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MEASUREMENT AND CHARACTERIZATION OF THE PRESSURE-SINKAGE RELATIONSHIP FOR SNOW OBTAINED USING A RAMMSONDE AND A BEVAMETER

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October 1990

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BY

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VEHICLE SYSTEMS DEVELOPMENT CORPORATION
OTTAWA, CANADA

MEASUREMENT AND CHARACTERIZATION OF THE PRESSURE-SINKAGE DATA FOR SNOW OBTAINED USING A RAMMSONDE AND A BEVAMETER

prepared for

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FOREWORD

This report describes the measurement and characterization of the pressure-sinkage data obtained in snow-covered fields in Fernie, British Columbia, during February 1990, using a Rammsonde cone penetrometer, a bevameter and Rammsonde cones attached to a bevameter.

The work was performed by Vehicle Systems Development Corporation, under contract to the Canadian Department of National Defence through the Department of Supply and Services. The Principal Investigator was Dr. J.Y. Wong. The field data were collected by Messrs. J. Preston-Thomas and C. Smith and were processed by Messrs. S.T. Chen, J. Preston-Thomas and C. Smith under the direction of Dr. J.Y. Wong. The Scientific Authority for the Contract was Dr. G.J. Irwin, Vehicle Mobility Section, Defence Research Establishment Suffield.

The measuring equipment, including a Rammsonde, a bevameter and a terrain data acquisition system, was provided by Vehicle Mobility Section, Defence Research Establishment Suffield. The physical properties of the snow covers, including the temperature, density and grain size distributions, were provided by Vehicle Mobility Section, Defence Research Establishment Suffield and included in this report as Appendix A.

SUMMARY

To examine the feasibility of using the pressure-sinkage data obtained with a Rammsonde as input to the computer simulation model NTVPM-85 for predicting tracked vehicle performance over snow, a series of measurements of the penetration resistance of fresh and preconditioned snow was made using a Rammsonde, and compared with those obtained with a bevameter and Rammsonde cones attached to the bevameter.

This report describes the results of the field measurements made using the three types of device, as well as the approaches to the characterization of the pressure-sinkage data obtained.

It is found that the data obtained using the Rammsonde, the bevameter and the Rammsonde cone attached to the bevameter are, in general, comparable, considering the possible variations of terrain conditions in the field. It is shown that the pressure-sinkage equations proposed by Bekker could form a common basis for characterizing the data obtained using the three different techniques.

It is found that in soft, fresh snow (with density less than 0.2 g/cm^3), the small Rammsonde cone of 4 cm in diameter cannot be used to obtain meaningful pressure-sinkage data within a certain snow depth. Under these circumstances, the use of the large Rammsonde cone of 10 cm in diameter is recommended. Over preconditioned snow, both the small and large Rammsonde cones could provide comparable data.

The size effect of the sensing element (such as the diameter of the Rammsonde cone or the bevameter sinkage plate) on the pressure-sinkage relationships was examined. It is found that in

many cases, the values of the pressure-sinkage parameters derived from data obtained using a single sensing element of 10 cm in diameter are comparable to those obtained using two sizes of sensing elements of 4 and 10 cm in diameter.

The amount of data collected during the period of February 7-21, 1990, upon which this report was based, was relatively limited. To further evaluate the adequacy of using the Rammsonde technique to obtain pressure-sinkage data as input to NTVPM-85 for predicting tracked vehicle performance over snow, additional experimental and analytical studies over a wider range of snow conditions are recommended.

1. INTRODUCTION

The Nepean Tracked Vehicle Performance Model, NTVPM, developed by Vehicle Systems Development Corporation, is a comprehensive computer simulation model for predicting and evaluating the tractive performance of tracked vehicles over unprepared terrain. Its basic features have been validated over a variety of terrains, including mineral terrain, muskeg and snow-covered terrain (Wong, 1986a and 1989a; Wong and Preston-Thomas, 1986 and 1988). NTVPM has been gaining increasingly wide acceptance by industry and governmental agencies. It has been used to assist Hagglund Vehicle AB of Sweden in the development of a new generation of light armoured fighting vehicles, in examining the approaches to the further improvement of the performance of the all-terrain vehicle BV206 and in the evaluation of competing designs for a proposed main battle tank for the Swedish armed forces (Wong, 1986b and 1989b; Wong and Preston-Thomas, 1989). It has also been used in evaluating the effects of design modifications on the mobility of the main battle tank Leopard C1 for the Canadian Department of National Defence and in the evaluation of the mobility of a variety of container handling equipment used by the U.S. Marine Corps (Wong, 1986c, d and e; Wong and Preston-Thomas, 1987a and c). More recently, it has been used to assist Singapore Technologies (Ordnance) in the evaluation of competing designs for a light armoured fighting vehicle.

Vehicle Mobility Section (VMS) of the Defence Research Establishment Suffield (DRES) has entered into an agreement with NATO Panel II/GPE6 to contribute a snow module to the NATO Reference Mobility Model (NRMM). In this connection, VMS has selected NTVPM as the basis for the development of the snow module. NTVPM currently requires terrain parameters, including the pressure-sinkage and shear strength parameters, obtained using a bevameter as input. VMS has indicated its desire to explore the feasibility of using the pressure-sinkage data obtained with a Rammsonde cone penetrometer as input to NTVPM.

To examine whether the pressure-sinkage data obtained with a Rammsonde can be used as input to NTVPM for predicting tracked vehicle performance, a series of measurements of the pressure-sinkage relationships of snow-covered fields in Fernie, British Columbia was carried out using the Rammsonde and the bevameter during the period of February 7-21, 1990. At the same time, the tractive performance of an all-terrain vehicle, BV206, was measured over the same areas, so as to provide experimental data for evaluating the adequacy of using the pressure-sinkage relationships obtained using a Rammsonde as input for predicting tracked vehicle performance.

This report describes the measurement and characterization of the pressure-sinkage relationships obtained using a Rammsonde, a bevameter and Rammsonde cones attached to the bevameter.

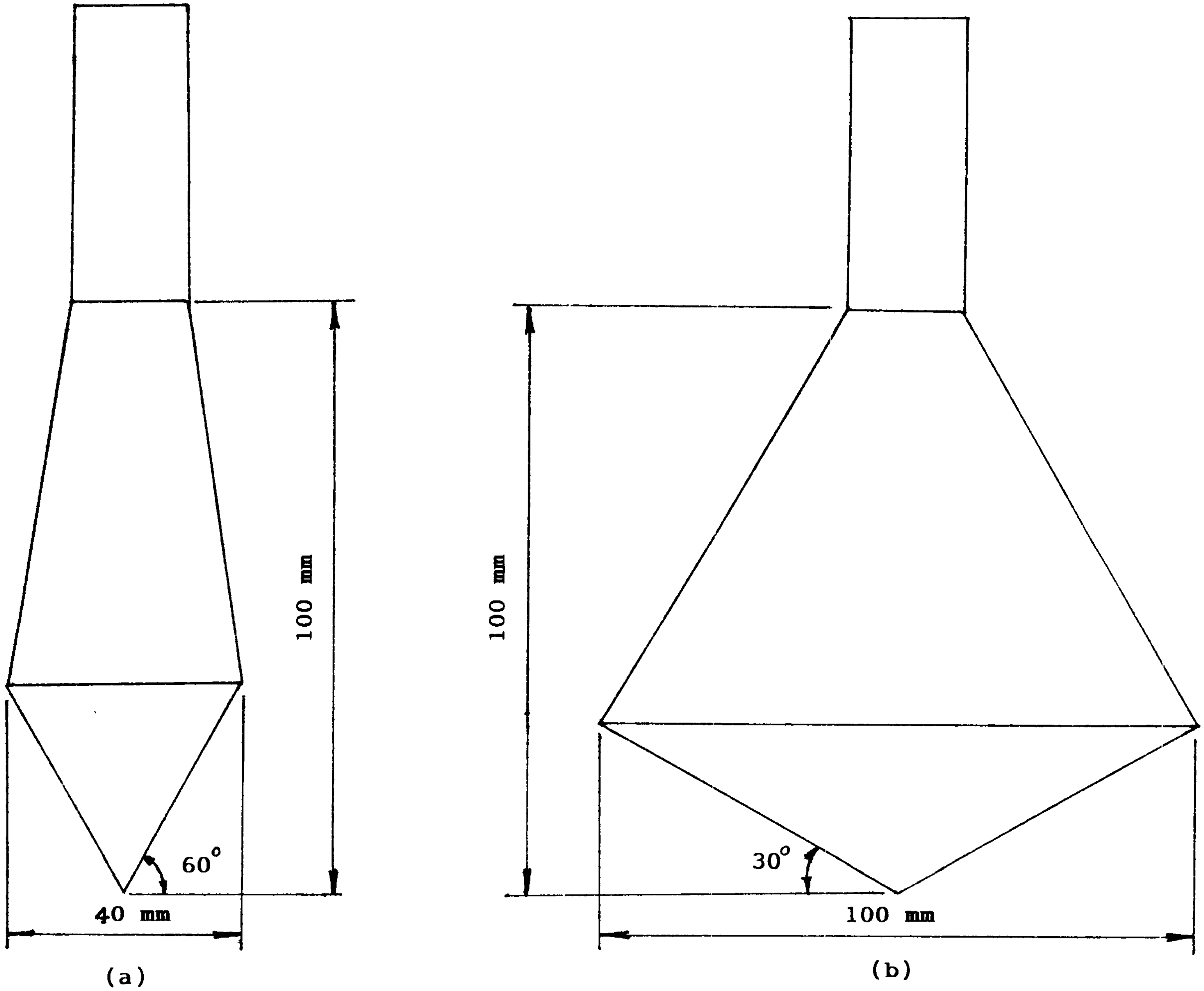

Fig. 2.1 The small and large Rammsonde cones used in field testing

some drop height (range from 0 to 50 cm) usually allows a suitable rate of penetration in a great variety of snows.

The Rammsonde resistance (ram resistance or hardness) is computed from the following expression:

$$R = \frac{Whn}{z} + W + Q \tag{2.1}$$

where R - ram resistance, kg
W - weight of drop hammer, kg
h - height of drop, cm
n - number of hammer blows
x - penetration after n blows, cm
Q - weight of penetrometer, kg.

It should be mentioned that using the above equation for determining the ram resistance, the energy loss during impact between the hammer and the penetrometer has been neglected.

Representative data for the Rammsonde resistance (hardness) as a function of depth (sinkage) obtained using the 4 and 10 cm diameter cones, in a fresh snow field in Fernie, B.C., are shown in Figs. 2.2 and 2.3, respectively. Representative data for the Rammsonde resistance obtained using the 4 and 10 cm diameter cones, in a snow cover which was been preconditioned by the passage of the tracks of a BV206, are shown in Figs. 2.4 and 2.5, respectively.

A complete set of Rammsonde resistance data obtained in Fernie, B.C. during the period of February 7-21, 1990 is given in Appendix B.

To obtain the pressure-sinkage relationships, the Rammsonde resistance R is converted to pressure p, by dividing the resistance R by the projected contact area of the cone, using the following expression:

$$p = R \times 9.81/A \tag{2.2}$$

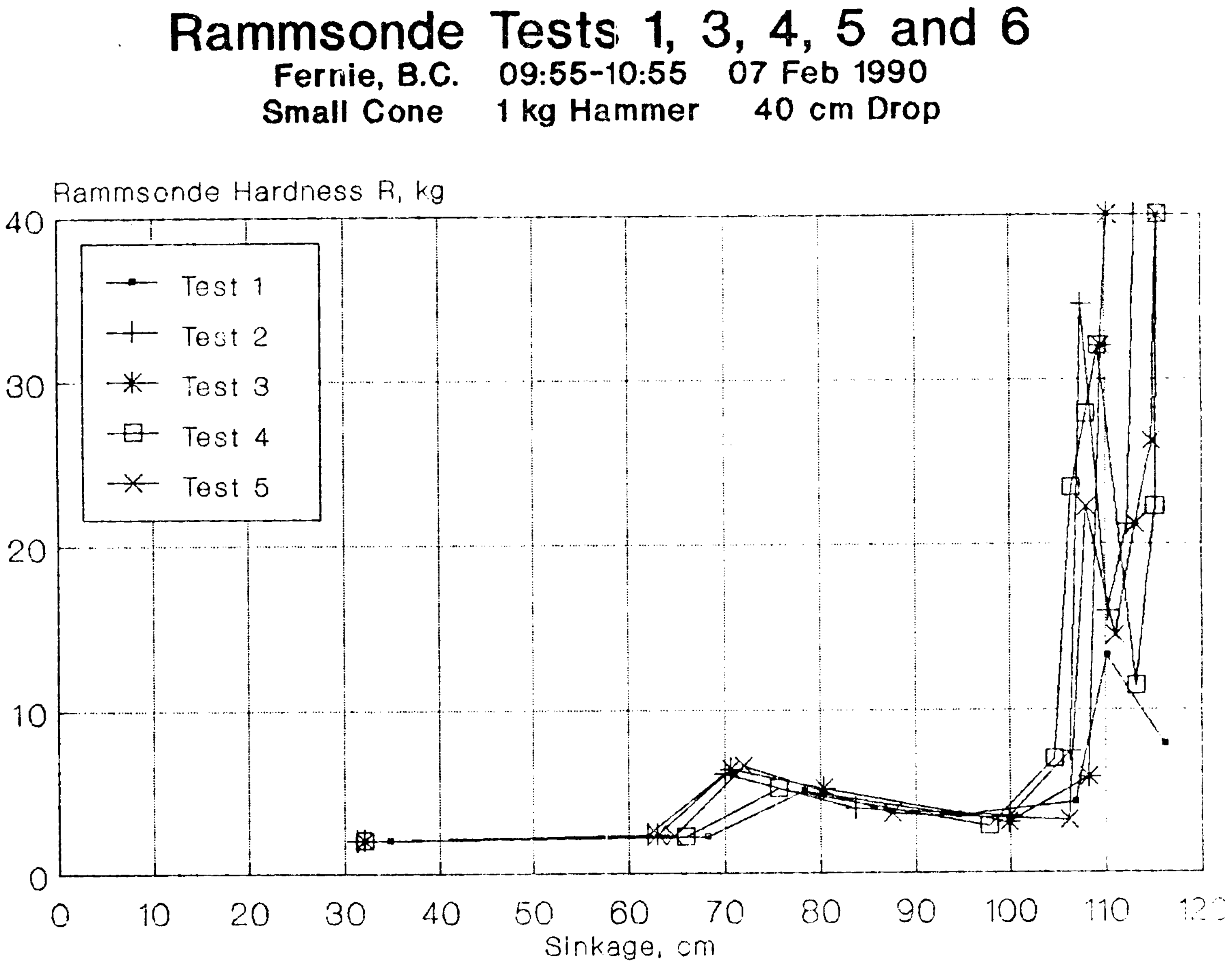

Fig. 2.2 Rammsonde hardness - sinkage relationship for a fresh snow obtained using a small cone

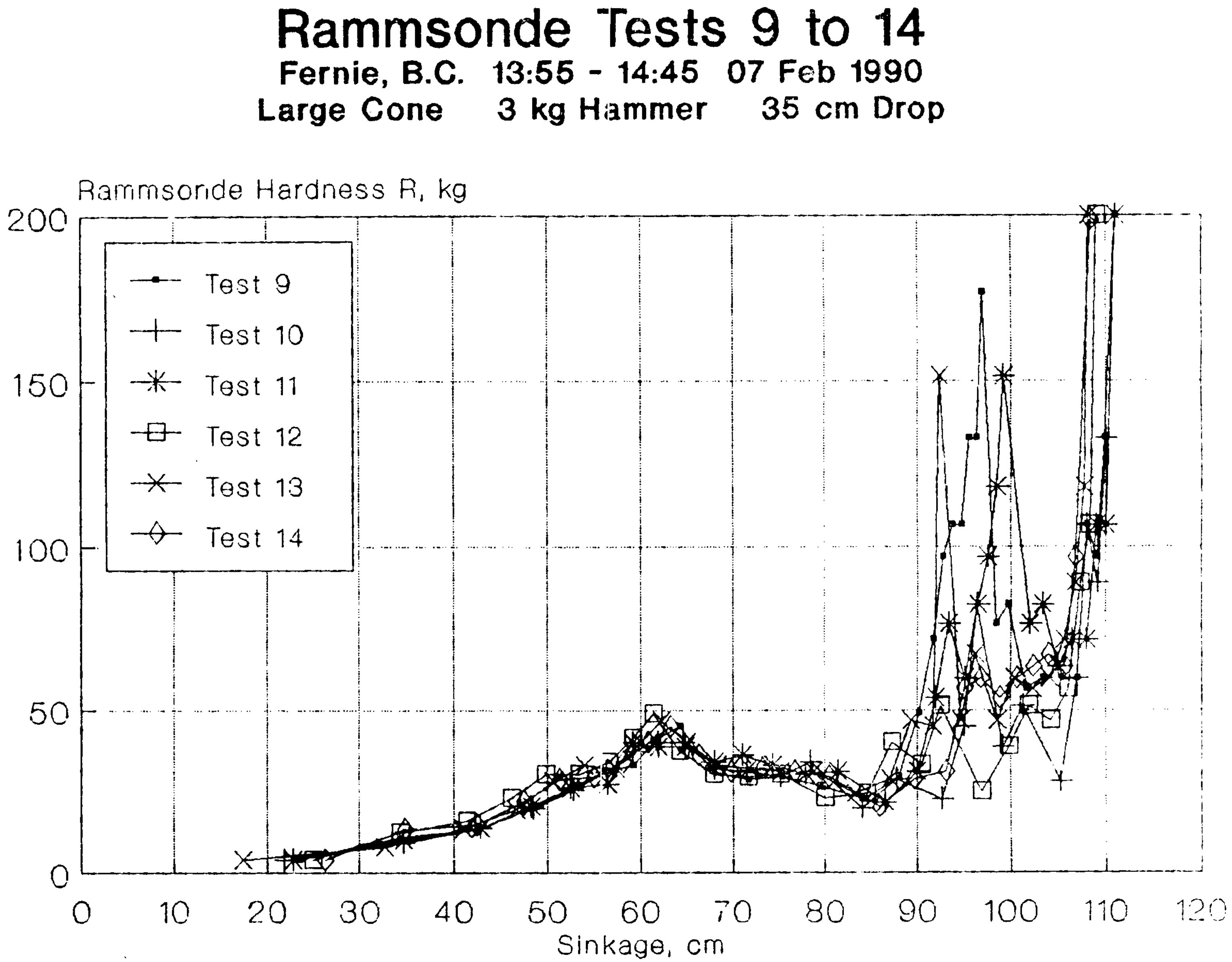

Fig. 2.3 Rammsonde hardness-sinkage relationship for a fresh snow obtained using a large cone

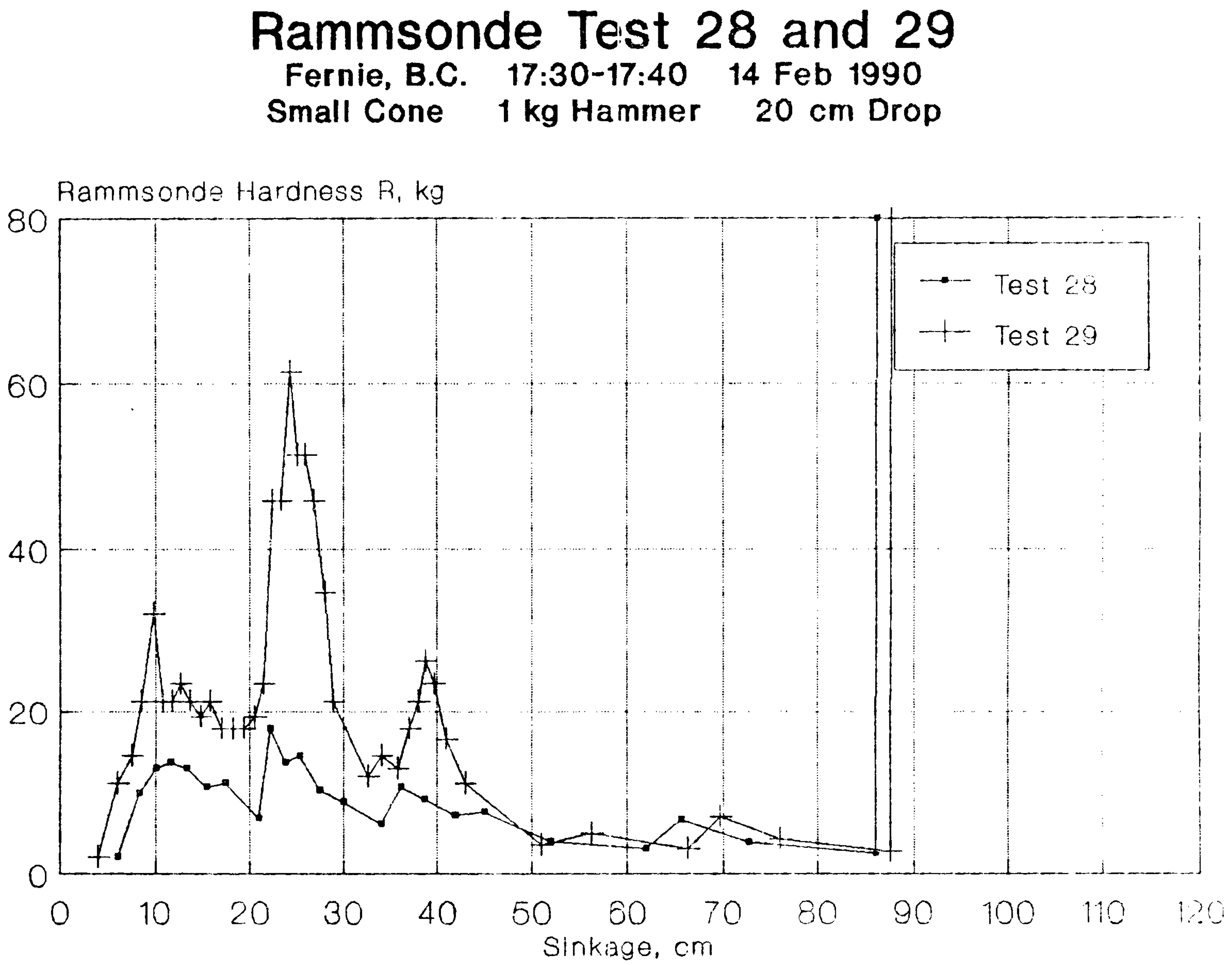

Fig. 2.4 Rammsonde hardness-sinkage relationship for a preconditioned snow obtained using a small cone

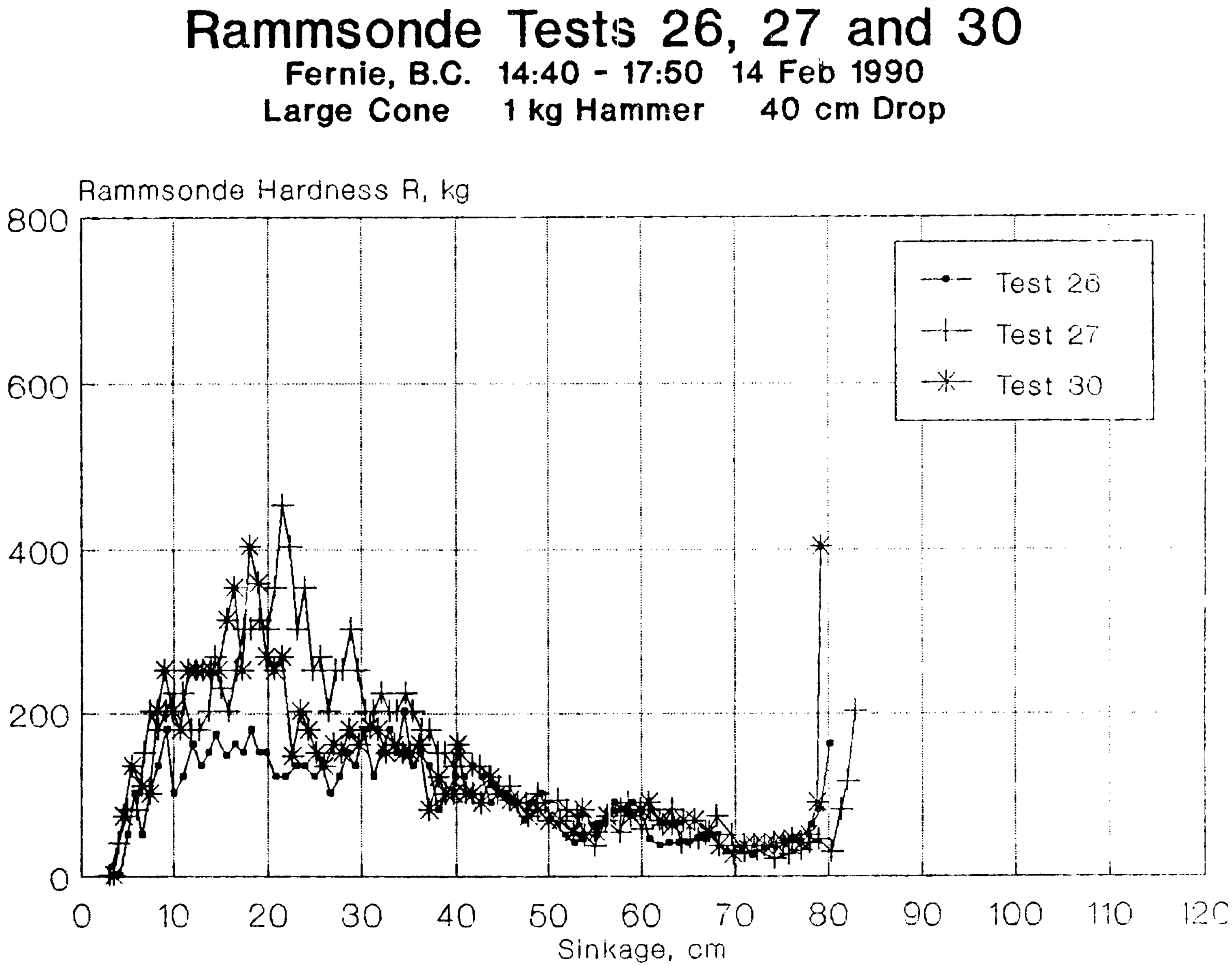

Fig. 2.5 **Rammsonde hardness-sinkage relationship for a preconditioned snow obtained using a large cone**

where p is the ram pressure, N/m^2; 9.81 is the acceleration due to gravity in m/S^2; R is the ram resistance in kg and A is the projected contact area of the cone in m^2.

Following the above-noted procedure, the ram resistance-sinkage relationships determined by the Rammsonde can be converted to pressure (ram pressure)-sinkage relationships. Figures 2.6 and 2.7 show representative pressure-sinkage relationships obtained using the 4 and 10 cm diameter cones in a fresh snow, respectively. Representative pressure-sinkage relationships obtained using the 4 and 10 cm diameter cones in a preconditioned snow cover are shown in Figs. 2.8 and 2.9, respectively.

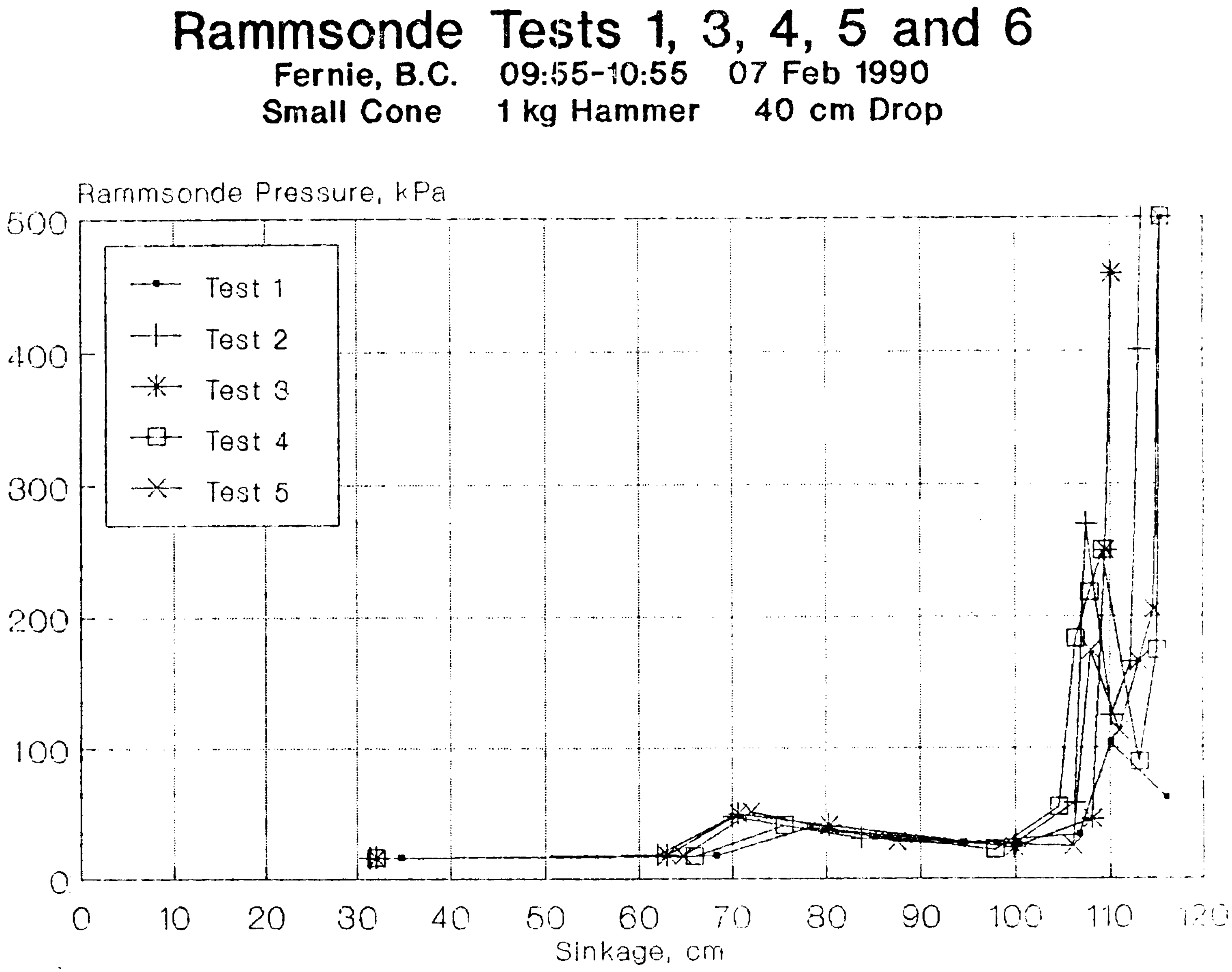

Fig. 2.6 Pressure-sinkage relationship for a fresh snow obtained using a small Rammsonde cone

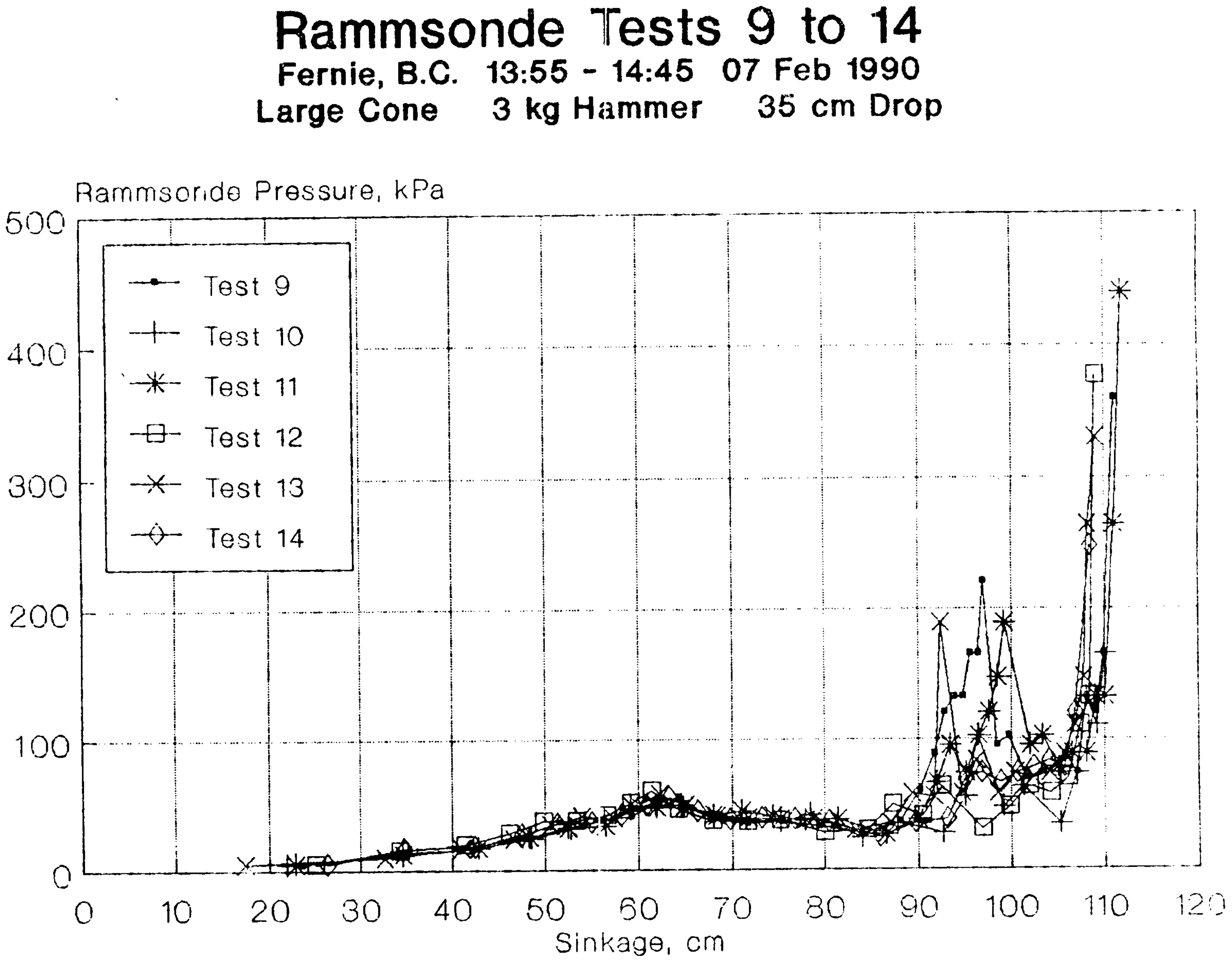

Fig. 2.7 Pressure-sinkage relationship for a fresh snow obtained using a large Rammsonde cone

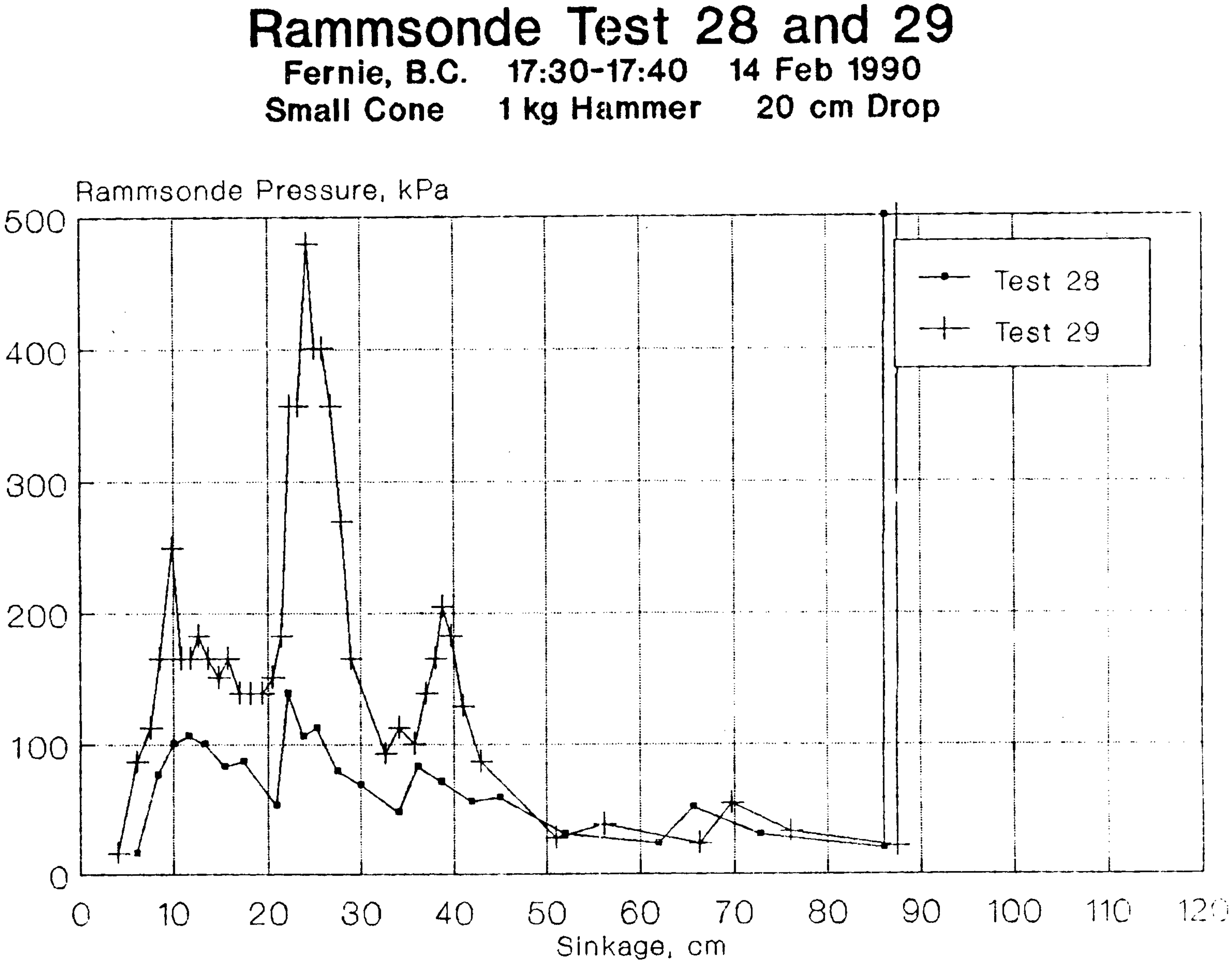

Fig. 2.8 Pressure-sinkage relationship for a preconditioned snow obtained using a small Rammsonde cone

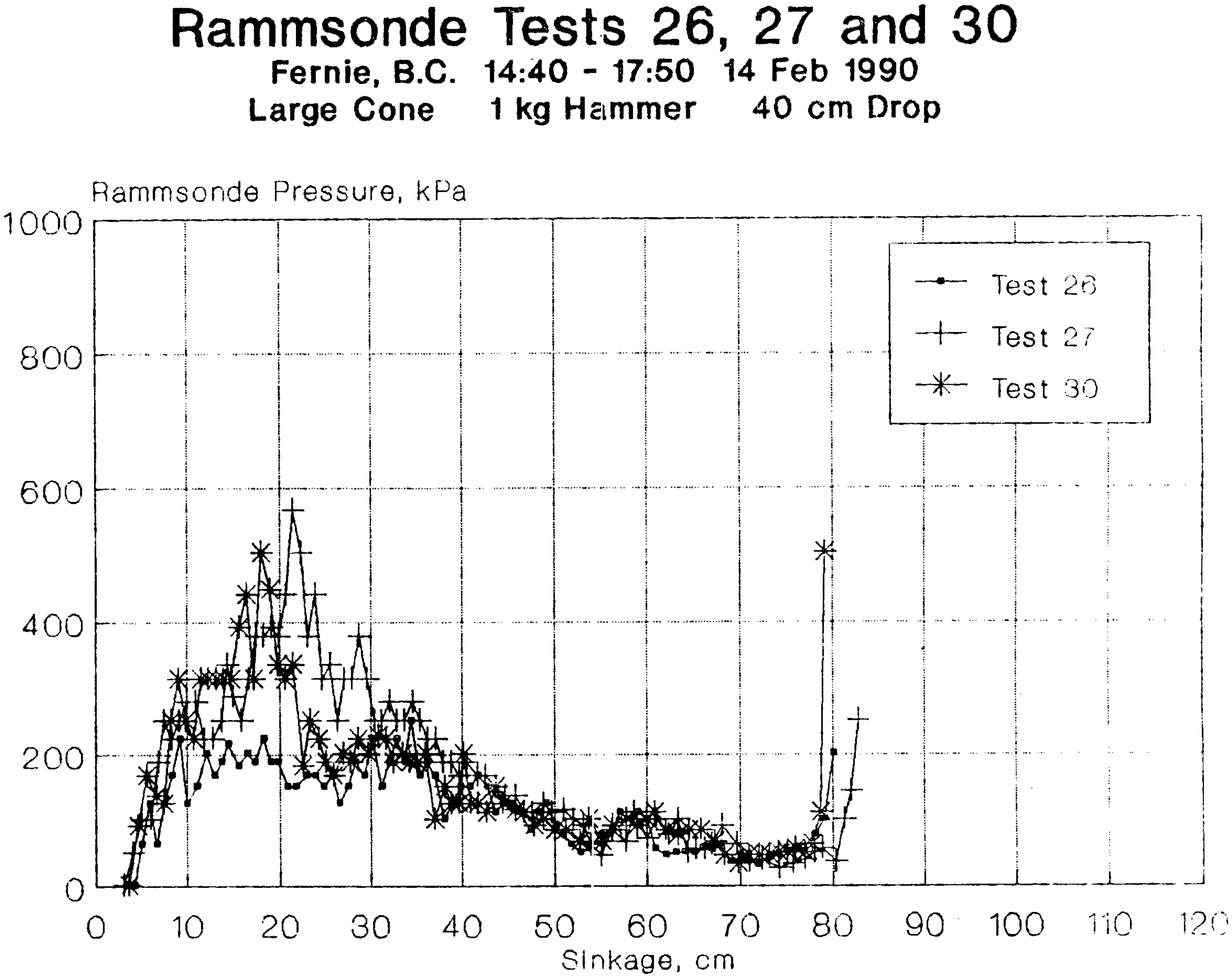

Fig. 2.9 Pressure-sinkage relationship for a preconditioned snow obtained using a large Rammsonde cone

2.2 Characterization of the Pressure-Sinkage Relationships

2.2.1 Characterization of Pressure-Sinkage Relationships Taking into Account Size Effect

To compare the data obtained using the Rammsonde with those obtained by the bevameter on a common basis, it is considered appropriate to characterize the pressure-sinkage relationships using expressions proposed by Bekker (1969). One of the widely known expressions is given by

$$p = (k_c/b + k_\phi)\, z^n \tag{2.3}$$

where p is pressure; b is the smaller dimension of a rectangular sensing element (plate) or the radius of a circular sensing element (plate or Rammsonde cone); n, k_C and k_ϕ are pressure-sinkage parameters.

Since in the above equation, the dimension of the sensing element is included, the pressure-sinkage relationship as defined by Eq. (2.3) is size dependent.

To determine the values of n, k_C and k_ϕ, pressure-sinkage tests must be carried out with at least two different sizes of sensing elements (pleates or Rammsonde cones). A computerized procedure for deriving the values of n, k_C and k_ϕ from experimental data has been developed by Wong (1980) and is gaining increasingly wide acceptance in practice.

Taking the logarithm of Eq. (2.3), one obtains

$$\ln p = \ln (k_c/b + k_\phi) + n \ln z \tag{2.4}$$

The above equation represents a straight line when plotting the data on a logarithmic scale. To obtain the best fitting line, the weighted least squares method is used to obtain the value of n, and the conventional least squares method is employed to derive the values of k_C and k_ϕ.

The value of n is obtained by introducing a weighting factor W_r and by minimizing the following function

$$W_r\left[\ln p - \ln\left(k_c/b + k_\phi\right) - n\ln z\right]^2 \tag{2.5}$$

If an equal liability to error for all observations is assumed, the weighting factor may be taken as

$$W_r = p^2 \tag{2.6}$$

Thus to obtain the best value of n for a particular set of test data, the following function must be minimized

$$F = \Sigma p^2\left[\ln p - \ln\left(k_c/b + k_\phi\right) - n\ln z\right]^2$$

or

$$F = \Sigma p^2\left[\ln p - \ln k_{eq} - n\ln z\right]^2 \tag{2.7}$$

where $k_{eq} = k_c/b + k_\phi$.

To minimize the value of the function F, the first partial derivatives of F with respect to n and k_{eq} are taken and set to zero. This leads to the following two equations:

$$\ln k_{eq}\Sigma p^2 \ln z + n\Sigma p^2\left(\ln z\right)^2 = \Sigma p^2 \ln p \ln z \tag{2.8}$$

$$\ln k_{eq}\Sigma p^2 + n\Sigma p^2 \ln z = \Sigma p^2 \ln p \tag{2.9}$$

Solving these two equations simultaneously, one can obtain the best fitting value for n for a particular set of data

$$n = \frac{\Sigma p^2 \Sigma p^2 \ln p \ln z - \Sigma p^2 \ln p \Sigma p^2 \ln z}{\Sigma p^2 \Sigma p^2\left(\ln z\right)^2 - \left(\Sigma p^2 \ln z\right)^2} \tag{2.10}$$

It should be mentioned that in practice the values of n calculated from the two sets of data obtained using two different sizes of sensing elements are seldom identical, even under controlled laboratory conditions. Since the Bekker equation implies that for a particular type of terrain, there is a unique value of n, an average value n_{av} is taken

$$n_{av} = \frac{(n)_{b=b_1} + (n)_{b=b_2}}{2} \tag{2.11}$$

where $(n)_{b=b1}$ and $(n)_{b=b2}$ represent the value of n obtained from the two sets of data using sensing elements (plates or Rammsonde cones) with dimension b_1 and b_2, respectively.

The value of n_{av} is then used to calculate the value of k_{eq} for a particular set of data using the conventional least squares method, that is, by minimzing the following function

$$F_1 = \Sigma \left(p - k_{eq} z^n\right)^2 \tag{2.12}$$

Taking the first derivative of F_1 with respect to k_{eq} and setting it to zero, one obtains

$$k_{eq} = \frac{\Sigma p z^n}{\Sigma z^{2n}} \tag{2.13}$$

From the two sets of test data, two values of k_{eq} can be derived, one from the data obtained using a sensing element (plate or Rammsonde cone) with dimension b_1, $(k_{eq})_{b=b1}$, and the other from the data obtained using a sensing element (plate or Rammsonde cone) with dimension b_2, $(k_{eq})_{b=b2}$. Thus the values of k_c and k_ϕ can be calculated by

$$k_c = \frac{(k_{eq})_{b=b_1} - (k_{eq})_{b=b_2}}{b_2 - b_1} b_1 b_2 \tag{2.14}$$

$$k_\phi = (k_{eq})_{b=b_1} - \left[\frac{(k_{eq})_{b=b_1} - (k_{eq})_{b=b_2}}{b_2 - b_1}\right] b_2 \tag{2.15}$$

The above procedure has been programmed and implemented in a software package (see Wong and Chen, User's Guide to a Software Package for Processing Terrain Data obtained using the Rammsonde and the Bevameter, 1990).

To evaluate the goodness-of-fit using the above noted procedure, the following parameter ϵ is used, which is equal to one minus the ratio of the r.m.s. error to the mean value of the pressure:

$$\epsilon = 1 - \left[\sqrt{\sum (p_m - p_c)^2 / (N-2)}\right] / \left(\sum p_m / N\right) \tag{2.16}$$

where p_m is the measured pressure, p_c is the calculated pressure using the procedure described above, and N is the number of data points used for the curve fitting. When ϵ is equal to 1 (or 100%), the fit is perfect.

The above-noted procedure was employed to derive the values of n, k_c and k_ϕ from the pressure-sinkage data obtained using the Rammsonde.

Tables 2.1 and 2.2 show the values of n, k_c and k_ϕ derived from data obtained using the Rammsonde with 4 and 10 cm diameter cones in the fresh and preconditioned snow, respectively. It should be noted that the preconditioned snow for February 15, 1990 was allowed to age for 21 hours, before measurements were taken. A complete set of results obtained using Eq. (2.3) to fit individual groups of experimental data measured by the Rammsonde is given in Appendix B.

It should be noted that the snow covers tested were generally nonuniform. Consequently, the resistance to penetration varied greatly with depth, and the values of n, k_c and k_ϕ derived would be highly dependent upon the sinkage range selected. From the point of view of vehicle performance prediction, it is important to select an appropriate sinkage range (preferably corresponding to the expected vehicle sinkage) for deriving the pressure-sinkage parameters, n, k_c and k_ϕ . In other words, only that range of terrain data relevant to the operation of a given vehicle should be selected for processing and characterization.

Table 2.1 Pressure-Sinkage Parameters for Fresh Snow

(Using Equation: p = (k_c/b + k_phi) * z^n)

Date		Bevameter		Rammsonde Cone		Rammsonde Cone on Bevemeter	
	Diameter, cm	4	10	4	10	4	10
Feb. 7	Fitting Range, cm			0 - 80			
	n ,			1.1017			
	k_c , kN/m^(n+1)			-1.3820			
	k_phi, kN/m^(n+2)			116.00			
	Goodnees of Fit, %			56.19	61.27		
Feb. 8	Fitting Range, cm	0 - 50					
	n ,	1.2545					
	k_c , kN/m^(n+1)	-2.7774					
	k_phi, kN/m^(n+2)	224.22					
	Goodnees of Fit, %	65.68	77.49				
Feb. 9	Fitting Range, cm					0 - 50	
	n ,					1.2831	
	k_c , kN/m^(n+1)					-1.0349	
	k_phi, kN/m^(n+2)					96.048	
	Goodnees of Fit, %					49.22	72.68
Feb. 12	Fitting Range, cm	0 - 30		0 - 17		0 - 30	
	n ,	.84019		1.0043		.90143	
	k_c , kN/m^(n+1)	2.5379		8.9595		-.78681	
	k_phi, kN/m^(n+2)	149.47		194.48		222.22	
	Goodnees of Fit, %	18.13	63.83	47.56	40.56	29.88	52.26

Date		Bevameter		Rammsonde Cone		Rammsonde Cone on Bevemeter	
	Diameter, cm	4	10	4	10	4	10
Feb. 13	Fitting Range, cm	0 - 15				0 - 15	
	n ,	.41646				.41990	
	k_c , kN/m^(n+1)	-.37661				.24241	
	k_phi, kN/m^(n+2)	162.29				128.68	
	Goodnees of Fit, %	31.18	45.95			20.84	49.51
Feb. 16	Fitting Range, cm			0 - 35			
	n ,			1.0859			
	k_c , kN/m^(n+1)			12.279			
	k_phi, kN/m^(n+2)			349.85			
	Goodnees of Fit, %			58.74	65.00		
Feb. 20	Fitting Range, cm	0 - 50		0 - 57.5		0 - 50	
	n ,	1.5110		1.4491		1.4518	
	k_c , kN/m^(n+1)	-.21952		8.6867		-7.4421	
	k_phi, kN/m^(n+2)	518.03		722.67		582.35	
	Goodnees of Fit, %	—	36.97	50.13	7.87	—	21.15
Feb. 21	Fitting Range, cm	0 - 50		0 - 59.5		0 - 45	
	n ,	1.4505		1.5267		1.7542	
	k_c , kN/m^(n+1)	-4.9070		7.6709		.78235	
	k_phi, kN/m^(n+2)	659.00		534.64		480.72	
	Goodnees of Fit, %	12.69	43.16	19.21	21.75	—	44.41

Table 2.2 Pressure-Sinkage Parameters for Preconditioned Snow

(Using Equation: p = (k_c/b + k_phi) * z^n)

Date		Bevameter		Rammsonde Cone		Rammsonde Cone on Bevemeter	
	Diameter, cm	4	10	4	10	4	10
Feb. 14	Fitting Range, cm	0 -4.5 & 0 - 5		0 - 12			
	n ,	.93008		.98340			
	k_c , kN/m^(n+1)	70.668		-19.061			
	k_phi, kN/m^(n+2)	1927.7		2546.2			
	Goodnees of Fit, %	56.97	74.41	65.21	64.31		
Feb. 15	Fitting Range, cm	0 - 4		0 - 10		0 - 6	
	n ,	1.0083		.93348		.90549	
	k_c , kN/m^(n+1)	86.146		11.429		-23.613	
	k_phi, kN/m^(n+2)	1632.2		2330.3		2297.5	
	Goodnees of Fit, %	67.60	54.38	49.78	39.61	57.54	63.50
Feb. 16	Fitting Range, cm	0 - 4 & 0 -3.5		0 - 10		0 - 14	
	n ,	.94851		.99818		.98193	
	k_c , kN/m^(n+1)	4.0573		56.731		13.768	
	k_phi, kN/m^(n+2)	3555.0		1445.5		1198.9	
	Goodnees of Fit, %	27.54	61.23	54.26	59.07	47.72	63.01
Feb. 19	Fitting Range, cm	0 - 6		0 - 8.5		0 - 6	
	n ,	.98515		.79333		1.0196	
	k_c , kN/m^(n+1)	29.708		-3.1042		-1.8717	
	k_phi, kN/m^(n+2)	1585.2		1383.1		1889.4	
	Goodnees of Fit, %	62.56	74.27	28.89	63.31	41.77	52.59

2.2.2 Characterization of Pressure-Sinkage Relationship without Taking into Account Size Effect

As mentioned previously, the pressure-sinkage relationship as defined by Eq. (2.3) is size dependent, and there are three parameters n, k_c and k_ϕ to be derived from experimental data. Consequently, measurements must be carried out using at least two different sizes of sensing elements (plates or Rammsonde cones). In some cases, the size effect may not be significant or it may be desirable to simplify the data collection process. Under these circumstances, a simplified version of Eq. (2.3) as given below may be used

$$p = kz^n \tag{2.17}$$

where n and k are pressure-sinkage parameters. Since Eq. (2.17) contains only two pararmeters, n and k, they can be derived from experimental data obtained with a single sensing element (plate or Rammsonde cone).

It should be pointed out that under certain circumstances, it is in fact preferable to use Eq. (2.17) to characterize the pressure-sinkage relationships. For instance, a shown in Fig. 2.2, in fresh snow, the small Rammsonde cone of 4 cm in diameter could not provide adequate snow hardness data at depths less than approximately 60 cm. This is because the resistance to penetration of the cone with diameter of 4 cm was very low in the upper layer and the initial penetration of the cone even under its own weight was already considerable. On the other hand, using the 10 cm diameter Rammsonde cone, consistent hardness data could be obtained at depths higher than 20 cm, as shown in Fig. 2.3. Therefore, if Eq. (2.3) is used to characterize the pressure-sinkage relationship of the fresh snow within the range of 0 to 60 cm, then the data obtained using the 4 cm diameter cone would not be adequate for deriving reliable values for n, k_c and k_ϕ . Under these circumstances, using Eq. (2.17) and deriving the values for n and k from experimental data obtained using the 10 cm diameter core alone would be more meaningful.

Using Eq. (2.17), the best fitting values for n and k for a given set of data can be derived in a similar way as that described in Section 2.2.1. The value of n can be obtained using Eq. (2.10), whereas the best fitting value of k is given by (see Eq. (2.13))

$$k = \frac{\Sigma p z^n}{\Sigma z^{2n}} \tag{2.18}$$

Tables 2.3 and 2.4 show the values of n and k derived from data obtained using the Rammsonde with 4 and 10 cm diameter cones in the fresh and preconditioned snow, respectively. A complete set of results obtained using Eq. (2.17) to fit individual groups of experimental data measured by the Rammsonde is given in Appendix B.

Table 2.3 Pressure-Sinkage Parameters for Fresh Snow

(Using Equation: p = k * z^n)

Date		Bevameter		Rammsonde Cone		Rammsonde Cone on Bevemeter	
	Diameter, cm	4	10	4	10	4	10
Feb. 7	Fitting Range, cm			0 - 90	0 - 78		
	n ,			1.0499	1.0243		
	k , kPa/m^n			43.946	87.505		
	Goodnees of Fit, %			59.69	61.76		
Feb. 8	Fitting Range, cm	0 -44.5	0 - 50				
	n ,	1.2600	1.1054				
	k , kPa/m^n	81.418	138.33				
	Goodnees of Fit, %	62.13	77.69				
Feb. 9	Fitting Range, cm					0 - 50	0 - 77
	n ,					1.1103	1.1817
	k , kPa/m^n					37.142	73.974
	Goodnees of Fit, %					47.22	76.81
Feb. 12	Fitting Range, cm	0 - 30	0 - 33	0 - 18	0 - 16	0 - 36	0 - 27
	n ,	.94279	.74778	1.4712	1.4782	.96918	.96422
	k , kPa/m^n	279.74	172.35	1497.7	1101.1	283.02	204.33
	Goodnees of Fit, %	19.60	62.50	53.61	45.10	24.12	61.36
Feb. 13	Fitting Range, cm	0 - 22	0 - 35		0 - 27	0 - 15	0 - 15
	n ,	.47162	.48298		.42889	.40669	.43311
	k , kPa/m^n	191.78	227.23		309.38	136.24	137.96
	Goodnees of Fit, %	32.48	63.34		42.67	20.72	49.63

Date		Bevameter		Rammsonde Cone		Rammsonde Cone on Bevemeter	
	Diameter, cm	4	10	4	10	4	10
Feb. 16	Fitting Range, cm			0 - 35	0 - 36		
	n ,			1.2898	1.2724		
	k , kPa/m^n			1248.7	803.98		
	Goodnees of Fit, %			60.58	62.59		
Feb. 20	Fitting Range, cm	0 - 26	0 -29.7	0 - 55	0 - 62	0 - 44	0 - 55
	n ,	1.4676	1.4521	1.2121	1.4469	1.2462	1.4309
	k , kPa/m^n	257.28	169.18	1041.9	895.25	159.44	419.81
	Goodnees of Fit, %	—	47.51	51.61	16.00	—	30.15
Feb. 21	Fitting Range, cm	0 - 45	0 - 54	0 -65.5	0 -58.5	0 -55.5	0 - 50
	n ,	1.4996	1.4945	1.4865	1.4435	1.4647	1.4326
	k , kPa/m^n	452.41	533.90	876.83	649.64	396.10	330.15
	Goodnees of Fit, %	—	43.35	21.96	18.74	—	50.14

Table 2.4 Pressure-Sinkage Parameters for Preconditioned Snow

(Using Equation: p = k * z^n)

Date		Bevameter		Rammsonde Cone		Rammsonde Cone on Bevemeter	
	Diameter, cm	4	10	4	10	4	10
Feb. 14	Fitting Range, cm	0 -5.3	0 - 3	0 - 12	0 - 12		
	n ,	.98836	.98817	.99501	.97179		
	k , kPa/m^n	6592.9	5241.5	1645.2	2103.8		
	Goodnees of Fit, %	63.53	87.77	65.35	64.21		
Feb. 15	Fitting Range, cm	0 -6.4	0 -9.9	0 -10.5	0 - 9	0 -12.7	0 -7.5
	n ,	.97280	.66298	.89523	.97709	.97704	.93553
	k , kPa/m^n	5644.6	1164.0	2364.5	2976.5	1927.7	1787.1
	Goodnees of Fit, %	73.55	49.02	49.54	36.03	67.20	59.75
Feb. 16	Fitting Range, cm	0 -5.8	0 -3.9	0 - 10	0 - 10	0 -14.8	0 -11.5
	n ,	.82404	1.0150	1.0636	.93276	.97351	.86803
	k , kPa/m^n	2907.5	4463.2	5084.7	2168.5	1673.8	1118.2
	Goodnees of Fit, %	48.73	63.25	55.08	58.14	48.00	59.61
Feb. 19	Fitting Range, cm	0 - 6	0 - 6	0 -8.5	0 -8.5	0 -7.4	0 - 10
	n ,	.92673	1.0436	.60254	.98413	.99817	1.0198
	k , kPa/m^n	2548.9	2622.9	719.22	2313.3	1633.1	1724.3
	Goodnees of Fit, %	61.80	74.92	25.65	67.27	41.99	67.80

3. MEASUREMENT AND CHARACTERIZATION OF THE PRESSURE-SINKAGE RELATIONSHIPS OBTAINED USING A BEVAMETER

3.1 The Bevameter

The bevameter technique, originally conceived and developed by Bekker (1969), is based on the premise that terrain properties pertinent to vehicle mobility can best be measured under loading conditions similar to those exerted by an off-road vehicle. A vehicle exerts vertical and horizontal loads on the terrain surface. To simulate these loading conditions, the original bevameter technique comprises two separate sets of tests. One is plate penetration test and the other is shear test. In the penetration tests, a plate of suitable size is used to simulate the contact area of a vehicle running gear, and the pressure-sinkage relationship of the terrain is measured. Based on the measurements, vehicle sinkage and motion resistance can be predicted. In the shear tests, the shear stress-displacement relationship and shear strength of the terrain are measured. Based on the results of shear tests, the tractive effort-slip characteristics and the maximum traction of a vehicle may be estimated.

To provide data for predicting the multipass performance of the vehicle running gear, the measurement of the response of the terrain to repetitive normal and shear loadings has recently been included as part of terrain evaluation process using the bevameter technique (Wong, 1986a and 1989a; Wong and Preston-Thomas, 1986 and 1988). To predict the additional vehicle sinkage due to slip, the measurement of the slip-sinkage relationships have also been added as part of the bevameter tests (Wong, 1989a).

The bevameter used in measuring the mechanical properties of the snow covers in Fernie, British Columbia was provided by Vehicle Mobility Section, Defence Research Establishment Suffield and is shown in Fig. 3.1. The plates used in measuring the pressure-sinkage relationships were of circular shape with diameters of 4 and 10 cm. In some tests, plates with diameters of 12, 15, 18, 23 and 28 cm were also used. However, in this report, only the experimental data obtained using plates of 4 and 10 cm in diameter are reported and compared with those obtained using the Rammsonde with cones of 4 and 10 cm in diameter.

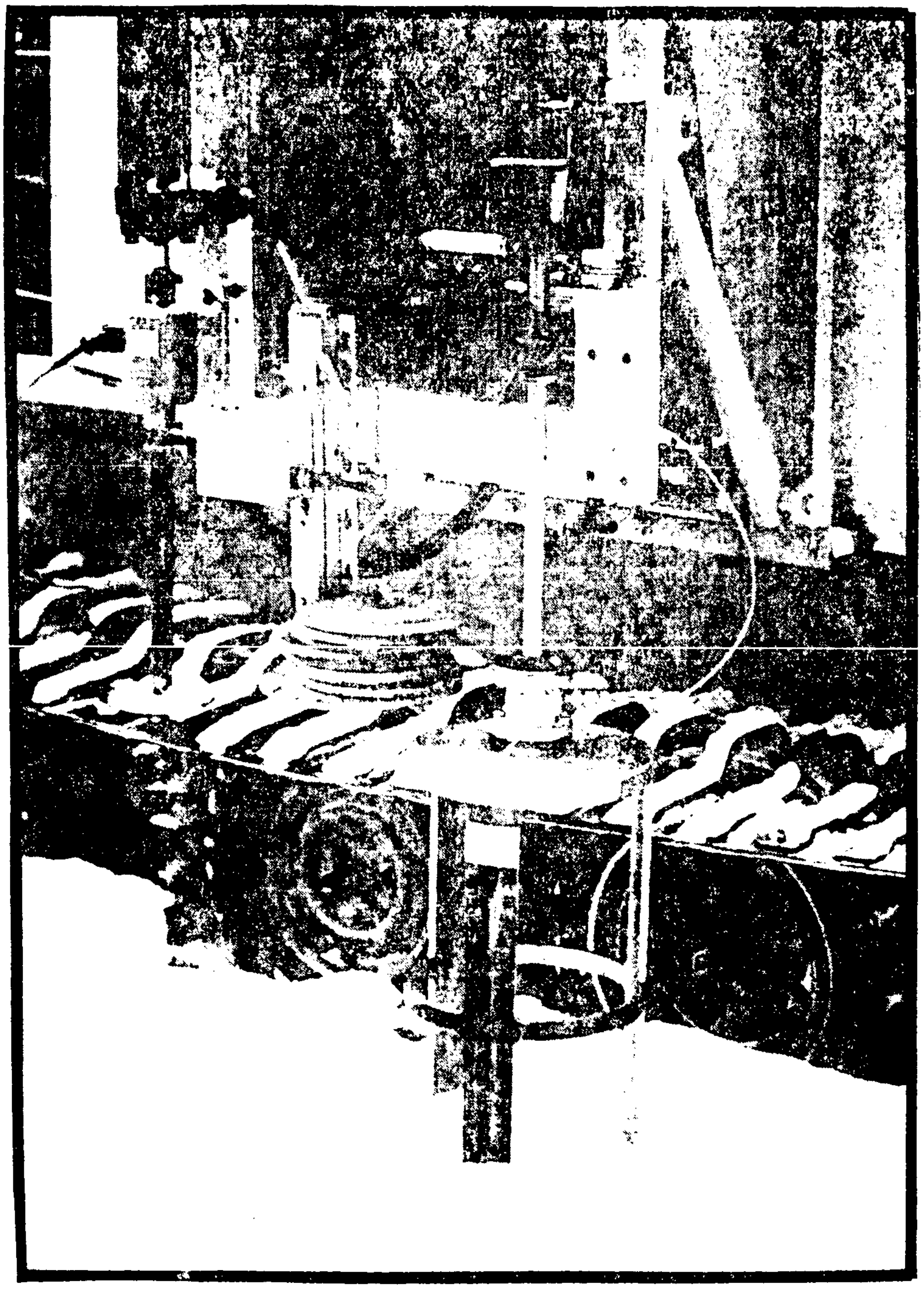

Fig. 3.1 The bevameter used in field testing

3.2 Characterization of the Pressure-Sinkage Relationships

3.2.1 Characterization of Pressure-Sinkage Relationships Taking into Account Size Effect

To compare the data obtained using the bevameter with those obtained by the Rammsonde on a common based, Eq. (2.3) described in Section 2.2.1 was used to characterize the pressure-sinkage data obtained with the bevameter. As mentioned previously, Eq. (2.3) takes into account the size effect. The values of the pressure sinkage parameters, n, k_c and k_ϕ , were derived from experimental data using the procedures described in Section 2.2.1.

Tables 2.1 and 2.2 show the values of n, k_c and k_ϕ derived from experimental data obtained using the bevameter with 4 and 10 cm diameter plates in the fresh and preconditioned snow, respectively. A complete set of results obtained using Eq. (2.3) to fit individual groups of experimental data measured by the bevameter is given in Appendix C.

4. MEASUREMENT AND CHARACTERIZATION OF THE PRESSURE-SINKAGE RELATIONSHIPS OBTAINED USING RAMMSONDE CONES ATTACHED TO A BEVAMETER

4.1 Measurement with Rammsonde Cones Attached to a Bevameter

As mentioned in Section 2.1, with the standard Rammsonde technique, the penetration of the cones into the snow was effected by the impact of the hammer dropped from a given height. In the calculation of the Rammsonde resistance using Eq. (2.1), the energy loss during impact is completely ignored. It has been reported that Eq. (2.1) may overestimate the actual resistance. To examine this problem, the Rammsonde cones were attached to the shaft of the bevameter in place of the sinkage plates and steady penetration tests at a constant speed were carried out.

4.2 Characterization of the Pressure-Sinkage Relationships

4.2.1 Characterization of Pressure-Sinkage Relationships Taking into Account Size Effect

Similar to the characterization of the data obtained using the standard Rammsonde technique, Eq. (2.3) described in Section 2.2.1 was used to characterize the pressure-sinkage data obtained with Rammsonde cones attached to the bevameter. The values of the pressure-sinkage parameters, n, k_c and k_ϕ , were derived from experimental data using the procedures described in Section 2.2.1.

Tables 2.1 and 2.2 show the values of n, k_c and k_ϕ derived from experimental data obtained using Rammsonde cones with diameters of 4 and 10 cm attached to the bevameter in the fresh and preconditioned snow, respectively. A complete set of results obtained using Eq. (2.3) to fit individual groups of experimental data measured by Rammsonde cones attached to the bevameter is given in Appendix D.

4.2.2 Characterization of Pressure-Sinkage Relationships without Taking into Account Size Effect

Similar to the operation with the standard Rammsonde technique, under certain circumstances, it may be desirable, or even preferable, to characterize the pressure-sinkage data obtained with Rammsonde cones attached to the bevameter using Eq. (2.17), without taking size effect into account. The procedure used for deriving the values of the pressure-sinkage parameters, n and k, from experimental data obtained using Rammsonde cones attached to the bevameter is the same as that described in Section 2.2.2.

Tables 2.3 and 2.4 show the values of n and k derived from data obtained using Rammsonde cones with diameters of 4 and 10 cm attached to the bevameter in the fresh and preconditioned snow, respectively. A complete set of results obtained using Eq. (2.17) to fit individual groups of experimental data measured by Rammsonde cones attached to the bevameter is given in Appendix D.

5. OBSERVATIONS

A. Based on the field data collected, it appears that in many cases the pressure-sinkage relationships measured by a Rammsonde, a bevameter and a Rammsonde cone attached to a bevameter, show similar characteristics. Figures 5.1, 5.2 and 5.3 show the pressure-sinkage relationships for fresh snow measured, during the period of February 7-9, 1990, using a Rammsonde, a bevameter and a Rammsonde cone attached to a bevameter, respectively. The pressure-sinkage relationships for a preconditioned snow obtained using the three different types of device on February 16, 1990 are shown in Figs. 5.4, 5.5 and 5.6.

Tables 2.1 to 2.4 show that while the values of the pressure-sinkage parameters derived from data obtained using different types of device are not the same, they vary in a limited range.

Taking into account the possible variations in terrain conditions in the field, the data obtained using the three different techniques should, in general, be regarded as comparable.

B. In fresh snow, the small Rammsonde cone of 4 cm in diameter could not be used to obtain meaningful pressure-sinkage data within a certain snow depth as shown in Fig. 2.2. This is because the resistance to penetration of the small cone in the upper layer of fresh snow (with density less than 0.2 g/cm^3 approximately) is such that the initial penetration under its own weight is already very high. Consequently, no data can be obtained within a considerable range of snow depth. In fresh snow with density less than $0.2 g/cm^3$, the use of the Rammsonde cone with diameter of 10 cm is recommended.

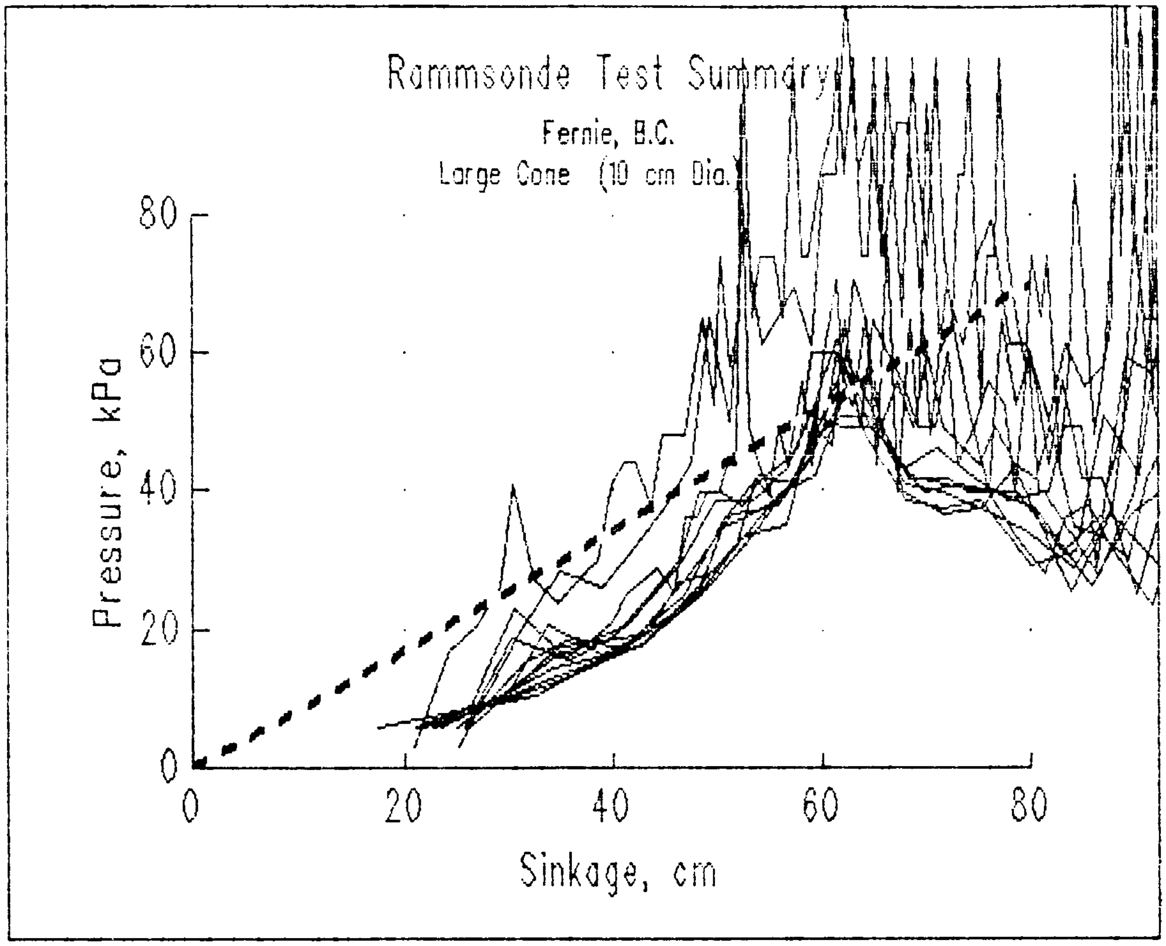

Fig. 5.1 Pressure-sinkage relationship for a fresh snow obtained using the Rammsonde

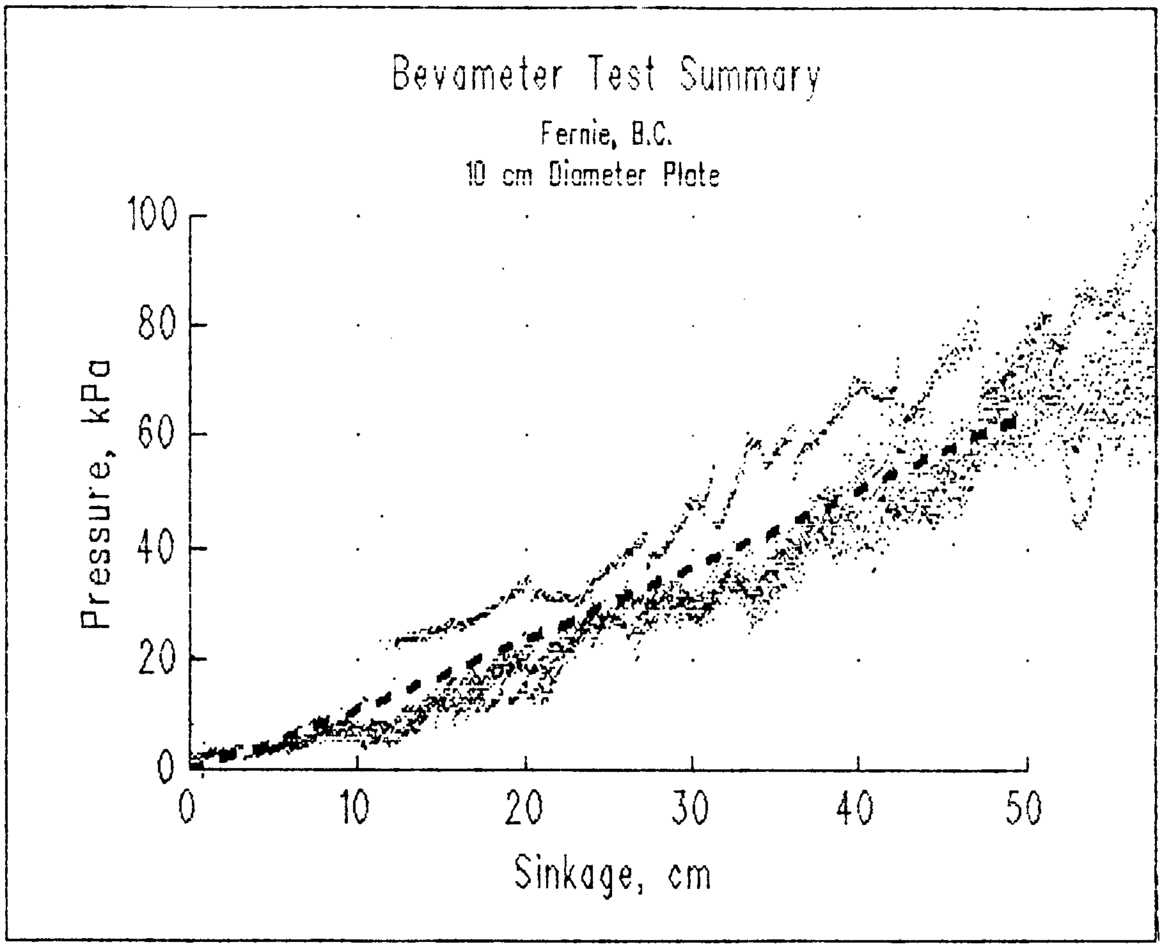

Fig. 5.2 Pressure-sinkage relationship for a fresh snow obtained using the bevameter

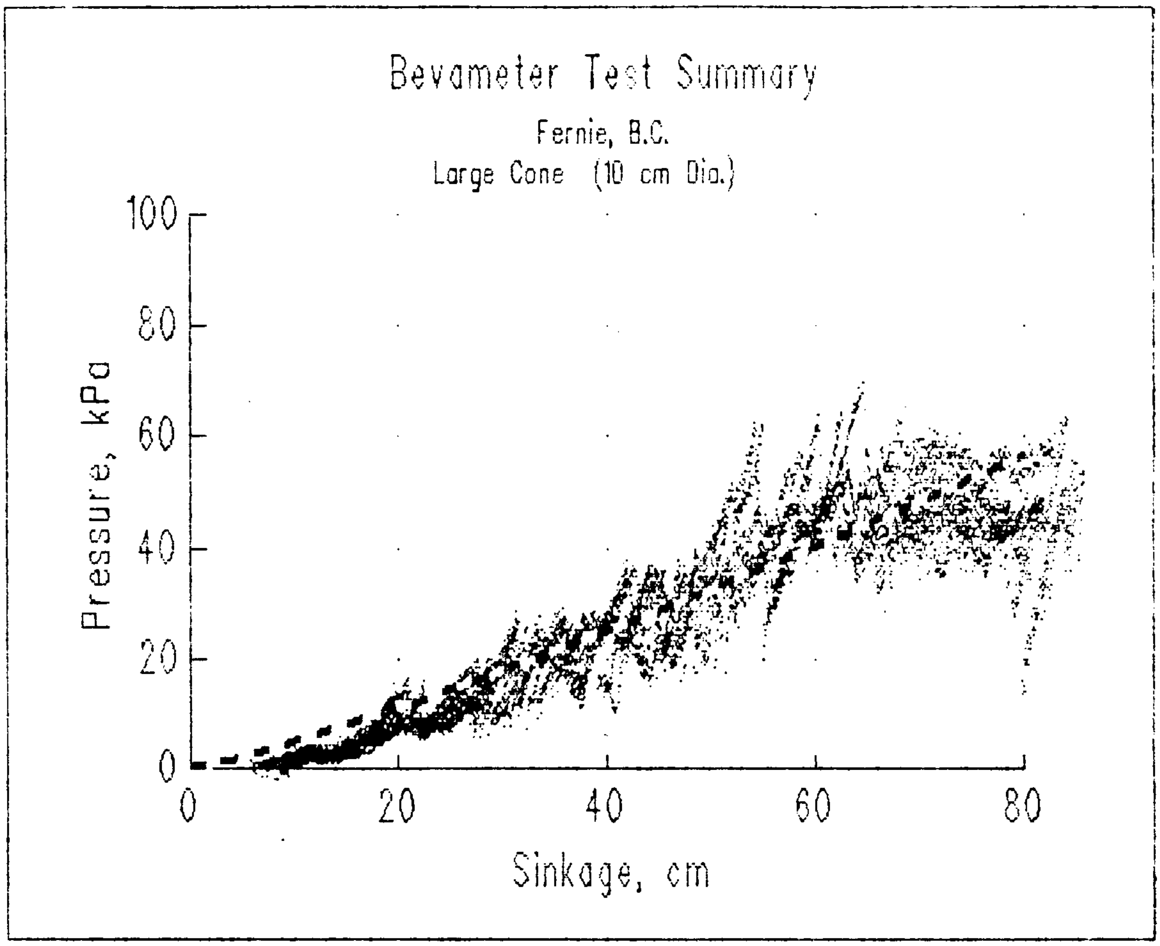

Fig. 5.3 Pressure-sinkage relationship for a fresh snow obtained using a Rammsonde cone attached to the bevameter

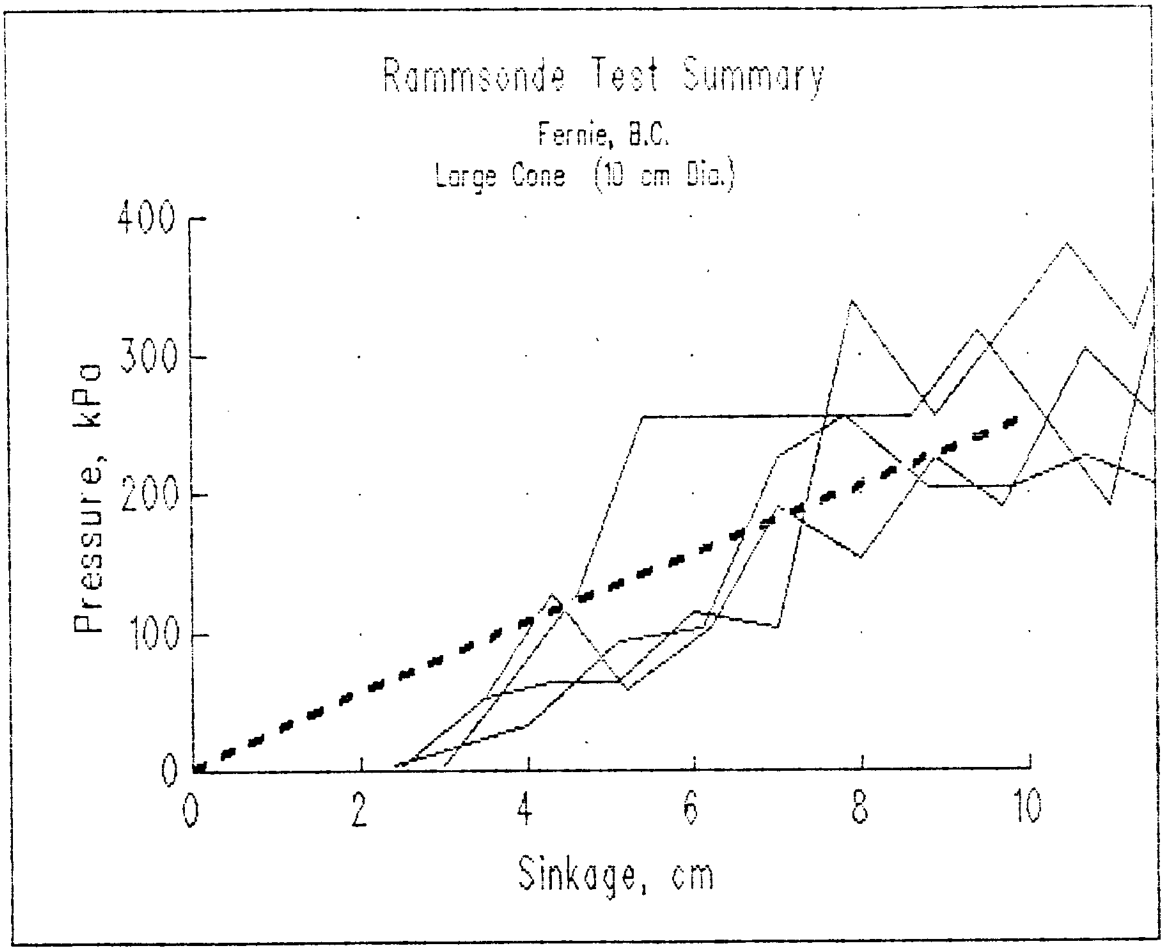

Fig. 5.4 Pressure-sinkage relationship for a preconditioned snow obtained using the Rammsonde

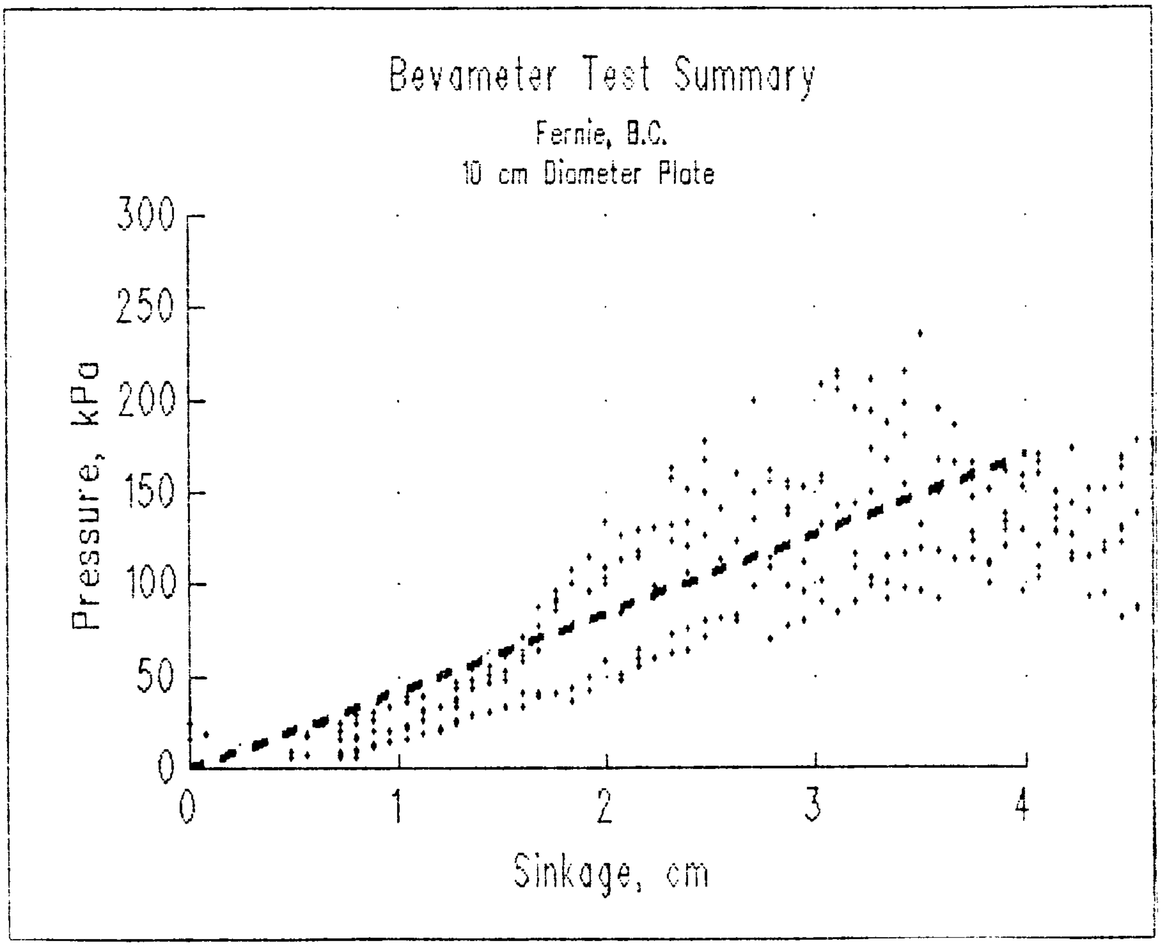

Fig. 5.5 Pressure-sinkage relationship for a preconditioned snow obtained using the bevameter

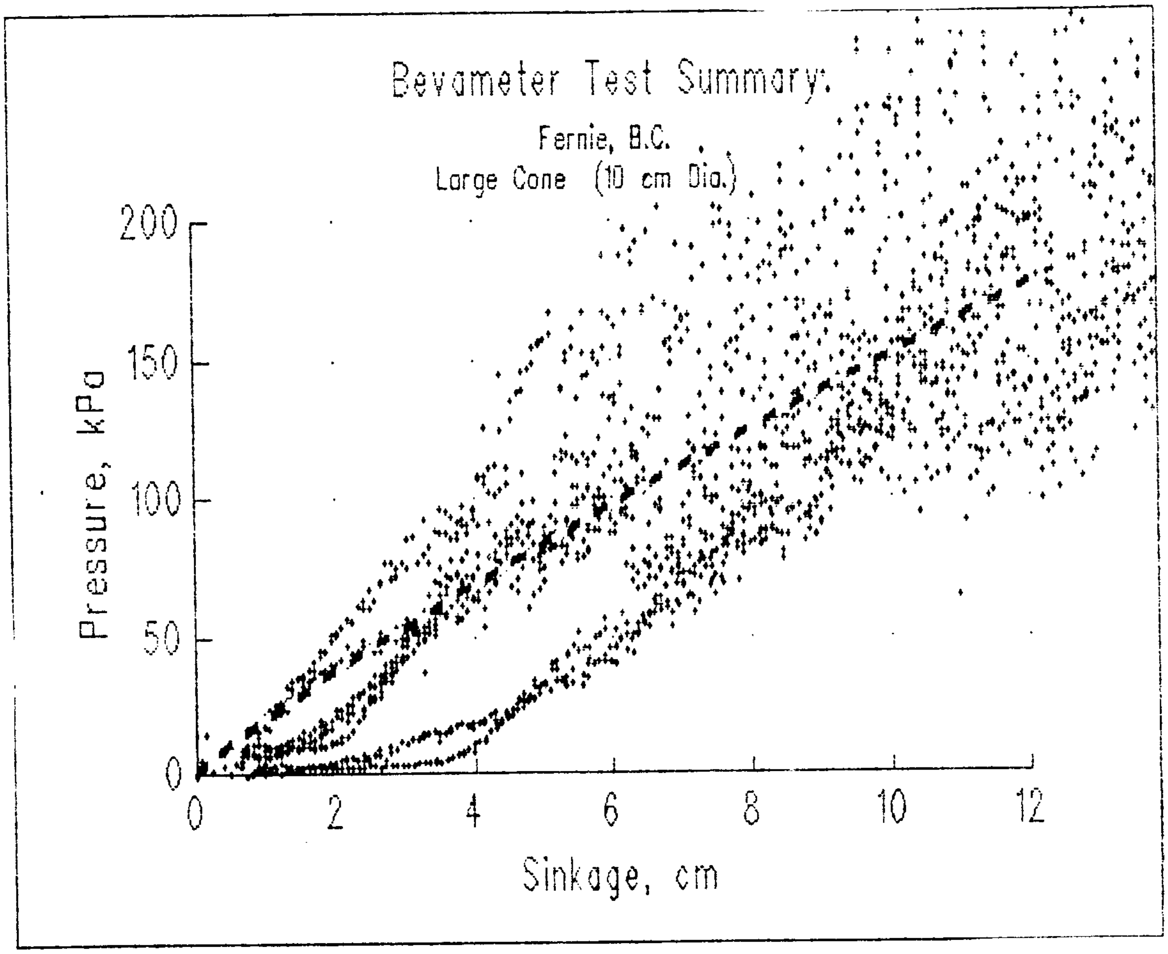

Fig. 5.6 Pressure-sinkage relationship for a preconditioned snow obtained using a Rammsonde cone attached to the bevameter

On preconditioned snow, however, the small Rammsonde cone of 4 cm in diameter can be used effectively to obtain pressure-sinkage data over a wide range of depth. The data obtained using the small cone are comparable to those obtained using the large Rammsonde cone of 10 cm in diameter, as shown in Figs. 2.4 and 2.5, respectively.

C. It is shown that in general, the pressure-sinkage equations proposed by Bekker could form a common basis for characterizing the data obtained using the Rammsonde, the bevameter, and Rammsonde cones on the bevameter.

Two expressions, $p=(k_c/b+k_\phi)z^n$ and $p=kz^n$, have been used to characterize the pressure-sinkage data. The first expression takes into account size effect. Consequently, the pressure-sinkage parameters, n, k_c and k_ϕ , can only be derived from measurements obtained using at least two different sizes of sensing elements. For the second expression, the pressure-sinkage parameter, n and k, can be derived from data obtained using only one size of sensing element.

In many cases, the small Rammsonde cone with 4 cm diameter cannot provide meaningfull pressure-sinkage data for the upper layer of fresh snow (with density less than 0.2 g/cm^3). Consequently, the values of pressure-sinkage paramters, n, k_c and $k\phi$ based on data obtained using the small cone may not be reliable. Under these circumstances, it would seem preferable to use the expression $p=kz^n$ to characterize the pressure-sinkage relationships and to derive the values of n and k from data obtained using the Rammsonde cone with 10 cm diameter.

D. For cases where both the small and the large sensing elements can provide reasonable data, the values of the pressure-sinkage parameters derived from data obtained using a single sensing element of 10 cm in diameter are comparable to those obtained using two sizes of sensing elements of 4 and 10 cm in diameter.

E. Since snow covers in the field are seldom uniform, the resistance to penetration varies greatly with depth, and the values of the parameters used to characterize the pressure-sinkage relationships are highly dependent upon the sinkage range selected. From the point of view of vehicle performance prediction, it is important to select an appropriate sinkage range, corresponding to the expected sinkage of the vehicle (or vehicles) in question, for deriving the values of pressure-sinkage parameters.

F. The amount of data collected during the period of February 7-21, 1990, upon which the report was based, was relatively limited. To further evaluate the validity of using the Rammsonde technique to obtain pressure-sinkage data as input to NTVPM-85 for predicting tracked vehicle performance over snow, additional experimental and analytical studies over a wider range of snow conditions are recommended.

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