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SHINJO BRANCH

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ABSTRACT

Detailed snow settlement data taken at Nagaoka, Niigata Prefecture, at the Institute of Snow and Ice Studies is compared to computer based analyses of the same snow settlement configuration. The daily measured snow settlement data includes: (1) layer geometry, density, temperature, water content, and crystal-ographic type; and (2) atmospheric conditions. The observed data, from the winter of 1970-71, shows development of an equi-temperature snowpack condition, developing after about 3 weeks from initiation of data collection on 1 February 1971. Measured snow viscosity of dry snow was adapted to the computer based model of the settlement problem. Results of the analysis show that from 2 February to 9 February, the experimental and computed settlements are within 10%, with rates of settlement in general agreement. By 9 February ground surface latent heat apparently raised the water content in selected layers to approximately 5%, which resulted in acceleration of settlement from the dry snow rates. Four days later on 13 February the entire snowpack shows accelerated settlement and the dry snow viscosity coefficients are generally inapplicable.

The results of this study show the general applicability of computer based methodology to snow settlement investigations. However, the need exists for measurement of the compressive viscous coefficient of snow when free water content exceeds 4 to 5 %.

INTRODUCTION

In the analysis of snow as it occurs in snowpack, it is necessary to consider the material as viscoelastic. This means that the snow deforms with lapse of time. In horizontal snowpack the dominant time dependent deformation is settlement. In sloping snowpack that is stationary with respect to the basal surface upon which it is placed, the dominant deformation is both settlement and slope-parallel flow, called creep. With creep occurring along the slope, settlement is taken perpendicular to the slope. Since natural snowpack occurs in layers of different density, and snow viscosity is a function of density, it is necessary to model the layering in an analysis of settlement and creep. An additional complication is that the viscous coefficients for snow are different in tension and compression, so that an equivalent orthotropy occurs under combined loading, if both tensile and compressive stresses act.

To make a viscoelastic analysis of snowpack, information of primary importance is a knowledge of the viscous coefficients as functions of snow density. For snow the basic reference is to results reported by Shinojima (1967) in which tensile, compressive and shear viscous coefficients were measured over a density range $100 < \rho < 500 \text{ kg}\cdot\text{m}^{-3}$, and at temperatures from 0 to -15°C . Interpretation of this data in order to apply it to combined loading conditions is summarized by Lang, Sommerfeld (1977). Evidence to date on snow creep at low rates is that the material may be approximated as linear viscoelastic, which is consistent with reported material data. Within the framework of linear viscoelasticity, the theory associated with snow settlement and creep analysis is reviewed herein. Following this the theory is applied to a snow settlement problem for which extensive physical measurements were taken. The analysis is carried out using a finite element representation of the layered snow settlement slab. Deformations are compared with corresponding physical measurements of the well documented

settlement experiment. Conclusions from the analysis compared with the experimental results reflect the current state-of-the-act in this area of snow mechanics.

ONE-DIMENSIONAL LINEAR VISCOELASTICITY THEORY

Standard texts abound on detailed development of the linear theory of viscoelasticity (Flügge, 1967), so only snow related aspects are considered herein. Snow, as with other natural occurring viscoelastic materials, is represented by a Burger body model or series of these. The Burger body is a four-element viscoelastic model that exhibits both short-term material elasticity and long-term viscous flow. This 4 parameter fluid model is shown in Figure 1. If a stress is applied at nodes 1 and 2, the series elastic spring, k_1 , instantly deforms to provide short term elastic response. If ϵ' is the strain associated with this deformation then

$$\sigma = k_1 \epsilon'$$

Stress, σ , applied to the series viscous element results in a material flow, if at rate $\dot{\epsilon}''$, then

$$\sigma = \eta_1 \dot{\epsilon}''$$

Thus, total strain, ϵ_1 , and total strain rate, $\dot{\epsilon}_1$, of the series elements is then

$$\epsilon_1 = \epsilon' + \epsilon'' \quad \text{and} \quad \dot{\epsilon}_1 = \dot{\epsilon}' + \dot{\epsilon}''$$

In the parallel spring-viscous element part of the model the stress divides between the elements, so that

$$\sigma = k_2 \epsilon_2 + \eta_2 \dot{\epsilon}_2$$

where ϵ_2 is the strain, and $\dot{\epsilon}_2$ is the strain rate across the parallel elements. Total strain and strain rate of the Burger body is then

$$\epsilon = \epsilon_1 + \epsilon_2 \quad \text{and} \quad \dot{\epsilon} = \dot{\epsilon}_1 + \dot{\epsilon}_2$$

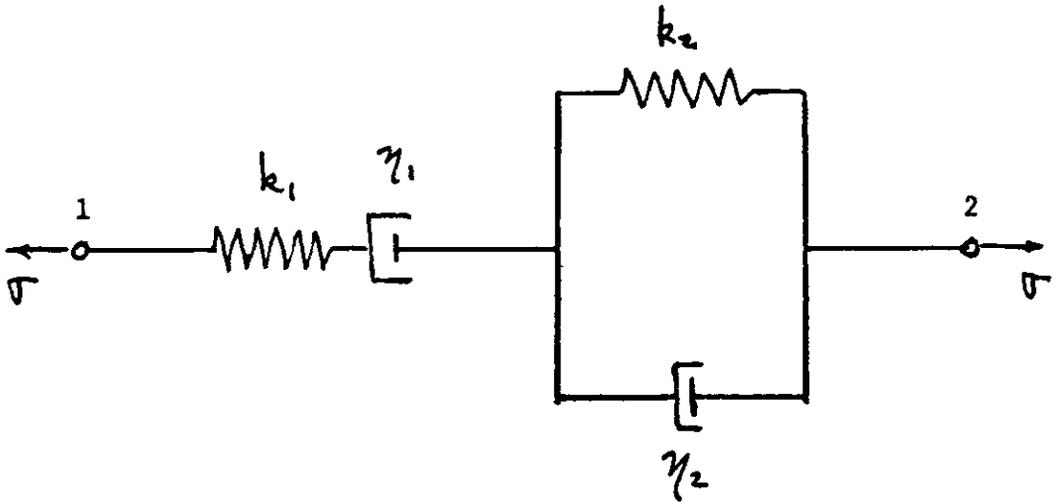


Figure 1 : Four parameter fluid element

Combining these equations, a single constitutive equation between total strain and its derivatives and total stress and its derivatives is obtained, namely

$$k_1 k_2 \eta_1 \dot{\epsilon} + k_1 \eta_1 \eta_2 \ddot{\epsilon} = k_1 k_2 \sigma + (\eta_1 k_2 + \eta_2 k_1 + \eta_1 \eta_2) \dot{\sigma} + \eta_1 \eta_2 \ddot{\sigma}$$

or

$$\sigma + \left(\frac{\eta_1}{k_1} + \frac{\eta_2}{k_2} + \frac{\eta_1 \eta_2}{k_1 k_2} \right) \dot{\sigma} + \frac{\eta_1 \eta_2}{k_1 k_2} \ddot{\sigma} = \eta_1 \dot{\epsilon} + \frac{\eta_1 \eta_2}{k_2} \ddot{\epsilon}$$

In the notation of Flügge (1967) the differential operators are written

$$P\sigma = Q\epsilon$$

where

$$P = 1 + p_1 \frac{d}{dt} + p_2 \frac{d^2}{dt^2}$$

$$Q = q_1 \frac{d}{dt} + q_2 \frac{d^2}{dt^2}$$

$$p_1 = \frac{\eta_1}{k_1} + \frac{\eta_2}{k_2} + \frac{\eta_1 \eta_2}{k_1 k_2}$$

$$p_2 = \frac{\eta_1 \eta_2}{k_1 k_2}$$

$$q_1 = \eta_1$$

$$q_2 = \frac{\eta_1 \eta_2}{k_2}$$

Laplace Transform (L.T.) techniques are usually applied in the further solution methodology of linear viscoelasticity. The idea behind the L.T. is to convert differential equations into algebraic equations, rearrange the equations in a particular way, then take the inverse L.T. to obtain the final solution. The L.T. theory is given by Churchill (1958), and only a brief summary is included herein.

Given any function, of say time t , the L.T. of the function is

$$\bar{f}(s) = \int_0^{\infty} f(t) e^{-st} dt$$

The L.T. of the derivatives of $f(t)$ are obtained by integration by parts,

$$\int_0^{\infty} \dot{f}(t) e^{-st} dt = -f(0) + s\bar{f}(s)$$

$$\int_0^{\infty} \ddot{f}(t) e^{-st} dt = -\dot{f}(0) + s f(0) + s^2 \bar{f}(s)$$

etc. In these equations $f(0)$ and $\dot{f}(0)$ are the values of $f(t)$ and $\dot{f}(t)$ at $t=0$. If the system starts from rest (initial quiescence) then $f(0)=\dot{f}(0)=0$, and

$$L.T. (f(t)) = \bar{f}(s)$$

$$L.T. (\dot{f}(t)) = s\bar{f}(s)$$

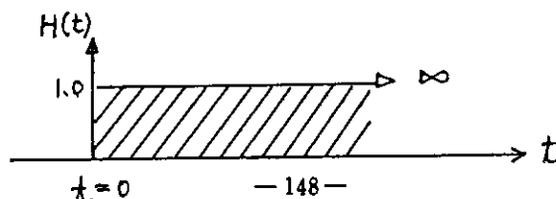
$$L.T. (\ddot{f}(t)) = s^2 \bar{f}(s)$$

Thus, the L.T. of a differential equation yields an algebraic equation in the L.T. coefficient s . The L.T. of many different functions, $f(t)$, have been tabulated, so that solution of linear differential equations reduces to a tabular lookup, which is both fast and easy. This procedure can be demonstrated with the viscoelastic problem currently under consideration. If the Burger body is assumed to be initially quiescent, then the L.T. of the previous differential operators is simply

$$\mathcal{P} = 1 + p_1 s + p_2 s^2$$

$$\mathcal{Q} = q_1 s + q_2 s^2$$

where script letters indicate the L.T. Correct interpretation of the above L.T. operation requires us to remember that the differential operators always act on some independent variable. A discontinuous function of importance in L.T. operations is the Heaviside step function defined by



Assuming initial quiescence, it can be shown that

$$L.T. (H(t)) = 1/s \quad \text{for } t > 0$$

which will be used in the following development.

Returning to our constitutive equation and taking the L.T. yields

$$\bar{\epsilon} = \bar{\sigma} \frac{(\eta_1 s + k_1)(\eta_2 s + k_2) + k_1 \eta_1 s}{k_1 \eta_1 s (\eta_2 s + k_2)}$$

Consider response of the Burger body to a step increase in stress at $t = 0$.

This is represented by

$$\sigma(t) = \sigma_0 H(t) \quad t > 0$$

where σ_0 is the stress increment. Taking the L.T. of this function yields

$$\bar{\sigma} = \sigma_0 \frac{1}{s}$$

and

$$\bar{\epsilon}(s) = \frac{\sigma_0}{k_1 \eta_1} \left[\frac{(\eta_1 s + k_1)(\eta_2 s + k_2) + k_1 \eta_1 s}{s^2 (\eta_2 s + k_2)} \right]$$

This equation is rearranged into a partial fractions form consistent with L.T. theory, namely

$$\bar{\epsilon}(s) = \frac{\sigma_0}{k_1 \eta_1} \left[\frac{\eta_1}{s} + \frac{k_1}{s^2} + \frac{k_1 \eta_1}{s(\eta_2 s + k_2)} \right]$$

which is now in a form where the inverse L.T. is readily completed using L.T. tables. The result is

$$\epsilon(t) = \sigma_0 \left[\frac{t}{\eta_1} + \frac{1}{k_1} + \frac{1}{k_2} (1 - e^{-\lambda t}) \right]$$

where

$$\lambda = \frac{k_2}{\eta_2}$$

This solution for strain is the time dependent deformational response of the Burger body model to a step input of applied stress. In the viscoelastic literature this is a standard test condition, called the creep test. Another standard test is the stress relaxation test, wherein the model is subjected to a step increase in strain, and the solution for stress as a function of time is derived by methods similar to the derivation of the creep response given above.

Having the solution for strain as a function of time, some characteristics of the Burger body can be deduced from limiting conditions. For example, setting $t = 0$ in this equation we obtain

$$\epsilon_0 = \frac{\sigma_0}{k_1}$$

the initial elastic deformation due to stress σ_0 . As t increases the material creeps for all time (under load σ_0) eventually at a constant stationary rate defined by $\lim_{t \rightarrow \infty} \left(\frac{d\epsilon}{dt} \right) = \frac{\sigma_0}{\eta_1}$. Thus, η_1 , the series viscous element, establishes the stationary or steady creep of the material. The material response for all $t > 0$ is shown in Figure 2. Our interest is in the steady creep response phase of the deformation, as it pertains to snow.

THREE-DIMENSIONAL LINEAR VISCOELASTIC THEORY

Consider first elastic equations in three dimensions. Stress is divided into hydrostatic and deviatoric components, as follows

$$\begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix} = \begin{bmatrix} s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & s \end{bmatrix} + \begin{bmatrix} s_x & s_{xy} & s_{xz} \\ s_{xy} & s_y & s_{yz} \\ s_{xz} & s_{yz} & s_z \end{bmatrix}$$

HYDROSTATIC and DEVIATORIC

where

$$s = \frac{1}{3} (\sigma_x + \sigma_y + \sigma_z)$$

$$s_x + s_y + s_z = 0$$

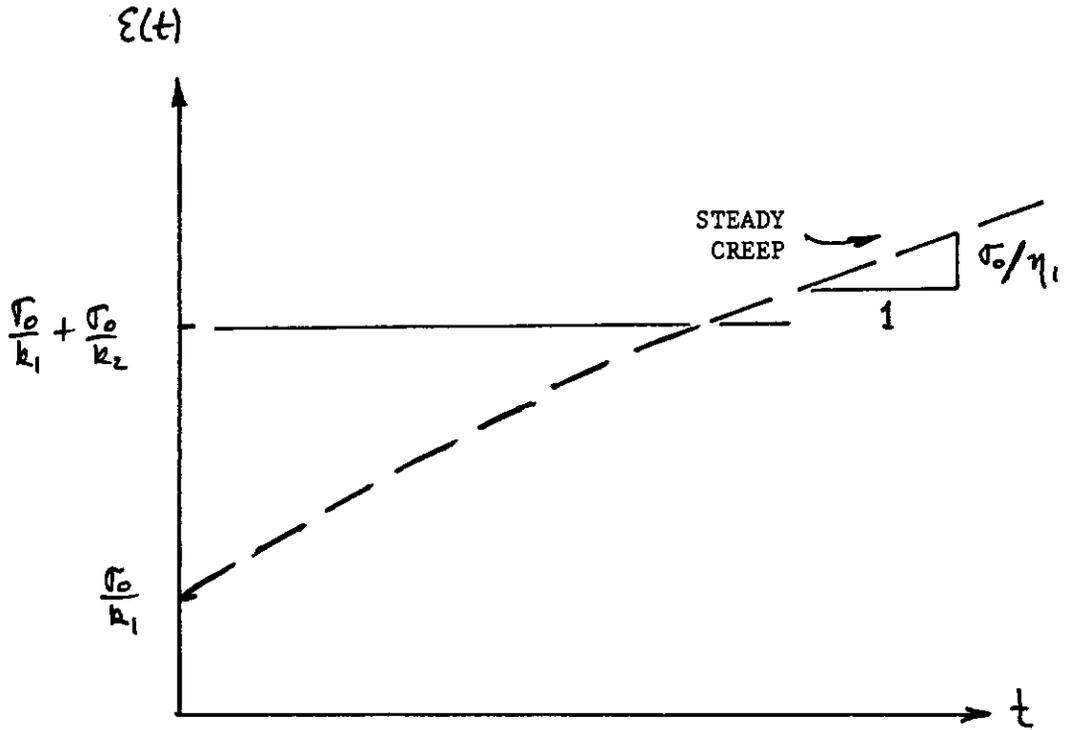


Figure 2 : Burger Body Creep Response

For strain the same split can be made

$$\begin{bmatrix} \epsilon_x & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{xy} & \epsilon_y & \epsilon_{yz} \\ \epsilon_{xz} & \epsilon_{yz} & \epsilon_z \end{bmatrix} = \begin{bmatrix} e & 0 & 0 \\ 0 & e & 0 \\ 0 & 0 & e \end{bmatrix} + \begin{bmatrix} e_x & e_{xy} & e_{xz} \\ e_{xy} & e_y & e_{yz} \\ e_{xz} & e_{yz} & e_z \end{bmatrix}$$

HYDROSTATIC DEVIATORIC

with $e = \frac{1}{3}(\epsilon_x + \epsilon_y + \epsilon_z)$ and $e_x + e_y + e_z = 0$

If K is the bulk modulus and G is the shear modulus, then for an elastic material

$$\Delta = K(3e) \quad \text{and} \quad \tau_{xy} = G(2\epsilon_{xy}) \text{ etc.}$$

For a viscoelastic material that is isotropic, a hydrostatic stress must produce a dilatation, or volume change, with no distortion, and Δ and e are related by

$$P''\Delta = Q''e$$

Likewise the deviatoric quantities relate similarly

$$P'\Delta_{ij} = Q'e_{ij}$$

Or

$$3K \rightarrow \frac{Q''}{P''} \qquad 2G \rightarrow \frac{Q'}{P'}$$

where for the elastic case $P''=1$, $Q''=3K$, $P'=1$ and $Q'=2G$. Taking the L.T. of these differential operators, we have

$$3K \rightarrow \frac{2''(s)}{P''(s)} \qquad 2G \rightarrow \frac{2'(s)}{P'(s)}$$

and the general correspondance principle of linear viscoelasticity is:

If the solution of an elastic problem is known, then the L.T. of the solution of the corresponding viscoelastic problem may be found by replacing the elastic constants K and G by the operator quotients above, and the actual loads by their L.T.s.

Since K and G are not as common as E and ν the conversion is provided,

$$E \rightarrow \frac{32'2''}{2P'2''+2'P''} \quad \nu \rightarrow \frac{P'2''-2'P''}{2P'2''+2'P''}$$

Consider next the elastic solution to the horizontal snowslab settlement problem.

HORIZONTAL SNOWSLAB SETTLEMENT

A column of snow of depth h is placed on a rigid support, and acted upon by gravity. Strain in the z direction is prevented because of identical columns at either side, and this condition requires

$$\epsilon_z = 0$$

$$\therefore \sigma_z = \nu(\sigma_x + \sigma_y)$$

The remaining constitutive equations in the x, y plane are

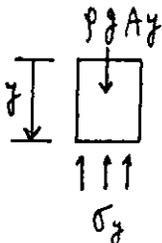
$$E\epsilon_x = (1-\nu^2)\sigma_x - \nu(1+\nu)\sigma_y$$

$$E\epsilon_y = (1-\nu^2)\sigma_y - \nu(1+\nu)\sigma_x$$

But, for the same reason that $\epsilon_z = 0$, also $\epsilon_x = 0$ so that

$$\sigma_x = \frac{\nu}{1-\nu} \sigma_y \quad \text{and} \quad \sigma_z = \sigma_x$$

To determine σ_y at any depth y , consider equilibrium of the column,



$$\sum F_y = 0 \Rightarrow \sigma_y = -P g y \text{ (COMPRESSION)}$$

$$\text{then } \sigma_x = \sigma_z = -\frac{\nu}{1-\nu} P g y \text{ (COMPRESSION)}$$

So all stresses are compressive and an isotropic condition may be assumed regarding the tensile-compressive state of the snow.

For deformation consider

$$\epsilon_y = \frac{\partial \nu}{\partial y} = -\frac{(1-\nu^2)}{E} P g y + \frac{\nu(1+\nu)}{E} \frac{\nu}{1-\nu} P g y$$

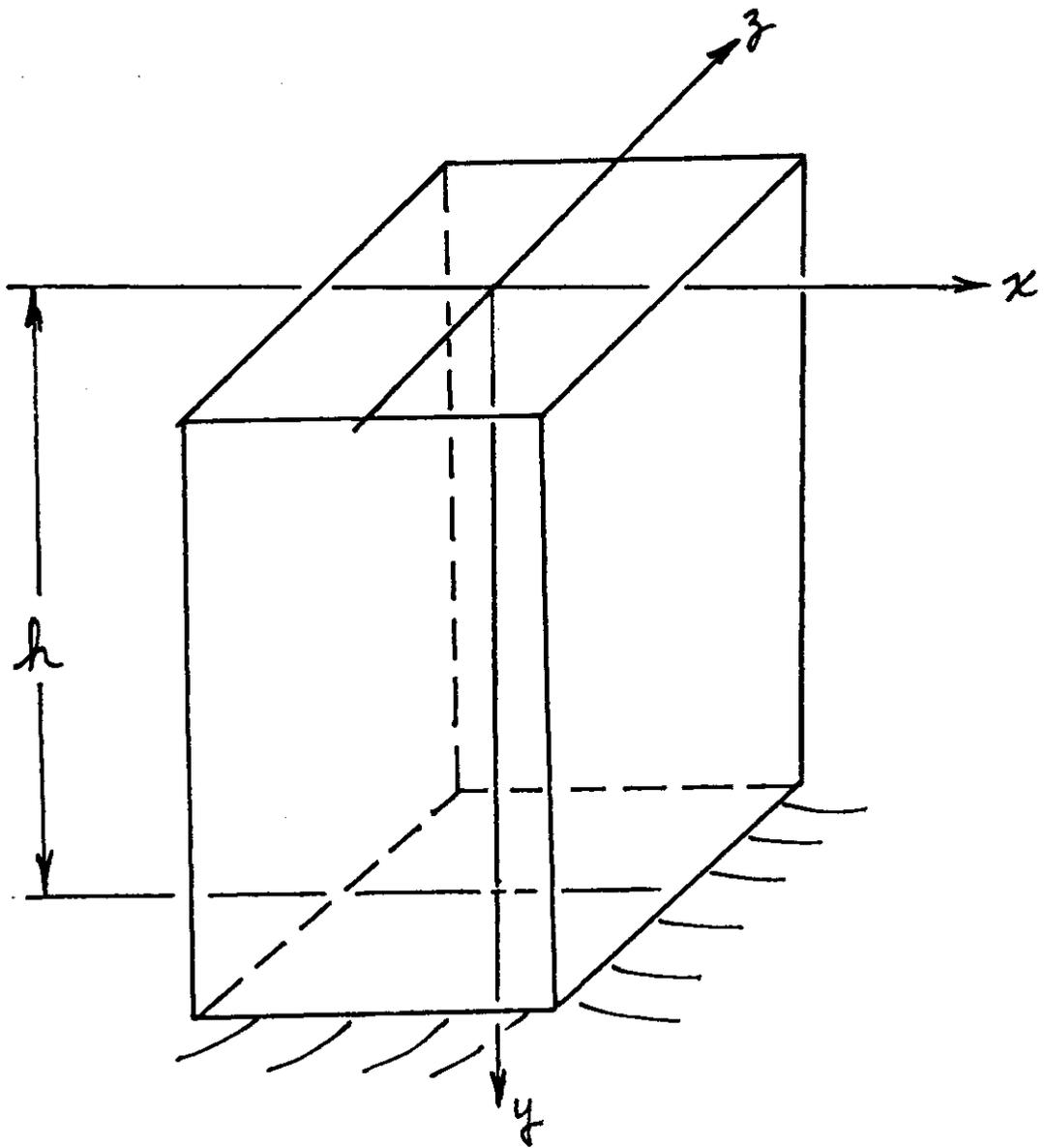


Figure 3 : Snow Column Geometry

but $V \neq V(x, y)$ so $\frac{\partial V}{\partial y} \rightarrow \frac{dV}{dy}$ and

$$V(y) = \left[-\frac{1-\nu^2}{E} + \frac{\nu^2(1+\nu)}{E(1-\nu)} \right] \frac{\rho g y^2}{2} + C_1$$

at $y=h$, $v=0$ which evaluates C_1 and the final solution is

$$V(y) = \rho g \left[\frac{(1-2\nu)(1+\nu)}{2E(1-\nu)} \right] (h^2 - y^2)$$

The maximum deflection occurs at the upper surface of the column and equals

$$V(0) = \rho g \left[\frac{(1-2\nu)(1+\nu)}{2E(1-\nu)} \right] h^2$$

An important result of this derivation is the determination of a plane strain condition relative to the settlement problem. This is a simplification of the general 3D viscoelastic equations, which is investigated below.

For plane strain in the x, y plane, the elastic constitutive law is

$$\epsilon_x = \frac{1-\nu^2}{E} \sigma_x - \frac{\nu(1+\nu)}{E} \sigma_y$$

or, expressed in terms of the bulk modulus and shear modulus

$$\epsilon_x = \frac{(3k+4g)}{4g(3k+g)} \sigma_x - \frac{(3k-2g)}{4g(3k+g)} \sigma_y$$

If now the correspondance principle is applied

$$3k \rightarrow \frac{Q''}{\rho''} \quad 2g \rightarrow \frac{Q'}{\rho'}$$

and the constitutive equations become

$$(2Q''\rho' + Q'\rho'')Q'\epsilon_x = (P'Q'' + 2Q'\rho'')P'\sigma_x - (Q''\rho' - Q'\rho'')P'\sigma_y$$

$$(2Q''\rho' + Q'\rho'')Q'\epsilon_y = (P'Q'' + 2Q'\rho'')P'\sigma_y - (Q''\rho' - Q'\rho'')P'\sigma_x$$

or, in terms of the L.T. assuming initial quiescence,

$$\bar{\epsilon}_x = \frac{(P'Q'' + 2Q'\rho'')P'}{(2Q''\rho' + 2Q'\rho'')Q'} \bar{\sigma}_x - \frac{(Q''\rho' - Q'\rho'')P'}{(2Q''\rho' + 2Q'\rho'')Q'} \bar{\sigma}_y$$

For the Burger body model, the differential operators have already been derived, and distinguishing the hydrostatic from the deviatoric, we have

$$P'' = 1 + p_1 \frac{d}{dt} + p_2 \frac{d^2}{dt^2}$$

hydrostatic :

$$Q'' = q_1 \frac{d}{dt} + q_2 \frac{d^2}{dt^2}$$

$$P' = 1 + p_1^* \frac{d}{dt} + p_2^* \frac{d^2}{dt^2}$$

deviatoric :

$$Q' = q_1^* \frac{d}{dt} + q_2^* \frac{d^2}{dt^2}$$

Steady state response of the Burger body was previously shown to be the continuing deformation of the series viscous elements, identified by q_1 and q_1^* in the differential operators above. Thus, for steady-state response the above operators reduce to

$$P'' = 1 \quad Q'' = q_1 \frac{d}{dt} \quad P' = 1 \quad Q' = q_1^* \frac{d}{dt}$$

and the L.T. versions become

$$P'' = 1 \quad Q'' = q_1 s \quad P' = 1 \quad Q' = q_1^* s$$

so that

$$S \bar{\epsilon}_x = \frac{(q_1 + 2q_1^*)}{(2q_1 + q_1^*)q_1^*} \bar{\sigma}_x - \frac{q_1 - q_1^*}{(2q_1 + q_1^*)q_1^*} \bar{\sigma}_y$$

The inverse L.T. assuming initial quiescence is

$$\dot{\epsilon}_x = \frac{q_1 + 2q_1^*}{(2q_1 + q_1^*)q_1^*} \sigma_x - \frac{q_1 - q_1^*}{(2q_1 + q_1^*)q_1^*} \sigma_y$$

which is the solution for strain rate $\dot{\epsilon}_x$ in terms of only the secondary viscous element parameters and stress components σ_x and σ_y . A similar equation is obtained for $\dot{\epsilon}_y$, namely

$$\dot{\epsilon}_y = \frac{q_1 + 2q_1^*}{(2q_1 + q_1^*)q_1^*} \sigma_y - \frac{q_1 - q_1^*}{(2q_1 + q_1^*)q_1^*} \sigma_x$$

If we compare this equation to the corresponding elastic equation for plane strain, which is

$$\epsilon_y = \frac{3k + 4G}{4G(3k + 4G)} \sigma_y - \frac{3k - 2G}{4G(3k + 4G)} \sigma_x$$

correspondance is established if

$$3k \rightarrow q_1 = \text{dilatational series viscous element}$$

$$2G \rightarrow q_1^* = \text{deviatoric series viscous element}$$

We now wish to make use of experimental data on snow to establish the material coefficients for plane strain. One set of experimental data by Shinojima (1967), is the secondary viscous response of snow in uniaxial compression. For this the corresponding elastic equation is

$$\sigma_x = E \epsilon_x = \frac{9kG}{3k + 4G} \epsilon_x$$

Designating the Shinojima viscous parameter by η so that $\sigma_x = \eta \dot{\epsilon}_x$.
correspondance gives

$$\frac{18kG}{6k + 2G} = \frac{3(3k)(2G)}{2(3k) + 2G} \rightarrow \frac{3q_1 q_1^*}{2q_1 + q_1^*} = \eta$$

which is one equation from which q_1 and q_1^* can be evaluated. Other data by Lang and Brown (1975), establishes a secondary creep Poisson's ratio of $\nu = 0.27$ for snow in compression. This sets up a second correspondance based upon the Poissonic equivalence, namely

$$\nu = \frac{1}{2} \frac{3k - 2G}{3k + 4G} \rightarrow \frac{q_1 - q_1^*}{2q_1 + q_1^*} = \nu$$

From this equation we find that

$$\frac{q_1^*}{q_1} = \frac{1 - 2\nu}{1 + \nu}$$

Which, when substituted into the first equation yields

$$q_1^* = \frac{\eta}{1 + \nu}$$

so that

$$q_1 = \frac{\eta}{1 - 2\nu}$$

Having found these, the constitutive equation for plane strain, then becomes

$$\begin{Bmatrix} \dot{\epsilon}_x \\ \dot{\epsilon}_y \\ \dot{\gamma}_{xy} \end{Bmatrix} = \frac{1+\nu}{\eta} \begin{bmatrix} (1-\nu) & -\nu & 0 \\ -\nu & (1-\nu) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}$$

or, inverting, we have

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{\eta}{(1-2\nu)(1+\nu)} \begin{bmatrix} (1-\nu) & \nu & 0 \\ \nu & (1-\nu) & 0 \\ 0 & 0 & (1-2\nu) \end{bmatrix} \begin{Bmatrix} \dot{\epsilon}_x \\ \dot{\epsilon}_y \\ \dot{\gamma}_{xy} \end{Bmatrix}$$

which is the elastic constitutive equation for plane strain with viscous coefficient η replacing material modulus E. With this correspondance now known, we see that an elastic finite element analysis computer program may be used to evaluate steady-state viscoelastic settlement.

In following sections, data from a snow settlement experiment is analyzed numerically. The computer program used to model the settlement problem is a finite element code which can be used to analyze linear orthotropic planar elasticity (LOPE) problems.

DESCRIPTION OF SETTLEMENT EXPERIMENT AND DATA

During the winter of 1970-71 a horizontal, naturally occurring snow-pack was monitored on a daily basis for layer geometry, density, temperature, water content, and crystallographic type, as well as atmospheric conditions, by Nakamura and Kemmotsu. Reporting of part of the results of this study, on the overall settlement viscosity, is by Nakamura and Kemmotsu (1971). Data used in the present study is in preparation for publication, and any inquiry concerning the data should be directed to the authors above. The experiment was carried out in Nagaoka City at the Institute of Snow and Ice Studies, located 20km from the Sea of Japan, on the west coast of central Honshu Island, Japan. In this coastal environment with dominant

near freezing winter temperatures, snowpack has a strong tendency to become equi-temperature, and for the snowpack to develop water content. This, in fact, occurred with the experimental snowpack by March 1971, so evaluation of settlement of the pack was carried out starting with data on 2 February 1971. Snowpack layering with its crystallographic type were tabulated for each day; however, the data was also plotted for easy reference by Nakamura and Kemmotsu (Figure 4). From review of this plot it is seen that data for the month of February is defined in greater detail than what was in evidence later in March, as the snowpack became wet. Dominant layers in the snowpack are labeled A, B, D, C, E and F in Figure 4, which were traced for all or a significant part of the month of February. The density of these layers, as measured daily, is shown in Figure 5, for reference purposes only. In computer modeling of settlement, tabulated data was used that gives the thickness and density of all layers in the snowpack. The tabulated data that was used between 2 Feb. and 15 Feb. is listed in Appendix A. Estimation of the free water content in the different layers, identified in Figure 4, is given in Figure 6. Atmospheric maximum, minimum and mean temperatures for the month of February 1971 are shown in Figure 7.

Some comments are appropriate to make on the data that has been given. Relative to snowpack layering, layer density and thickness are considered to be accurate to third place roundoff. However, the data of Figure 4 supposedly does not indicate this accuracy, as there are daily fluxuations that show layer rises rather than settlement. But this is attributed to the manner in which the data was taken. In order that each day's reading not be subject to the previous days snowpack exposure, approximately 30 cm of snowpack was cut away from the previous days vertical face on each succeeding day. This procedure introduces the possibility of local material variations causing some data scatter which could not be avoided. Also, each day's readings were taken between 9:00 and 11:00 am, without information known on the exact time each day that new snowfall occurred,

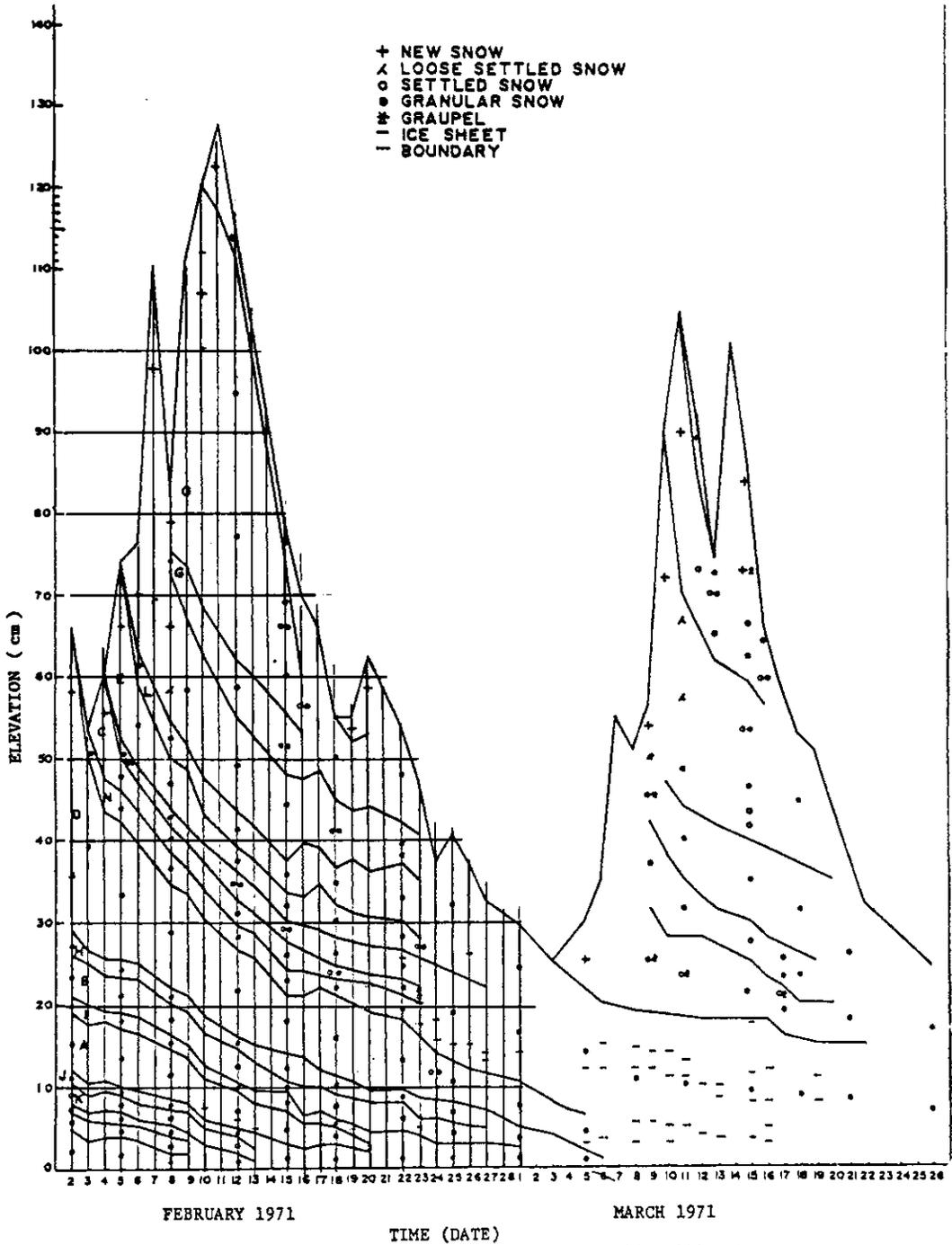


Figure 4 : Snowpack layering and crystallographic identification

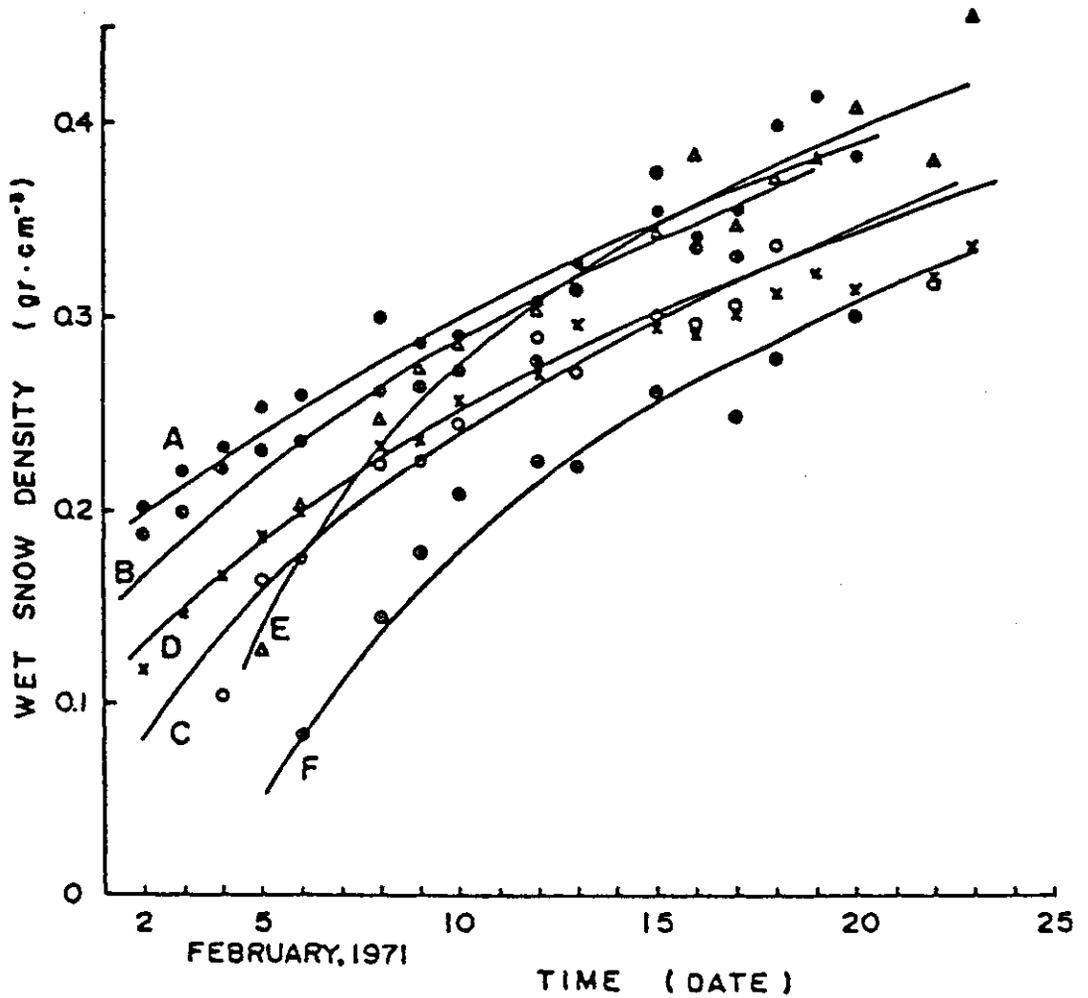


Figure 5 : Layer Density Variation During Feb. 1971

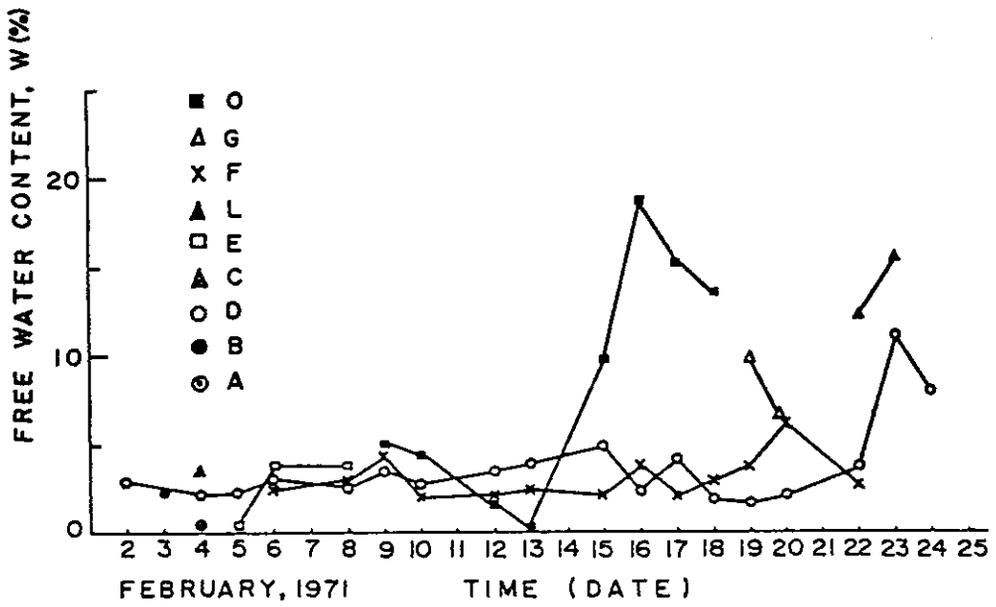


Figure 6 : Free Water Content Variation During Feb. 1971

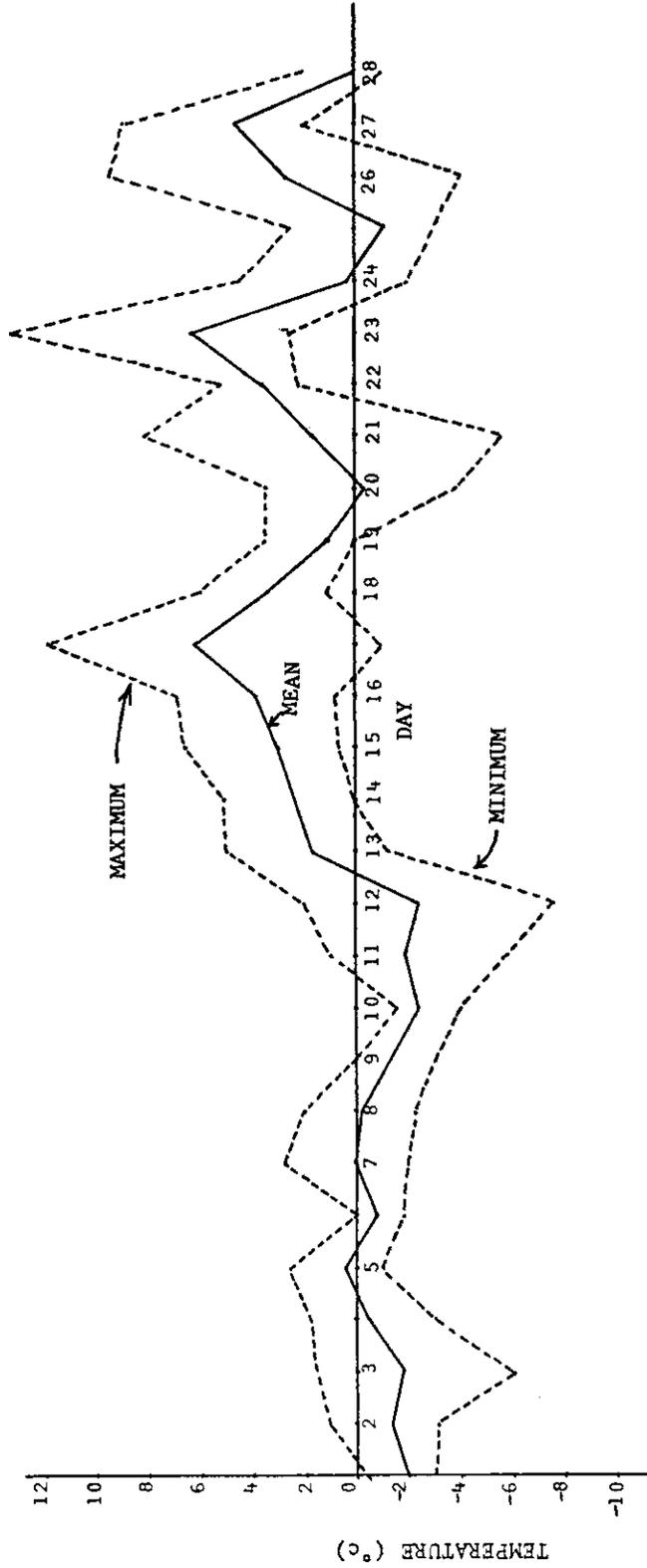


Figure 7 : Maximum, Minimum and Mean Temperature Versus Day at Test Site in Nagaoka for February 1971

so lines connecting the top surface data points are an approximation. On 2 February layers A and B were already established from snowfall in January, whereas layer D was formed from new snowfall. With respect to the layer density measurements, layer E deviates from the norm shown for all other layers, and cause for this difference is unknown.

SNOW VISCOSITY COEFFICIENT

The viscosity coefficient η is defined by Shinojima (1967) in terms of snow density and snow temperature in equation form as

$$\eta = 3.984 \times 10^{-3} \left[e^{25.3 \rho + 9.58 \times 10^{-2} |T|} \right]$$

where η is in the units N·day/cm² snow density is ρ in gm·cm⁻³, and T is snow temperature in °C. This explicit equation for secondary viscosity of a Burger body representation for snow is for short duration tests of natural occurring dry snow taken from fields in Shiozawa (Niigata prefecture) and Sapporo (Hokkaido prefecture) Japan. Short duration tests were for durations less than 30 min, during which the secondary creep rate was estimated. Referring back to the constitutive equation between stress and strain rate, and writing it

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{13} & 0 \\ C_{13} & C_{33} & 0 \\ 0 & 0 & C_{44} \end{bmatrix} \begin{Bmatrix} \dot{\epsilon}_x \\ \dot{\epsilon}_y \\ \dot{\gamma}_{xy} \end{Bmatrix}$$

the coefficients are

$$C_{11} = C_{33} = \frac{\eta(1-\nu)}{(1-2\nu)(1+\nu)} \quad C_{44} = \frac{\eta}{1+\nu}$$

$$C_{13} = \frac{\eta\nu}{(1-2\nu)(1+\nu)}$$

Setting $\nu = 0.27$, as noted previously, coefficient C_{11} is plotted in Figure 8

using the above equation for η , and for $T = 0^\circ\text{C}$ as a solid line designated

"short duration". Although not expressed in equation form, Shinojima reports also the secondary creep coefficient measured from long duration creep tests of 60 hours. From this data the "x" entries are shown in Figure 8. The dashed line fit to these data points is satisfactory except in the low density range, where one data point indicates possible deviation from linearity. In computer based evaluation of settlement, use of the short duration data gave settlement rates lower than what was observed physically. The seemingly small shift to the dashed line, results in significantly higher settlement rates that more closely match the experimental results. Thus, settlement is sensitive to specification of the viscous coefficient, but also, in the present situation, that snowpack temperature is near or at $T = 0^{\circ}\text{C}$ complicates the modeling. The Shinojima coefficients are for dry snow. The experimental results on settlement were obtained with snowpack that had water content, which increased during the month. At what fraction of water content snow ceases to be dry and becomes wet is not known. Thus, it is not known quantitatively when the Shinojima coefficients are applicable, and when not applicable, except in the actual computer modeling. However, in the experimental work measurement of water content was difficult, and data was not obtained for all layers for each day. Thus, it is not possible to correlate viscosity with water content from this study, except in a qualitative sense. Thus, this modeling, in one respect, is carried out to assess the applicability of the Shinojima viscosity data to the snowpack settlement problem under typical mid-winter conditions.

COMPUTER ANALYSIS OF SETTLEMENT

The finite element modeling of the snowpack was a one-to-one matching of the experimental data, taken from the tabulated listings. For example, the finite element representation of the snowpack on 4 Feb. 1971 is shown in Figure 9, which can be compared directly with the 4 Feb. data sheet in Appendix A. The model is made up of 15 elements, using 32 gridpoints.

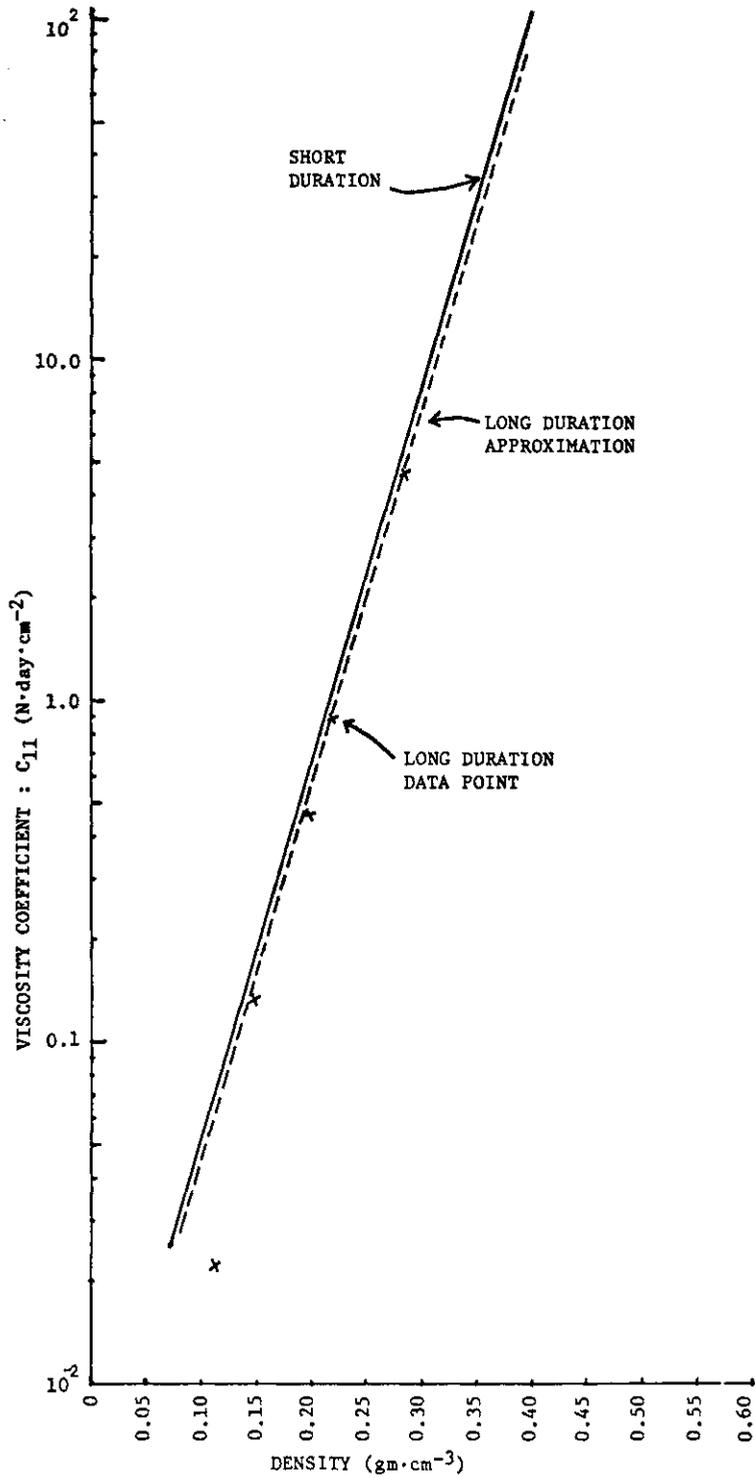


Figure 8 : Secondary Creep Viscosity versus snow density at temperature $T = 0^\circ\text{C}$

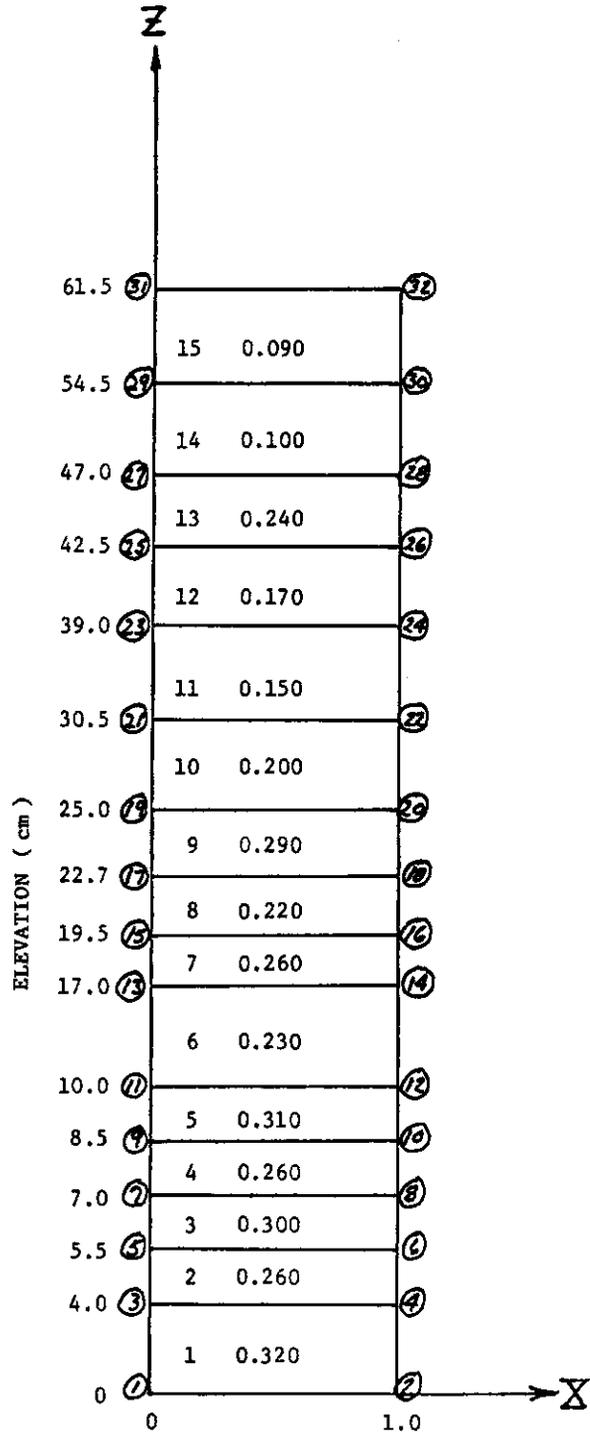


Figure 9 : Finite Element Model of 4 Feb. 1971 Snowpack.

The elevation of each set of gridpoints is shown, and within each element the layer density is given. Thus for element #1, the gridpoints are 3, 1, 2, 4, and the layer density is $\rho = 0.320\text{gm}\cdot\text{cm}^{-3}$. Based upon this density, viscous coefficient C_{11} can be read from Figure 8, and the other constitutive coefficients C_{13} , C_{33} and C_{44} then computed. These coefficients are then the constitutive representation of the snow in the first layer. This procedure is followed in order to define like quantities for all layers. Based upon these material descriptions, and inputting the gravitational constant g , the settlement of each gridpoint per day is computed, as well as the stresses in each finite element, which equal the weight of snow above each finite element centroid to the top surface.

At each new day for which density and elevation data was taken (Appendix A) a new finite element representation of the slab was set up, and layer displacements computed over that 24 hour period. These displacements were then added to the total of the previous days displacements in order to determine the layer elevation for each day. By this procedure it is evident that any error made for any reason on one day affected the total displacement of all following days. Particular difficulty of this nature was experienced in startup calculations on the new layers that deposited during February. These were layers D, C, E and F, which initially deposited with low snow densities less than $0.100\text{gm}\cdot\text{cm}^{-3}$. By means of the computer study it became evident that coefficients read from the straight-line approximation of the Shinojima data in Figure 8 did not fit the settlement rates observed in new layers over a period of time of about 2 days. Whether this is due to low density shift of the viscosity coefficient approximation in Figure 8, or to instability in new-fallen snow could not be distinguished in this evaluation. However, after determining that the initial densification of new layers could not be modeled, a time delay of 2 days was imposed upon each layer prior to account taken of that layer settlement. However, since layers A and B were deposited prior to 2 Feb. 1971, their settlement was computed starting on

2 Feb. For the other layers their computational starting dates were

layer D → 4 Feb.

layer C → 6 Feb.

layer E → 7 Feb.

layer F → 10 Feb.

The computed results on elevation of each layer for each day are tabulated in Appendix B, and are plotted in Figure 10.

RESULTS OF COMPUTER STUDY OF SNOWPACK SETTLEMENT

The results of the computer study on evaluation of settlement of horizontal snowpack, with comparison to experimental data, is shown in Figure 10. All discussion that follows is in reference to the data presented in Figure 10 unless noted otherwise.

One basic question that prompted this analysis is whether the Shinojima long duration viscosity versus density data can be applied to snowpack settlement, and the answer is a qualified affirmative. In general comparison between computed and experimental layer settlement, agreement within 10% error is obtained, which is indicative of precise data compilation relative to the experimental measurements. Recognizing that small perturbations in measurements can produce a propagating error in correspondance between computed and measured layer elevation, this error, however, should have only secondary effect on rate of settlement. Rate of settlement pertains to the slope of the layer elevation lines in Figure 10, which show general agreement from the start of the settlement calculation on 2 Feb. up to the curved dashed line. Thus, the density-viscosity relationship reflected in the Shinojima data is verified in the settlement results, at least over a part of the total settlement profile. The curved dashed line in Figure 10 separates an initial region of general rate correspondance, and a later region in which the experimental rates of settlement show significant

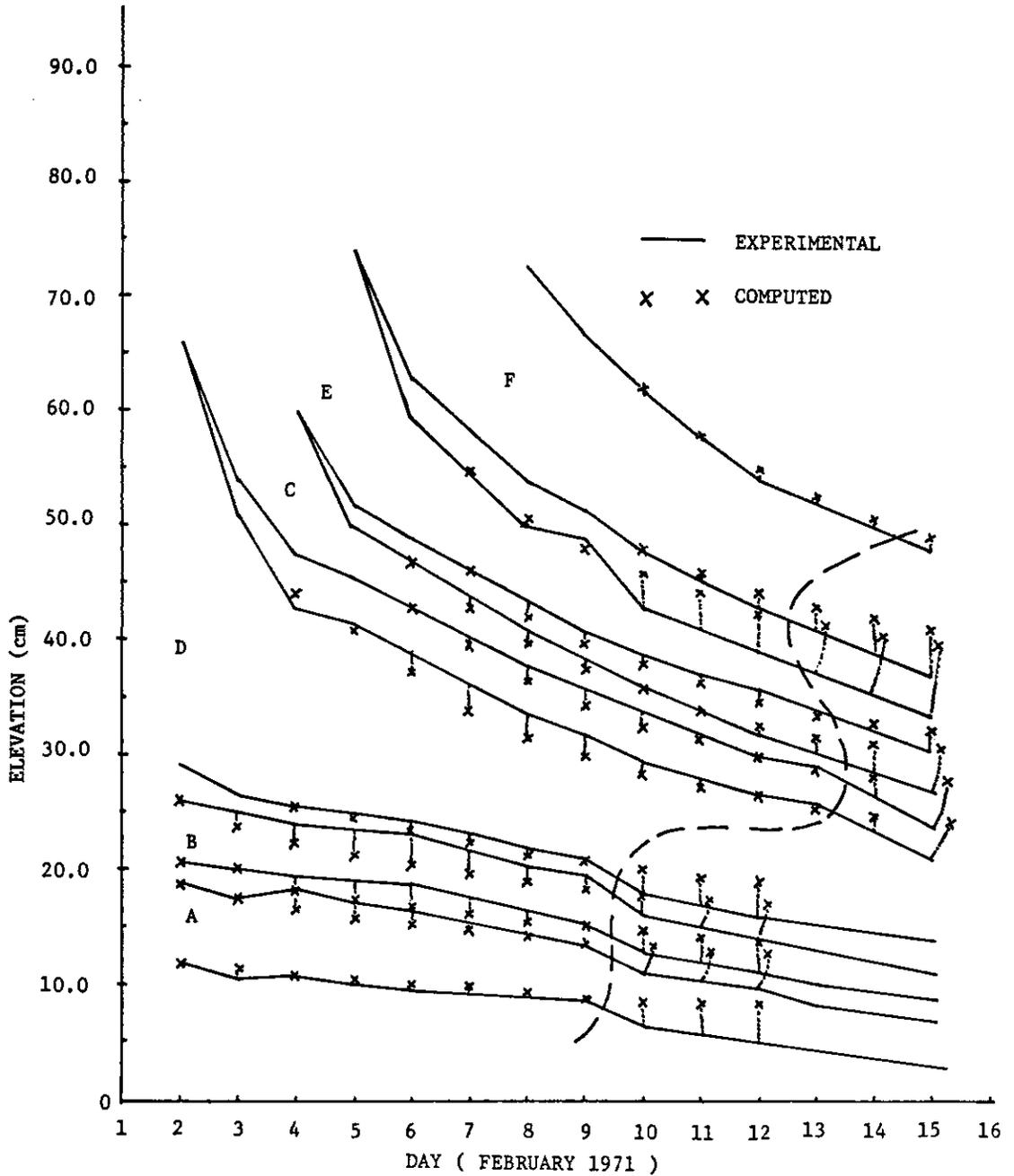


Figure 10 : EXPERIMENTAL AND COMPUTED LAYER DISPLACEMENT FROM 2 FEB. TO 15 FEB. 1971

acceleration compared to the computer predicted results. This is attributed to two processes going on within the snowpack, both processes relating to the free water content within the pack. For layers A and B and the lower part of layer D, latent heat from the ground surface is apparently causing increase in free water content. This reaches some threshold level during 9 Feb. that causes the rate of settlement to increase at a time when the density of these layers is increasing and settlement rate should decrease, as is shown by the computer results. That free water content is increasing during this time is shown for layer D in Figure 6, and if a threshold value of free water content is selected it would be between 4 and 5%.

The same type of divergence in computed versus experimental settlement rates is seen also for layers C and E approximately 4 days later, and is apparently the time when the entire snowpack goes isothermal with increasing water content. It is at this time that a general warming trend occurred atmospherically, as noted by the temperature profile in Figure 7. This trend apparently continues, where by 23 Feb. recognition of layering in the snowpack is generally obscured (Figure 4).

As noted with regard to density in Figure 5, layer E shows anomalous characteristics from all other layers. Relative to the computer study, layer E settles at a higher rate than what is predicted, based upon dry-snow density, which suggests that this layer had a free water content above the threshold value. Evidence of this is also found in the experimental data. Referring to Figure 7, it is seen that the mean atmospheric temperature between 3 and 5 Feb. rose above freezing, and that during this time layer E deposited. This is in evidence also in Figure 7 where free water content in layer E is at a relatively large value near 5% very soon after initial deposition. Thus, the indication is that layer E at the time of or soon after deposition, acquired sufficient water content that application of the Shinojima dry-snow viscous coefficients is not appropriate.

A conclusion evident from this study is that analysis of creep and

settlement of snow is feasible, if the material description is sufficiently defined. For the wet snow conditions prevalent in Japan, analysis depends upon the following:

1. Measurement of the free water content in snowpack for which an analysis is to be carried out, and
2. Experimental measurement of the viscosity-free water content relationship for wet snow of different densities. This would supplement the dry-snow data of Shinojima which has been shown to be applicable to snow of sufficiently low water content, which, however, at the present time is not quantitatively known.

A second conclusion from this investigation is that the Shinojima dry-snow, long-duration viscosity coefficients for low-density snow do not model the settlement of newly fallen snow. The lowest density snow that is indicated in the Shinojima reporting, for which viscosity was measured, is $\rho = 0.112 \text{ gm}\cdot\text{cm}^{-3}$. However, this snow was probably a sintered, partially metamorphosed type that is not characteristic of newly fallen snow. Allowing a 2 day initial consolidation of newly-fallen snow, at least in the Niigata locale, is sufficient time after which the Shinojima coefficients can be used. Lack of data on settlement of newly fallen snow is not considered as serious a matter as viscosity of wet snow.

Finally, it is well to point out that in order to obtain accurate computer results, that layer identification, particularly of the lower density layers, is extremely important. The experimental data taken for this settlement study was very complete, with attention given to the details of layer identification, thickness and elevation. Unless data of this detail is taken, it is unlikely that good analytic results can be obtained. Thus, in each settlement or creep problem, it is necessary to decide to what extent data measurements are to be taken, particularly, relative to whether or not analysis is to be part of the total evaluation. Computer based finite element analysis is becoming increasingly useful as one means of

experimentation, as this methodology yields relatively fast, inexpensive results, compared to physical experimentation, when correctly applied to complex problems.

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APPENDIX A

EXPERIMENTAL DATA : 2 FEB 1971
THROUGH 15 FEB 1971

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT		FREE WATER CONTENT			
	HEIGHT ON THE GROUND (cm)	SNOW TYPE*	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL (cm)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g·wt/cm ²)	SUMMED UP WEIGHT (g·wt/cm ²)	NAME OF SNOW SPECIFIC TYPE	REMARKS	HEIGHT (cm)
Feb. 2, 1971 10 ^h 30 ^m -12 ⁰⁰ ^m 66 cm - T.N., K.K.	60-66	N	63	0	57-60	3.0	8.7	0.087	60-66, 0.328	0.328		48-60	3.0
	43-60	N	58	0	47-50	3.0	9.6	0.096	50-66, 1.13	1.13		29-48	8.4
	29-43	S1	52	-0.1	43-46	3.0	9.0	0.090	46-66, 1.28	1.28			
	26-29	G	41	-0.7	37-40	3.0	12.8	0.128	40-46, 0.55	1.83			
	21-26	S	32	-0.8	29-32	3.0	18.6	0.186	32-40, 0.936	2.77			
	19-21	G	24	-0.3	21-24	3.0	18.6	0.186	20-32, 2.14	4.91			
	12-19	S	15	-0.1	15-18	3.0	20.3	0.203	18-20, 0.81	5.72			
	10.5-12	G	10	0.0	8-11	3.0	23.8	0.238	11-18, 1.44	7.16	A(12-19) ^m		
	8-10.5	S	5	0.0	5-8	3.0	24.0	0.240	8-11, 0.85	8.01			
	7-8	G	4	0									
	5-7	S											
	0-5	G											

* N : NEW SNOW
S1 : PARTLY SETTLED SNOW
S : SETTLED SNOW
G1 : GRANULAR SNOW WITH SMALL GRAINS
G : GRANULAR SNOW WITH LARGE GRAINS

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT		FREE WATER CONTENT			
	HEIGHT ON THE GROUND (cm)	SNOW TYPE	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL (cm)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g-wt/cm ²) · (g-wt/cm ²)	SUMMED NAME OF SNOW UP SPECIFIC TYPE WEIGHT LAYER	REMARKS	HEIGHT (cm)	W (%)
Feb. 3, 1971 10 ^h 30m-12 ^h 10 ^m FINE 53.5 cm - T.N., K.K.	50.5-53.5	G ₁	50.5	-0.1	48-45	3.0	11.6	0.116		N	100cc*	20-25	2.3
	48.5-50.5	S ₁	44	-2.6	40-43	3.0	11.0	0.110		N	"	11-17	0.5
	48.0-48.5	BAND	40	-2.6	42-45	3.0	10.2	0.102		N	"	10.5-17.5	0.9
	40.0-48.0	S ₁	34	-2.0	37-34	3.0	15.2	0.152		N, S ₁	"		
	38.5-40.0	BAND	27.5	-1.4	27-30	3.0	20.5	0.205		S	"		
	26.5-38.5	S ₁	22	-0.6	21-24	3.0	19.8	0.198		S	"		
	25.0-26.5	G	9.5	-0.2	13.5-16.5	3.0	22.3	0.223		A	"		
	20.0-25.0	S ₁	8	0.0	0-2.8	2.8	34.8	0.25		S	50cm ² **		
	17.5-20.0	G ₁	4.5	-0.1	0-1.8	1.8	19.6	0.22		S	"		
	10.5-17.5	S	0	-0.1									
	9.0-10.5	G							1.16				
	7.0-9.0	S			48-53.5	5.5			0.478				
	6.0-7.0	G			43-48	5			0.704				
	3.5-6.0	S			37-43	6			1.12				
	0-1.5	G			30-37	3			1.38				
					24-30	6			1.44				
					16.5-24	8.5			1.73		A		
					9-16.5	7.5			0.765				
					6-9	3			1.30				
					0-6	6			10.08				
				20-25	5								
				7-9	2								

* VOLUME OF A SNOW SAMPLER
** CROSS SECTION OF A CYLINDRICAL SAMPLER

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT		FREE WATER CONTENT	
	HEIGHT ON THE GROUND (cm)	HEIGHT ON THE SNOW TYPE	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g-wet/cm ²) · (g-wet/cm ²)	SURMED NAME OF SNOW UP SPECIFIC TYPE WEIGHT LAYER	HEIGHT. (cm)	W (%)
Feb. 4, 1971 10 ^h 00 ^m - h m CLEAR 61.5 cm 14 cm T.N., K.K.	47.5-60.5	N	59	0	61.5-54.5	5.5, 6.2	26.3	0.089	0.526	47.5-60.5	3.5
	43.5-47.5	G	56	0	54.5-47	6.0	30.9	0.103	0.618	26-46	2.2
	37.0	BAND	50	0	47-42.5	4.0	47.2	0.236	0.944		
	25.5-43.5	S	39.5	0	42.5-39	3.0	25.2	0.166	0.504		
	23.5-25.5	G	29	-0.1	39-35.5	3.0	22.2	0.148	0.444		
	19.2-23.5	S	21.5	-0.2	35.5-30.5	4.5, 5.0	36.2	0.151	0.724		
	18.0-19.2	G	14	0	30.5-25.0	5.5	54.5	0.198	1.09		
	10.8-18.0	S	8	0	25.0-22.7	2.5	35.9	0.289	0.718		
	9.5-10.8	G	4	0	22.7-19.5	3.0	33.2	0.221	0.664		
	7.2-9.5	S	0	0	19.5-17.0	2.3	30.3	0.263	0.604		
	5.7-7.2	G			17.0-10.0	6.0	70.2	0.234	1.40		
	4.0-5.7	S			10.0-8.5	1.5	23.9	0.313	0.478		
	0-4.0(3.5)	G			8.5-7.0	1.3	17.2	0.264	0.344		
					7.0-5.5	1.0	14.9	0.298	0.298		
					5.5-4.0	1.2	15.7	0.261	0.314		
				4.0-0	4.2, 5.0	73.5	0.319	1.47			

 * CROSS SECTION: 50.0cm², CYLINDRICAL

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT			FREE WATER CONTENT		
	HEIGHT ON THE GROUND (cm)	SNOW TYPE	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL (cm)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g-wt/cm ²)	SUMMED NAME OF UP SPECIFIC TYPE WEIGHT LAYER	REMARKS	HEIGHT (cm)	W (%)
Feb. 5, 1971 10 ^h 40 ^m - CLOUDY 74 cm 21.5 cm T.N., K.K.	52.5-74.0	N	74	0	74-68	6.5	39.0	0.12	0.780	0.780	50Dec	N*	2.3
	50-52.5	G	70	0	68-62.5	5.5	32.2	0.12	0.644	1.424	"	N	0.4
	46.0-50	S	64	0	62.5-58	4.2	27.7	0.13	0.554	1.978	"	27-43	2.3
	44.5-46.0	G	57	-0.1	58-53.5	4.8	33.6	0.14	0.672	2.650	E		
	25.5-44.5	S	48	0	53.5-50	3.3	40.5	0.25	0.810	3.460	G,S		
	23.5-25.5	G	37	-0.1	50-45.5	3.6	29.4	0.16	0.588	4.048	C		
	19-23.5	S	30	-0.13	45.5-41.5	3.7	48.5	0.26	0.970	5.018	G		
	17-19	G	14	-0.1	41.5-37.5	4.0	34.2	0.17	0.684	5.702	S		
	10-17	S	4	0	37.5-33.5	4.0	32.7	0.16	0.654	6.356	D		
	9.0-10	G	0	0	33.5-30.0	3.7	35.0	0.19	0.700	7.056	S		
	7.0-9.0	S			30.0-26.0	4.0	44.7	0.22	0.894	7.950	S		
	5.5-7.0	G			26.0-23.5	2.2	33.7	0.31	0.674	8.624	G		
	4-5.5	S			23.5-20.0	3.5	40.3	0.23	0.806	9.430	B		
	0-4	G			20.0-17.3	2.7	35.3	0.26	0.706	10.136	G1		
					17.3-14.5	2.8	32.5	0.23	0.605	10.786	S		
					14.5-10.5	3.1	43.3	0.28	0.866	11.652	A		
				10.5-9.0	1.6	24.5	0.31	0.490	12.142	G1			
				9.0-7.3	1.6	22.8	0.28	0.456	12.598	K			
				7.3-5.5	0.7,1.3	15.2	0.30	0.304	12.902	G			
				5.5-3.5	1.7	22.5	0.26	0.450	13.352	S			
				3.5-0	3.3	57.3	0.35	1.15	14.502	G			

* NEW SNOW AT
THE SURFACE

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT		FREE WATER CONTENT				
	HEIGHT ON THE GROUND (cm)	HEIGHT ON THE SNOW TYPE	HEIGHT TEMP. (cm)	TEMP. (c°)	HEIGHT INTERVAL (cm)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g-wt/cm ²) · (g-wt/cm ²)	SUPPLIED NAME OF SPECIFIC TYPE WEIGHT LAYER	REMARKS	HEIGHT (cm)	W (%)	
Feb. 6, 1971 10 ^h 00 ^m -11 ^h 00 ^m SNOW 76.5 cm 13.5 cm T.N., K.K.	63-76.5	N	74	0	76.5-70	6.5	21.2	0.065	0.424	F	N	500cc	2.5	
	59-63	G	67	0	70-63	6.3	31.2	0.099	0.624	1.048	N	"	50-58	
	49.0-59	S	53	0	63-59	3.6	48.8	0.27	0.976	2.024	L	G	"	25-38
	47.0-49.0	G	45	0	59-55	3.6	37.2	0.21	0.744	2.768	S	"	"	"
	43.5-47.0	S	36	-0.1	55-49.5	4.7	46.1	0.20	0.922	3.690	E	S	"	"
	39.5-43.5	G	29	-0.03	49.5-46.5	3.3	41.7	0.25	0.834	4.524	S,G	"	"	"
	25.0-39.5	S	20	-0.1	46.5-43	3.0	26.5	0.18	0.530	5.054	C	"	"	"
	23.0-25.0	G	12	-0.1	43-39	3.5	46.0	0.26	0.920	5.974	G,S	"	"	"
	18.5-23.0	S	0	0	39-35.5	3.1	32.0	0.21	0.640	6.614	S	"	"	"
	16.5-18.5	G			35.5-32	3.8	33.1	0.17	0.662	7.236	D	"	"	"
	9.5-16.5	S			32-28.5	3.5	34.2	0.20	0.684	7.920	I	"	"	"
	8-9.5	G			28.5-24.5	4.1	46.0	0.22	0.920	8.840	S	"	"	"
	6-8	S			24.5-22.5	2.1	30.6	0.29	0.612	9.452	G	"	"	"
	5.3-6	G			22.5-18.0	4.3	50.7	0.24	1.01	10.462	B	S	"	"
	3.5-5.3	S			18.0-16.0	1.7	25.6	0.30	0.512	10.974	G	"	"	"
	0-3.5	G			16.0-12.5	2.9	37.8	0.26	0.756	11.730	A	S	"	"
					12.5-10	3.1, 2.7	38.2	0.26	0.764	12.494	S	"	"	"
					10-8	1.6	23.6	0.30	0.472	12.966	G	"	"	"
					8-6.3	1.5	20.7	0.28	0.414	13.380	K	S	"	"
					6.3-5	1.4	17.6	0.25	0.352	13.732	G	"	"	"
				5-3.3	1.5	18.7	0.25	0.374	14.106	S	"	"	"	
				3.3-0	3.3	56.4	0.31	1.13	15.236	G	"	"	"	

ALL : WET

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT			FREE WATER CONTENT		
	HEIGHT ON THE GROUND (cm)	SNOW TYPE	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL (cm)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g·wt/cm ²)	SUMMED NAME OF SNOW SPECIFIC TYPE WEIGHT LAYER (g·wt/cm ²)	REMARKS	HEIGHT (cm)	W (%)
Feb. 8, 1971 10h30 ^m -11h30 ^m CLEAR 82 cm 6.5 cm T.N., K.K.	75.5-82	N	80	0	82-78	3.2	14.4	0.090	0.288	0.288	GRAUPEL 500cc	55-70	2.9
	73-75.5	G	73	0	78-75.5	2.6	21.6	0.17	0.432	0.720	G	44-48	3.8
	60.5-73	N	66	0	75.5-71	4.5	44.2	0.20	0.884	1.604	G, S	23-35	2.6
	54.5-60.5	S1	57	0	71-66	4.7	34.8	0.15	0.696	2.300	N		
	50-54.5	G	48	0	66-60	5.8, 5.6	39.6	0.14	0.792	3.092	N		
	44-50	S	30	-0.1	60-55	7.6, 6.5	51.2	0.14	1.02	4.112	N		
	43-44	G	19	0	55-50	4.6, 4.4	62.7	0.28	1.25	5.362	G		
	42.0-43	G1	13	-0.1	50-43.5	5.7, 5.5	69.0	0.25	1.38	6.742	S		
	41.5-42	G	6	0	43.5-41	2.3	36.8	0.32	0.736	7.478	G		
	38.5-41.5	S	0	0	41-38	2.4	26.9	0.22	0.538	8.016	C		
	37-38.5	G			38-34.5	3.5	49.7	0.28	0.994	9.010	G		
	22-37	S			34.5-30	4.5	49.8	0.22	0.996	10.006	S		
	20-22	G			30-26	4.2	45.0	0.21	0.900	10.906	S		
	16.3-20	S			26-22	3.7	48.8	0.26	0.976	11.882	S		
	14.5-16.3	G			22-19.5	3.0, 2.6	44.9	0.32	0.898	12.780	G		
	8.5-14.5	S			19.5-16	3.6, 2.8	42.0	0.26	0.840	13.620	B		
	7.2-8.5	G			16-13.5	1.7, 2.0	31.7	0.33	0.634	14.254	G		
	5.3-7.2	S			13.5-10.5	3.0	44.3	0.30	0.886	15.140	S		
	4-5.3	G			10.5-8.5	1.6	25.6	0.32	0.512	15.652	A		
	2-4	S			8.5-7	1.5	24.0	0.32	0.480	16.132	G		
0-2	G			7-5.5	0.7, 1.9	15.5	0.24	0.310	16.442	K			
				5.5-4	1.0, 1.2	18.3	0.33	0.366	16.808	G			
				4-2	0.9, 1.4	15.2	0.25	0.304	17.112	S			
				0-2.5	2.5	41.2	0.33	0.824	17.936	G			

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT		FREE WATER CONTENT			
	HEIGHT ON THE GROUND (cm)	SNOW TYPE	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL (cm)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g·wt/cm ²)	SUMMED NAME OF SNOW UP SPECIFIC TYPE WEIGHT LAYER (g·wt/cm ²)	REMARKS	HEIGHT (cm)	W (%)
Feb. 9, 1971 9 ^h 45 ^m -11 ^h 00 ^m SNOW 111 cm 37.5 cm T.N., K.K.	73.5-111	N	109	0	111-105	5.5	20.6	0.074	0.412	0.412	500cc	N	5.0
	72-73.5	G	100	0	105-100	5.0	15.6	0.062	0.312	0.724	"	51-67	4.4
	70.5-72		90	0	100-95	4.6	15.4	0.066	0.308	1.032	"	20-32	3.5
	69-70.5	G	75	0	95-90	5.0	17.3	0.069	0.346	1.378	NEW SNOW	"	"
	67-69	W*	60	0	90-85	4.8	23.5	0.097	0.470	1.848		"	"
	51.5-67	S	45	0	85-80	4.8	27.3	0.11	0.546	2.394	"	"	"
	48.5-51.5	G	27	0	80-75	4.7	25.1	0.11	0.502	2.896	"	"	"
	43.5-48.5	S	12	0	75-70	4.0	40.8	0.20	0.816	3.712	"	"	"
	41.5-43.5	G,S	0	0	70-65	5.0	45.3	0.18	0.906	4.618	"	"	"
	39.5-41.5	G			65-61	3.6	31.8	0.18	0.636	5.254	"	"	"
	36.5-39.5	S			61-58	4.0	37.0	0.19	0.740	5.994	"	"	"
	33.5-36.5	G			58-55	3.5	28.2	0.16	0.564	6.558	"	"	"
	21-33.5	S			55-51	3.6	35.1	0.20	0.702	7.260	"	"	"
	19-21	G			51-45.5	5.0	71.3	0.29	1.43	8.690	"	"	"
	15-19	S			45.5-41.5	4.5	61.2	0.27	1.22	9.910	"	"	"
	13.5-15	G			41.5-39	2.3	36.1	0.33	0.762	10.672	"	"	"
	8-13.5	S			39-36.5	2.3	26.1	0.23	0.520	11.192	"	"	"
	7-8	G			36.5-32.5	3.5	50.2	0.29	1.00	12.192	"	"	"
	4.5-7	S			32.5-29.0	4.5	49.8	0.22	0.996	13.188	"	"	"
	3.5-4.5	G			29.0-25.5	4.2	45.3	0.22	0.906	14.094	"	"	"
2-3.5	S			25.5-22	3.5	47.6	0.27	0.952	15.046	"	"	"	
0-2	G			22-18.5	2.5	38.5	0.31	0.770	15.816	"	"	"	
				18.5-15.5	3.3	43.6	0.26	0.872	16.688	"	"	"	
				15.5-12	3.5	31.4	0.42	0.628	17.316	"	"	"	
				12-7	4.5	66.7	0.29	1.29	18.606	"	"	"	
				7-5.5	1.3	25.3	0.39	0.506	19.112	"	"	"	
				5.5-4.5	1.4	18.2	0.26	0.364	19.476	"	"	"	
				4.5-3.5	0.8	15.6	0.39	0.312	19.788	"	"	"	
				3.5-2.5	0.8	11.3	0.28	0.226	20.014	"	"	"	
				2.5-0	2.5	46.9	0.38	0.937	20.952	"	"	"	

* VERY WET LAYER

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY		WEIGHT		FREE WATER CONTENT						
	HEIGHT ON THE GROUND (cm)	SNOW TYPE	HEIGHT INTERVAL (cm)	TEMP. (c°)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g wt/cm ²)	SUMMED NAME OF SNOW UP SPECIFIC TYPE WEIGHT LAYER (g wt/cm ²)	REMARKS	HEIGHT (cm)	W (%)			
Feb. 10, 1971 9h45m-11h11m SNOW 123 cm 30.5 cm T.N., K.K.	92.5-123	N,DRY	122	-1.2	123-120	4.2	15.6	0.075	0.316	0.316	N	500cc	N	(-1.8)	
	112	BAND	110	-1.9	120-115	3.2,4.2	15.7	0.085	0.314	0.630	N	"	"	65-90	4.4
	103	BAND	100	-1.5	115-110	5	20.6	0.082	0.412	1.042	N	"	"	48-63	2.0
	92-92.5	G	90	-0.7	110-105	5	20.8	0.083	0.416	1.458	N	"	"	20-30	2.8
	91.5-92	S1	70	0	103-100	5	18.2	0.072	0.364	1.822	N	"	"		
	91-91.5	G	52	0	100-95	5	25.0	0.10	0.500	2.322	N	"	"		
	68.5-91	N,S1	25	-0.1	95-90	5	31.1	0.12	0.622	2.944	"	"	"		
	66-68.5	G	15	0	90-85	5	26.5	0.11	0.530	3.474	"	"	"		
	65.5-66	S	0	0	85-80	5.1	30.8	0.12	0.616	4.090	"	"	"		
	62.5-65.5	G			80-75	5	36.7	0.15	0.734	4.824	"	"	"		
	61.5-62.5	S			75-70	4	28.4	0.14	0.568	5.392	"	"	"		
	61-61.5	G			70-60.5	8.25	89.1	0.21	1.78	7.172	"	"	"		
	47.5-61	S			60.5-56.5	4.2	44.4	0.21	0.888	8.060	"	"	"		
	43-47.5	G			56.5-52	3.95	38.6	0.19	0.772	8.832	"	"	"		
	39.5-43	S			52-48	3.8	42.6	0.22	0.852	9.684	"	"	"		
	36-39.5	G,S			48-43	5.35	76.1	0.281	1.52	11.204	"	"	"		
	34-36	S			43-40	2.55	37.2	0.286	0.744	11.948	"	"	"		
	30.5-34	G			40-38.5	1.5	25.1	0.33	0.502	12.450	"	"	"		
	18.5-30.5	S			38.5-36	2.8	40.9	0.29	0.818	13.268	"	"	"		
	16.5-18.5	G			36-33.5	2.1.5	22.1	0.25	0.442	13.710	"	"	"		
12.5-16.5	S			33.5-30	3.5	53.1	0.30	1.060	14.770	"	"	"			
11-12.5	G			30-26	3.75	46.1	0.242	0.922	15.692	"	"	"			
7.5-11	S			26-22	3.8	47.5	0.25	0.950	16.642	"	"	"			
7.5	BAND			22-18	3.6	50.3	0.28	1.01	17.652	"	"	"			
5-6	G			18-15	2.6	45.5	0.35	0.910	18.562	"	"	"			
3-5	S			15-12	2.6	35.3	0.27	0.706	19.268	"	"	"			
0-3	G			12-10.5	2.5,1.5	36.8	0.35	0.696	19.964	"	"	"			
31-31.5	G1			10.5-6	4.3	62.7	0.29	1.25	21.214	"	"	"			
				6-3.5	3.1,2.4	44.1	0.32	0.882	22.096	"	"	"			
				3.5-0	3.2	63.7	0.40	1.27	23.366	"	"	"			

* NO GRANULAR SNOW

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT			FREE WATER CONTENT		
	HEIGHT ON THE GROUND (cm)	SNOW TYPE	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL (cm)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g·wt/cm ²)	SUMMED NAME OF UP SPECIFIC WEIGHT LAYER (g·wt/cm ²)	NAME OF SNOW REMARKS TYPE	HEIGHT (cm)	W (%)
Feb. 12, 1971 9h45m-11h00m CLEAR 115 cm - T.N., K.K.	112.5-115	N	113	-1.0	115-112.5	2.5	6.2	0.049	0.12	N	500cc	63-80	1.5
	111.5-112.5	G1	100	-3.7	112.5-111.5	1.5	15.7	0.209	0.314	G1	"	45-55	2.2
	62-111.5	S	90	-1.8	111.5-105	5.5	37.8	0.14	0.756	N	"	17-26	3.5
	55-62	G	80	0	105-100	4.6	28.5	0.12	0.570	N	"		
	43.5-55	S	65	-0.1	100-95	4.8	34.7	0.14	0.694	N	"		
	39-43.5	G	47	0	95-90	4.9	31.0	0.13	0.620	N	"		
	36-39	S	38	0	90-85	4.8	29.5	0.12	0.590	N	"		
	32.5-36	G,S	22	0	85-80	5.0	40.0	0.16	0.800	N	250cc		
	29.5-32.5	S	0	0	80-73.5	5.0	37.3	0.15	0.746	N	"		
	26.5-29.5	G	0	0	73.5-68.5	5.0	42.0	0.17	0.840	S1	"		
	16.0-26.5	S	0	0	68.5-62.5	5.0	46.3	0.19	0.926	S1	"		
	14.5-16.0	G	0	0	62.5-53.5	8.5	93.4	0.22	1.87	8.866	G,S1	500cc	
	10.5-14.5	S	0	0	53.5-48.5	5.0	54.7	0.22	1.09	9.936	S	250cc	
	9.5-10.5	G	0	0	48.5-43.5	5.0	58.4	0.23	1.17	11.106	S		
	6.0-9.5	S	0	0	43.5-39	5.4.5	70.5	0.29	1.41	12.516	G,S		
	5.0-6.0	BAND	0	0	39-35.5	2.7,3.0	44.2	0.30	0.884	13.400	E	500cc	
	4.0-5.0	G	0	0	35.5-32	3.6,3.3	58.6	0.33	1.17	14.570	G,S		
2.0-4.0	S	0	0	32-29.5	2.2	32.0	0.29	0.640	15.210	C			
0-2.0	G	0	0	29.5-26.0	3.4	54.8	0.32	1.10	16.310	G,S			
				26.0-21	5.0	64.2	0.26	1.28	17.590	D	250cc		
				21-15.5	4.5	64.1	0.28	1.28	18.870	S			
				15.5-13.5	2.2	32.6	0.30	0.652	19.522	G			
				13.5-10.5	3.3	45.6	0.28	0.912	20.434	B			
				10.5-8.5	1.9	29.7	0.31	0.594	21.028	G	500cc		
				8.5-5	3.7	57.3	0.31	1.15	22.178	A			
				5-0	4.5	81.2	0.36	1.63	23.808	G,S			

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT		FREE WATER CONTENT				
	HEIGHT ON THE GROUND (cm)	SNOW TYPE	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL (cm)	SAMPLED DEPTH (cm)	MASS (g)	DENSITY (g/cm ³)	WEIGHT (g-wt/cm ²)	SUMMED NAME OF UP SPECIFIC TYPE WEIGHT LAYER (g-wt/cm ²)	REMARKS	HEIGHT (cm)	W (%)	
Feb. 13, 1971 9 ^h 30 ^m -11 ^h 00 ^m CLOUDY 104 cm - T.N., K.K.	100-104	G	113	0	104-99	5.0	62.9	0.251	1.26	1.26	G	250cc	60-90	0.3
	60-100	WET S	90	-0.4	99-94	5.0	38.2	0.152	0.764	2.024	S1	"	48-52	2.5
	58-60	G	80	-0.6	94-85	5.0	36.0	0.144	0.720	2.744	S	"	15-25	3.9
	56.5-58	S	70	-0.4	85-82	5.0	33.8	0.135	0.676	3.420	S	"		
	54.5-56.5	G	61	-0.2	82-77.5	5.0	40.6	0.162	0.812	4.232	S	"		
	53.3	BAND	48	0	77.5-72	5.0	42.4	0.169	0.848	5.080	S	"		
	43.5-54.5	S	35	0	72-67	5.0	43.6	0.174	0.872	5.952	S	"		
	43.2-43.5	G	20	0	67-61.5	5.0	48.3	0.193	0.972	6.924	S	"		
	41.7-43.2	S	0	0	61.5-59	2.2	21.5	0.20	0.430	7.354	S	"		
	37.5-41.7	G	0	0	59-50	9.3	105.0	0.23	2.10	9.454	G	G,S	500cc	
	34.3-37.5	S	0	0	50-45	5.0	55.4	0.221	1.11	10.564	S	S	250cc	
	33.5-34.3	G1	0	0	45-41	3.5,3.7	43.4	0.23	0.868	11.432	F	S	"	
	33-33.5	S	0	0	41-37	4.2,5.0	72.6	0.30	1.45	12.882	L	G	"	
	32.5-33	G	0	0	37-34	2.7	44.3	0.33	0.886	13.768	E	S	"	
	32-32.5	S	0	0	34-30	3.6	59.0	0.33	1.18	14.948	G	"		
	31-32	G	0	0	30-28	1.9	25.9	0.27	0.518	15.466	C	S	"	
	28.5-31	S	0	0	28-24.5	3.3	60.4	0.37	1.21	16.676	S,C	"		
	25.5-28.5	C	0	0	24.5-21	3.0	44.0	0.29	0.880	17.556	S	"		
	15-25.5	S	0	0	21-18	3.0	43.1	0.29	0.862	18.418	D	S	"	
	13-15	G	0	0	18-15	2.7	42.1	0.31	0.842	19.260	S	"		
9.5-13	S	0	0	15-12	2.4	42.9	0.36	0.858	20.118	G	"			
8.0-9.5	G	0	0	12-10	2.0,2.6	36.1	0.31	0.722	20.840	B	S	"		
5	BAND	0	0	10-7.7	2.2,1.7	36.5	0.37	0.730	21.570	G	"			
3.5-8.0	S	0	0	7.7-4.2	3.0	49.2	0.33	0.984	22.554	A	S	"		
2.5-3.5	G	0	0	4.2-0	5.1,4.2	85.2	0.36	1.70	24.254	G,S	"			
1-2.5	S	0	0											
0-1	G	0	0											

DATE TIME WEATHER SNOW DEPTH (cm) DAILY NEW SNOW (cm) OBSERVERS	LAYER STRUCTURE		SNOW TEMP.		DENSITY			WEIGHT		FREE WATER CONTENT			
	HEIGHT ON THE GROUND (cm)	SNOW TYPE	HEIGHT (cm)	TEMP. (c°)	HEIGHT INTERVAL DEPTH (cm)	MASQ (g)	DENSITY (g/cm ³)	WEIGHT (g·wt/cm ²)	SUMMED UP WEIGHT LAYER (g·wt/cm ²)	NAME OF SNOW SPECIFIC TYPE	REMARKS	HEIGHT (cm)	W (%)
Feb. 15, 1971 9h15m— 79 cm — K.K., G.O.	74.5-79	G	SURFACE	0	79-75	88.2	0.352	1.76	1.76	G	25Dec	59-66	9.8
	70.5-74.5	WET S	72	0	74.5-71	36.3	0.21	0.726	2.486	S	"	39-48	2.1
	68-70.5	S	64	0	70-68	26.1	0.24	0.522	3.006	S	"	16-22	4.9
	65-68	G,S	58	0	68-65	30.4	0.24	0.608	3.616	G,S	"		
	55.5-65	S	42	0	65-60	51.2	0.204	1.02	4.636	S	"		
	48-55.5	G,S	31.5	0	60-56	44.1	0.24	0.882	5.518	S	"		
	37.5-48	WET S	18	0	56-48	7.0	0.37	2.59	8.108	G,S	"		
	33.5-37.5	G	0	0	48-43	5.0	0.262	1.31	9.418	S	"		
	30-33.5	S			43-37.5	5.0	0.258	1.29	10.708	S	"		
	28.5-30	G,S			37.5-33.5	3.8	0.31	1.17	11.878	G	"		
	27.5-28.5	G1			33.5-30	3.0	0.34	1.03	12.908	S	"		
	27-27.5	S, BAND			30-27	3.5	0.35	1.24	14.148	G,S	"		
	26.5-27	G1			27-24	2.6	0.30	0.784	14.932	C	"		
	24-26.5	S			24-22	2.4	0.33	0.796	15.728	C	"		
	22.2-24	G			22-14	5.0	0.295	1.48	17.208	D	"		
	21.5-22.2	S			14-10.5	3.5	0.42	1.48	18.688	G	"		
	21-21.5	G1			10.5-9.5	1.6	0.38	0.600	19.288	B	S(WET)	"	
14.0-21	S			9.5-7.0	2.0	0.45	0.908	20.196	G	"			
10.5-14.0	G			7.0-3.0	4.1	0.36	1.46	21.656	A	S, BAND	"		
9.5-10.5	S(WET)			3.0-0	2.8	0.56	1.58	23.236	G(WET)	"			
7-9.5	G												
3-7	S												
0-3	G												

APPENDIX B : ELEVATION AND ELEVATION CHANGE OF EACH LAYER
INTERFACE FROM 2 FEB 1971 TO 15 FEB 1971.

ELEV. DAY	A _L	A _U	B _L	B _U	D _L	D _U	C _L	C _U	E _L	E _U	F _L	F _U
2	12.0	19.0	21.0	26.0								
2-3	-0.6	-1.5	-1.8	-2.3								
3	11.4	17.5	19.2	23.7								
3-4	-0.6	-0.9	-1.1	-1.4								
4	10.8	16.6	18.1	22.3	25.5	44.5						
4-5	-0.2	-0.7	-0.7	-0.9	-1.0	-3.7						
5	10.6	15.9	17.4	21.4	24.5	40.8						
5-6	-0.3	-0.5	-0.6	-0.8	-1.0	-3.6						
6	10.3	15.4	16.8	20.6	23.5	37.2	43.0	47.0				
6-7	-0.4	-0.6	-0.6	-0.8	-1.0	-3.1	-3.3	-3.9				
7	9.9	14.8	16.2	19.8	22.5	34.1	39.7	43.1	46.0	55.0		
7-8	-0.4	-0.6	-0.6	-0.8	-1.0	-2.5	-3.2	-3.3	-3.9	-4.3		
8	9.5	14.2	15.6	19.0	21.5	31.6	36.5	39.8	42.1	50.7		
8-9	-0.4	-0.5	-0.5	-0.6	-0.7	-1.6	-2.0	-2.1	-2.2	-2.4		
9	9.1	13.7	15.1	18.4	20.8	30.0	34.5	37.7	39.9	48.3		
9-10	-0.3	-0.3	-0.3	-0.5	-0.6	-1.4	-1.7	-1.9	-2.0	-2.2		
10	8.8	13.4	14.8	17.9	20.2	28.6	32.8	35.8	37.9	46.1	48.0	62.0
10-11	-0.1	-0.3	-0.4	-0.4	-0.5	-1.2	-1.4	-1.5	-1.6	-1.7	-1.8	-3.6
11	8.7	13.1	14.4	17.5	19.7	27.4	31.4	34.3	36.3	44.4	46.2	58.4
11-12	-0.1	-0.3	-0.4	-0.4	-0.5	-1.1	-1.4	-1.4	-1.6	-1.7	-1.8	-3.3
12	8.6	12.8	14.0	17.1	19.2	26.3	30.0	32.9	34.7	42.7	44.4	55.1
12-13	-0.1	-0.3	-0.3	-0.4	-0.5	-1.0	-1.1	-1.2	-1.2	-1.4	-1.4	-2.4
13	8.5	12.5	13.7	16.7	18.7	25.3	28.9	31.7	33.5	41.3	43.0	52.7
13-14	-0.1	-0.1	-0.1	-0.2	-0.2	-0.4	-0.5	-0.5	-0.6	-0.7	-0.9	-1.8
14	8.4	12.4	13.6	16.5	18.5	24.9	28.4	31.2	32.9	40.6	42.1	50.9
14-15	-0.1	-0.1	-0.1	-0.2	-0.2	-0.4	-0.4	-0.5	-0.5	-0.7	-0.8	-1.6
15	8.3	12.3	13.5	16.3	18.3	24.5	28.0	30.7	32.4	39.9	41.3	49.3

(Manuscript prepared October 1983, Manuscript received February 13, 1984)

有限要素法による積雪の沈降解析

624. 14 : 681, 32

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新潟県長岡市に所在する雪害実験研究所構内で測定された詳細な積雪の野外における沈降データを、同じ積雪の沈降条件でのコンピューターによる解析結果と比較した。毎日測定された積雪の沈降データには次のものが含まれている。即ち、(1)層構造、密度、温度、含水量、雪の種類および、(2)気象条件である。この観察されたデータ(1970~1971年冬季)は等温下の積雪の変化を示しているもので、それは1971年2月1日の測定開始から約3週間後まで続いている。すでに乾雪について測定されていた積雪の粘性係数をこの沈降のコンピューターによるモデルに適用した。解析結果によれば、2月2日から2月9日までは観測と計算による沈降量は10パーセント以内でよく一致した。2月9日までに、明らかに地表からの熱によりいくつかの積雪層の含水量は5パーセント位までに増加し、このため乾雪の沈降速度よりは速くなった。2月13日以降では、全積雪層は加速された沈降を示し、そのためもはや乾雪の粘性係数は適用不可であった。

この研究の結果は、コンピューター利用によるこの方法が積雪の沈降への研究に適用しうることを示している。しかしながら、含水率が4~5パーセントを越えた時の圧縮粘性係数の測定が将来必要である。

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