+Q). \tag{4}$$

The last form that Equation (1) can assume is where the coefficient of restitution assumes some value between zero and one ($0 < \eta < 1$), which is the case for all real materials. The physical implication in this instance is that, during the period of impact between the ram and cone assembly, a certain amount of the energy of the system is lost and part is recovered. In this case Equation (1) remains unchanged.

Haefeli (Bader and others, 1939) has stated that the value of the coefficient of restitution may be considered large ($\eta \to 1$) on the basis that stresses outside the elastic range of the penetrometer do not occur. With this assumption, Equation (3) has been used when calculating the ram resistance. The value of $\eta = 1$ has recently been questioned (Waterhouse, 1966) and it has been suggested (Perla, 1969) that a more appropriate value for the coefficient of restitution should be taken as 0.5. The effect of using a coefficient of restitution of 0.5 in calculating the ram resistance is depicted in the ram profile shown in Figure 1b. The net effect is to reduce the higher ram values by a significant amount.

In determining the ram resistance, the resistive force measured is the average value for the depth of penetration. In most instances where a ram profile is taken, to expedite the actual data collection, Equation (3) is modified to the form

$$W = \frac{nhR}{S} + (R+Q) \tag{5}$$

where n represents the total number of drops of the hammer.

In using the ram profile for determining the relative strengths of various strata, the limitations of the relations which govern it should be kept in mind. For any depth of penetration, the ram number gives an average value of the snow's resistance to penetration; these values are then connected in the form of the discontinuous curve of the profile. This curve can then reflect either real discontinuities in the snow structure, or discontinuities which are functions of the governing relations of the instrument. Generally, the two types of discontinuities can be differentiated in the field and supplementary notes will indicate the precise position of the discontinuity.

The snow resistograph

The snow resistograph (Bradley, 1968) is an instrument capable of recording variations in the strength of the snowpack in a rapid and continuous manner. To obtain a relative strength profile of the snowpack using the resistograph (resistogram), the shaft of the instrument is

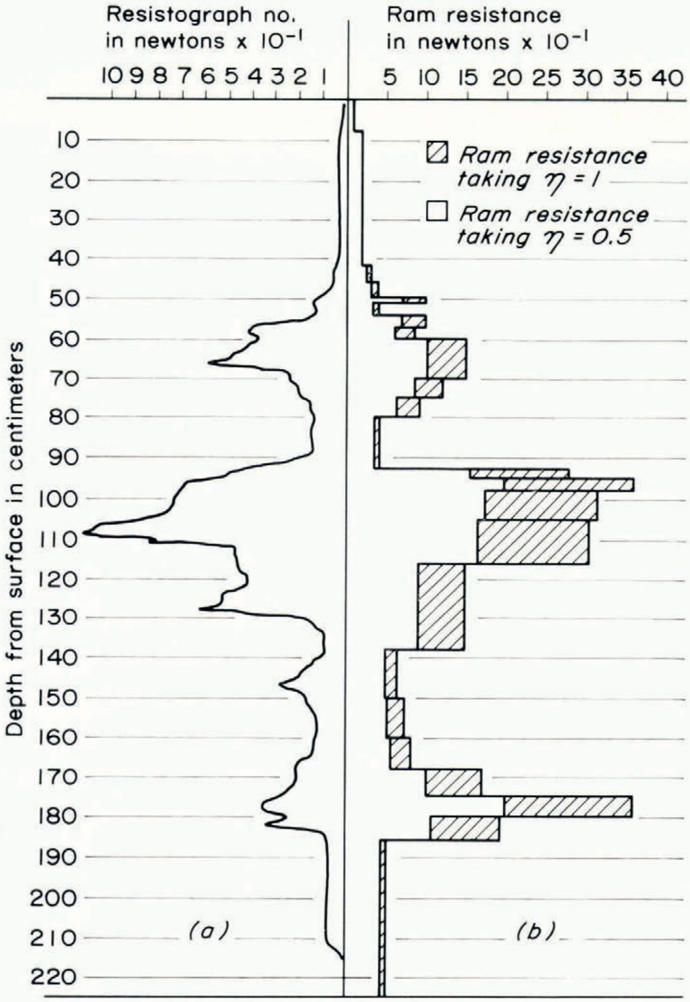

Fig. 1. (a) Resistograph profile made at Berthound Pass, Colorado; (b) Corresponding ram profile shows the effect of taking η as 1 and 0.5.

drawn through the snowpack. As the double cone probe at the tip of the instrument encounters the varying resistance within the pack, a record is traced on a paper tape. This tape is enclosed in a lucite case which protects it from snow and water damage. The system is arranged such that a number of resistograms can be made without removing the protective cover of the instrument. A reduction of 1 : 10 in the depth function of the resistogram over the actual snow depth is obtained through a gear train in the mechanism. Figure 1a shows a typical resistogram taken at Berthound Pass, Colorado, in comparison with a ram profile.

Unlike the record obtained with the ram penetrometer, the resistograph records structural variation of the snowpack in a continuous manner. Variations in the mechanical composition of the snow which show a discontinuity with the rest of the pack (i.e. ice layers) can be recognized by steep slopes (1 : 10) on the resistogram, while graded variations are indicated by lesser variations in the slope of the resistogram curve.

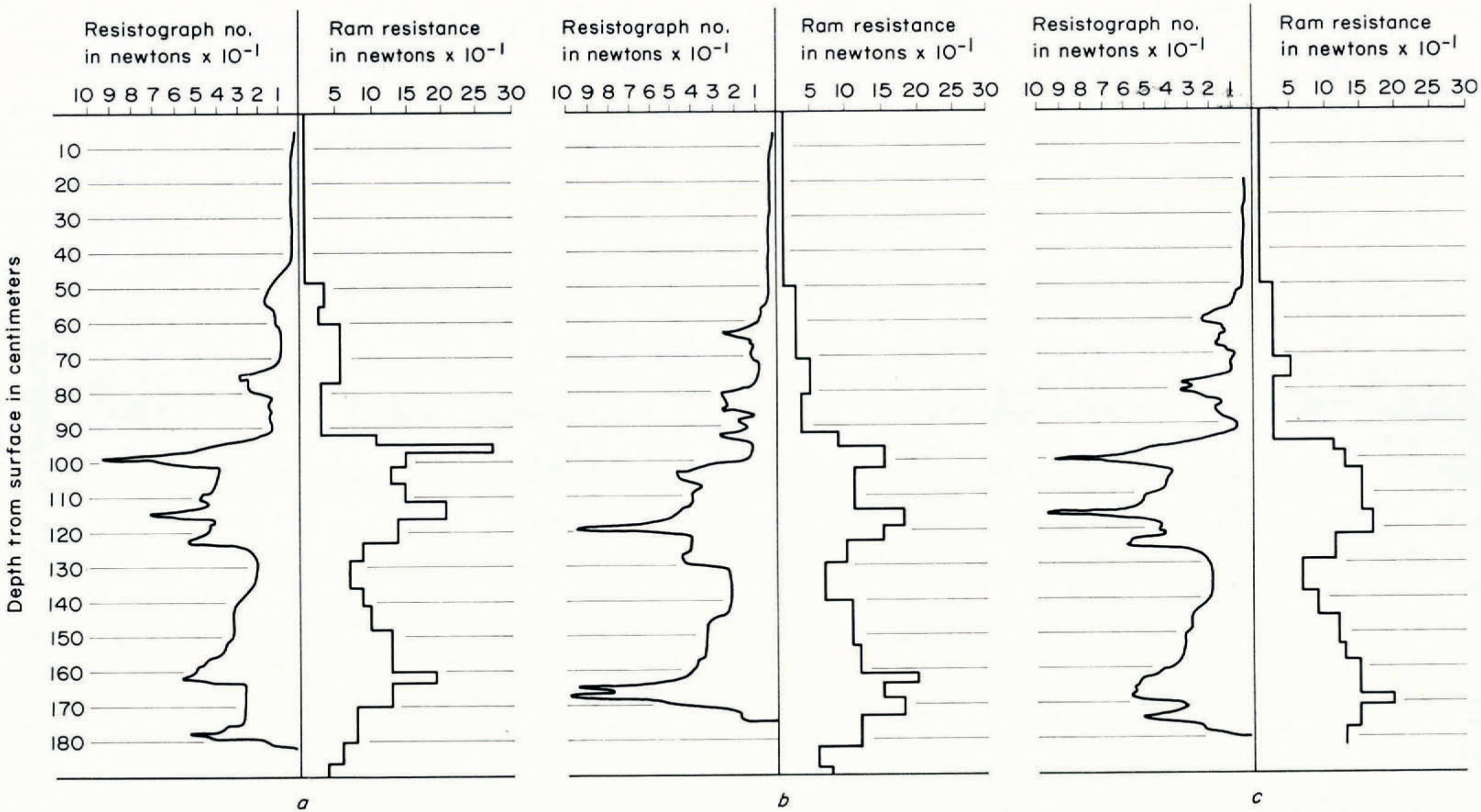

Fig. 2a–c. Three resistograms and corresponding ram profiles at Grayling Pass, Montana, during February 1971.

Comparative data

To compare the snow resistograph with the ram penetrometer, a number of profiles were made with each instrument. These tests were conducted in the area of Grayling Pass, Montana, during February and March 1971. The first set of data obtained was collected to judge the degree of autocorrelation of each instrument and also to compare the profiles obtained between the two. Three ram profiles were taken along a straight line equally spaced at 25 cm; parallel to the line of ram holes, and at a distance of 25 cm, three corresponding resistograms were obtained. Figure 2 indicates the results of this test.

As can be observed in Figure 2, both the ram and resistograph data indicated the same general stratigraphy in each of the profiles. In the case of the ram profile, especially in the 9–130 cm depth range, the two high peaks recorded in profile (a) seem to become less acute in profile (b). In profile (c) the resistance to penetration is shown as a monotonically increasing function from 100 to 123 cm in depth and then monotonically decreasing over the next 15 cm.

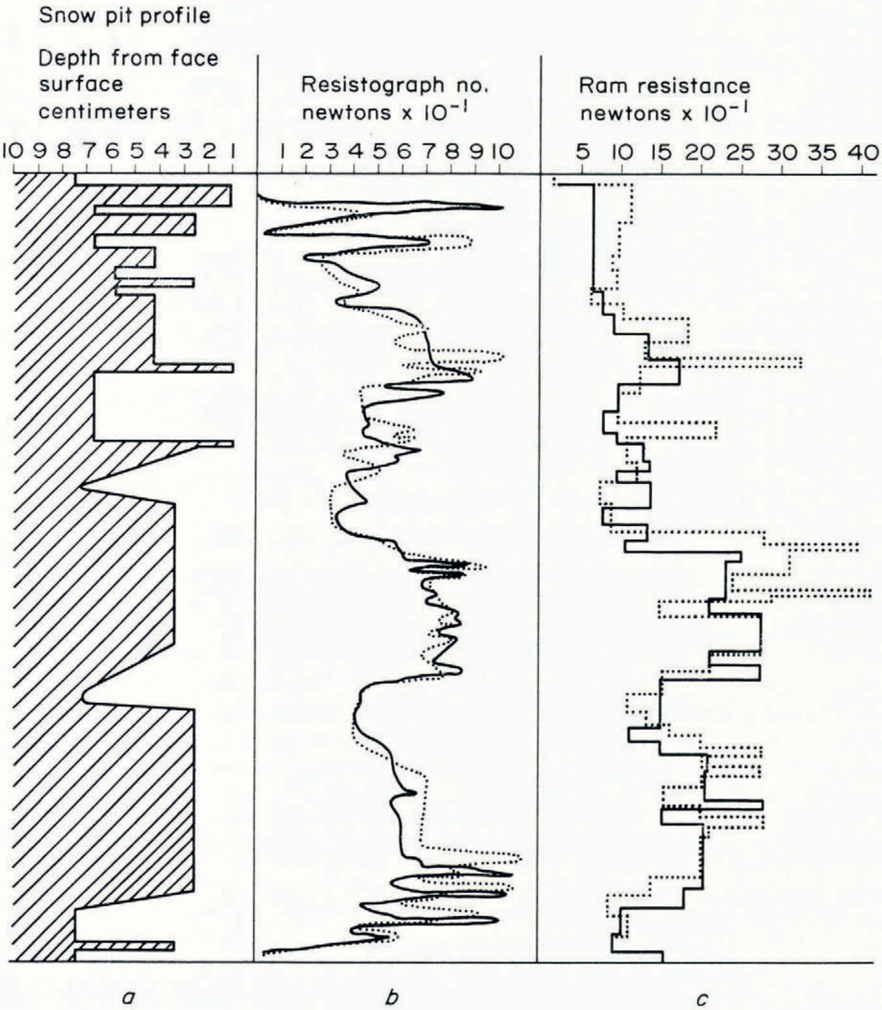

Fig. 3. (a) Snow-pit profile made by brushing of the pit wall; (b) Overlay of two corresponding resistograms; (c) Overlay of corresponding ram profiles. All data were collected at the same location.

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Each resistogram indicates three distinct discontinuities existing in the snowpack in this depth range.

In the second test, a snow pit was excavated after two ram profiles and two corresponding resistograms had been made. The results of this test are shown juxtaposed in Figure 3. The snow-pit profile is based on the investigator's observations of the relative resistance, after brushing the pit wall. In comparing the three profiles (Fig. 3) it can be seen that the resistogram recorded the upper ice layers while the ram apparently dropped through with no record.

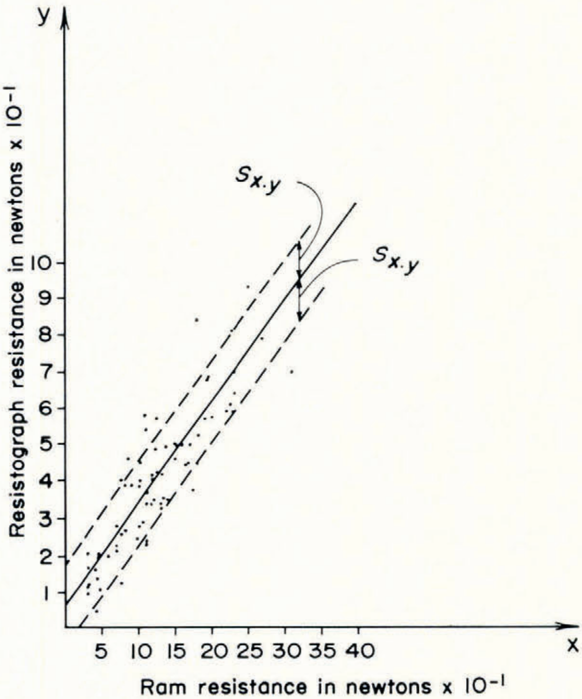

Fig. 4. Results of linear regression indicating regression line and standard estimate of error (S_{xy}). The data indicated a correlation coefficient (r) of 0.86.

To obtain a measure of the quantitative relationship between the two instruments, a linear regression analysis of the data was made using information obtained from six ram profiles and corresponding resistograms. The sample data were obtained by taking the average value of ram and resistograph numbers over equivalent 10 cm intervals of depth. A total of 80 data pairs was available for the analysis. The resulting regression equation is

$$y = 0.574 - 0.280x \quad (6)$$

where y represents the resistograph values in Newtons, and x represents the ram values in Newtons.

The analysis indicated a standard error of estimate (S_{xy}) of 1.1 N, and a correlation coefficient (r) of 0.86. The relationship is significant at the 1% level. The line of regression and standard error of estimate are shown in Figure 4.

In calculating the ram resistance for the purpose of comparison with the resistograph a coefficient of restitution of 0.5 was used as suggested by Perla (1969).

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Conclusion

It appears from our tests that there is a close correlation between snow strength as measured by the snow resistograph and that measured by the ram penetrometer. In spite of the fact that ram measurements are based on dynamic loading while resistograms are based on quasi-static loading, the data suggest that within the strength limits of these tests the two instruments are probably measuring the same snow properties.

Since there is such a high degree of correlation between ram and resistograph measurements, it is appropriate to mention again the time advantage of the resistograph. With it, one man can obtain a continuous and quantitative snow profile approximately 100 times faster than with the ram penetrometer. The current model of the resistograph is limited to 2.5 m of snow depth which is satisfactory for most of the northern Rocky Mountains. The design could readily be modified for greater snow depths if that proved advisable.

A disadvantage of the resistograph in comparison with the ram penetrometer lies in its lower ceiling for snow-strength measurement. This could be improved somewhat by re-designing the bit. On the other hand, as designed the resistograph is much *more* sensitive than the ram penetrometer to weak snow which in turn is more fundamental to the study of climax avalanches.

Acknowledgement

The authors wish to acknowledge the helpful criticisms of Drs Theodore Lang, John Montagne, Ronald Perla and Arlin Super.

MS. received 8 November 1971

REFERENCES

Bader, H., *and others*. 1939. Der Schnee und seine Metamorphose, von H. Bader, R. Haefeli, E. Bucher, J. Neher, O. Eckel, C. Thams, P. Niggli. *Beiträge zur Geologie der Schweiz. Geotechnische Serie. Hydrologie*, Lief. 3. [English translation: *U.S. Snow, Ice and Permafrost Research Establishment. Translation* 14, 1954.]

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. 1968. Instruments and methods. The resistograph and the compressive strength of snow. *Journal of Glaciology*, Vol. 7, No. 51, p. 499–506.

Perla, R. I. 1969. Strength tests on newly fallen snow. *Journal of Glaciology*, Vol. 8, No. 54, p. 427–40.

Waterhouse, R. 1966. Re-evaluation of the rammsonde hardness equation. *U.S. Cold Regions Research and Engineering Laboratory. Special Report* 100.