TR 202

Technical Report 202

ICE CAP STRAINS AND SOME EFFECTS ON ENGINEERING STRUCTURES

by

Malcolm Mellor and Sherwood Reed

DECEMBER 1967

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

Technical Report 202

ICE CAP STRAINS AND SOME EFFECTS ON ENGINEERING STRUCTURES

by

Malcolm Mellor and Sherwood Reed

DECEMBER 1967

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

DA Task 1VO25001A13001

PREFACE

This paper was prepared by Malcolm Mellor, Research Civil Engineer, Experimental Engineering Division (Mr. K.A. Linell, Chief); and Sherwood C. Reed, Research Civil Engineer, Construction Engineering Branch (Mr. E.F. Lobacz, Chief), Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

USA CRREL is an Army Materiel Command laboratory.

CONTENTS

ILLUSTRATIONS

SUMMARY

The components of strain for the upper layers of ice sheets are given in terms of ice flow velocity and snow accumulation rate. Methods of estimating the components of strain rate which are necessary for design of engineering structures are outlined, and representative measured values are given. The relation between observed structural deformation and ice cap straining is discussed.

ICE CAP STRAINS AND SOME EFFECTS ON ENGINEERING STRUCTURES

by

Malcolm Mellor and Sherwood Reed

INTRODUCTION

Since 1953 a number of major installations have been constructed on the permanent snowfields of Greenland and Antarctica, but their designers have been forced to work with incomplete information on the stress, strain and displacement fields of the site material in which the structures are buried. In particular, the consideration of strains in the snow of the ice cap has been effectively limited to an assessment of the vertical component of strain, and in most cases it has been tacitly assumed that other components of strain can be neglected over the limited areas occupied by typical installations. For many practical purposes there can be little quarrel with this approach, for compactive creep, or densification, of snow under gravity body forces is undoubtedly the source of the most rapid straining experienced by undisturbed material in the uppermost layers of an ice cap. However, it now appears that consideration should be given to other components of strain, particularly if the structures are of great lateral extent, or if they are intended to have a working life of 10 years or more.

Strain rates in the upper layers of an ice sheet are not difficult to measure, but the measurements are time-consuming, requiring observations over a period of 1 year or more. For preliminary design or for design at short notice, some important components of the strain rate tensor can be evaluated to a sufficient degree of accuracy by indirect methods.

STRAIN RATE COMPONENTS IN THE UPPER LAYERS OF AN ICE CAP

Consider a flat-lying expanse of a polar ice cap on which there is no appreciable surface relief. Snow accumulates on the surface at a rate which, averaged over a period of years, remains constant with time for several decades. Rectangular coordinates are taken with the x-direction horizontal and along the local direction of ice movement, the z-direction vertical, and the y-direction horizontal and normal to the direction of ice flow (Fig. 1). The origin is taken at the current snow surface. Since strains are continuous and time-dependent, it is convenient to consider strain rate $\dot{\varepsilon}$ rather than strain ε; if steady-state flow and accumulation conditions prevail, the strain rate at any point fixed in space will be invariant with time.

The vertical component of strain rate at depth z below the current snow surface, $\dot{\varepsilon}_{zz}$, is easily arrived at from Bader's (1960, 1962) snow densification theory. If a given snow layer moves vertically downward relative to the snow surface with velocity u_z, the vertical strain rate $\dot{\varepsilon}_{zz}$ is:

$$\dot{\varepsilon}_{zz} = \frac{\partial u_z}{\partial z} \quad (1)$$

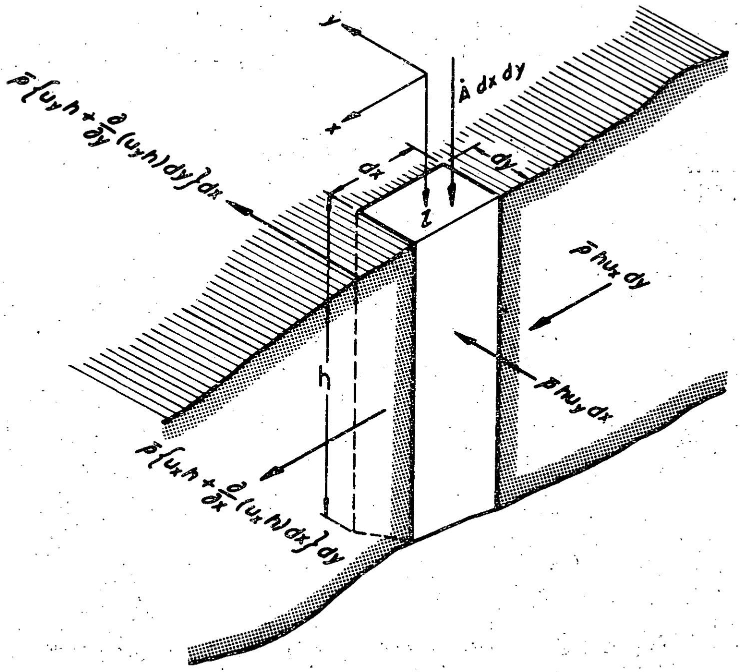

Figure 1. Mass flux through a vertical columnar element of the ice cap.

and

$$u_z = \frac{\partial z}{\partial t} = \frac{\partial z}{\partial \sigma_z} \cdot \frac{\partial \sigma_z}{\partial t} \tag{2}$$

where σ_z is the vertical component of stress (overburden pressure), which increases with time as snow accumulates at the surface. If $\dot{A}$ is the mass accumulation rate of snow, assumed constant over a period of decades,

$$\frac{\partial \sigma_z}{\partial t} = \dot{A}g. \tag{3}$$

Also,

$$\frac{\partial \sigma_z}{\partial z} = \rho g \tag{4}$$

and hence

$$\dot{\varepsilon}_{zz} = - \dot{A} \frac{1}{\rho^2} \frac{\partial \rho}{\partial z}. \tag{5}$$

Since $\dot{A}$, ρ and $\partial\rho/\partial z$ can all be measured at the site, $\dot{\varepsilon}_{zz}$ is deducible.

The transverse component of strain rate $\dot{\varepsilon}_{yy}$ is:

$$\dot{\varepsilon}_{yy} = \frac{\partial u_y}{\partial y}. \tag{6}$$

Although the component of velocity u_y is small compared with u_x, in general $\partial u_y / \partial y$ will not be zero owing to lateral convergence or divergence of the flow. Contour lines or form lines provide an indication of whether $\dot{\varepsilon}_{yy}$ is likely to be positive or negative: "valley" contours suggest negative (compressive) strain, while "ridge" contours suggest positive (extensive) strain.

The longitudinal component of strain rate $\dot{\varepsilon}_{xx}$ is:

$$\dot{\varepsilon}_{xx} = \frac{\partial u_x}{\partial x}. \tag{7}$$

Typical ice cap conditions are such that there is a systematic tendency toward positive values of $\dot{\varepsilon}_{xx}$ in the accumulation zone; the magnitude of $\dot{\varepsilon}_{xx}$ will usually tend to increase appreciably as the margins of the ice cap are approached. Unlike the relatively thin ice of valley glaciers, the thick ice of a polar ice sheet does not display simple conformation to undulations in its bed, and flexural strains from this source can probably be discounted. Longitudinal strains are likely to be controlled largely by snow accumulation, variation of ice thickness along the flow path, and convergence or divergence of flow. These effects can be assessed from a simple continuity consideration.

Consider a vertical columnar element through the ice cap, which is of height h, width dx, and thickness dy. Since the ice is thick, it may be assumed that u_x is invariant with z to within a small distance from the glacier bed, and for most practical purposes the surface velocity can be taken as a mean value over the height of the column. The velocity u_y is small compared with u_x. Also, since the depth-density relationship does not change significantly with time or with small lateral displacements, a constant mean ice density for the column $\bar{\rho}$ can be defined as

$$\frac{1}{h} \int_0^h \rho dz.$$

For a columnar element which is fixed in space, i.e. fixed relative to the bed of the ice cap, a consideration of mass flux through the element yields the following equation:

$$\frac{1}{h} \frac{\partial h}{\partial t} = \frac{\dot{A}}{\bar{\rho} h} - \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} \right) - \frac{u_x}{h} \frac{\partial h}{\partial x}. \tag{8}$$

In practice measurements are likely to be referred to an origin of coordinates which travels with the surface of the ice but, since the displacements involved are usually small, the values of strain rate measured in a moving (Lagrangian) coordinate system are not significantly different from those measured in a fixed (Euler) coordinate system.

Shear strains in the xz-plane will result from transverse gradients in the horizontal and vertical components of flow velocity, u_x and u_z respectively. Strain rate $\dot{\varepsilon}_{xz}$ is:

$$\dot{\varepsilon}_{xz} = \tfrac{1}{2}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right). \tag{9}$$

In the basal layers of ice caps there are certainly rapid variations of u_x with z, but in the uppermost layers of thick ice no such gradients have yet been detected. Since most engineering construction penetrates to no more than 1% of the ice cap thickness, it seems justifiable to assume that near the surface of a thick ice sheet $\partial u_x/\partial z = 0$. From eq 2, 3, 4, u_z can be expressed as $\dot{A}/\rho$, so that

$$\dot{\varepsilon}_{xz} \approx \tfrac{1}{2}\frac{\partial}{\partial x}\left(\frac{\dot{A}}{\rho}\right). \tag{10}$$

Over large distances there are systematic changes in $\dot{A}/\rho$, but taking typical values for Greenland and Antarctica it appears that $(\partial/\partial x)(\dot{A}/\rho)$ will not often exceed 10^{-6} yr^{-1}, which is believed to be too small to have any significant effect on most engineering structures. However, local variations, especially at sites subject to irregular snow drifting, may create significant shear strains.

Shear strain in the yz-plane is given by:

$$\dot{\varepsilon}_{yz} = \tfrac{1}{2}\left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}\right) \tag{11}$$

in which $\partial u_y/\partial z$ is virtually zero and $\partial u_z/\partial y$ depends on variations in accumulation rate. Thus

$$\dot{\varepsilon}_{yz} \approx \tfrac{1}{2}\frac{\partial}{\partial y}\left(\frac{\dot{A}}{\rho}\right) \tag{12}$$

and the remarks under eq 10 are broadly applicable to eq 12.

Shear strain rate in the xy-plane is:

$$\dot{\varepsilon}_{xy} = \tfrac{1}{2}\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right) \tag{13}$$

in which $\partial u_y/\partial x$ is usually small. If the slope of the glacier bed in the y-direction is steep, $\partial u_x/\partial y$ may reach significantly high values.

STRAINS IN VERTICAL PLANES

A good estimate of strains in vertical planes can be made if the accumulation rates and the depth-density profiles for the site are known. To determine shear strain rates $\dot{\varepsilon}_{xz}$ and $\dot{\varepsilon}_{yz}$ from eq 10 and 12 it is necessary to know how accumulation rate and the depth-density relation vary in the x and y directions but for many purposes it can be assumed that $\dot{\varepsilon}_{xz}$ and $\dot{\varepsilon}_{yz}$ are negligibly small at typical sites where there is no marked variation of accumulation rate caused by wind-drifting of snow. The vertical component of strain rate $\dot{\varepsilon}_{zz}$ varies strongly with depth z, typically from about 5×10^{-2} yr^{-1} within a meter of the surface down to $\sim 10^{-3}$ yr^{-1} at 30-m depth.

In Figure 2 representative values of $\dot{\varepsilon}_{zz}$ for ice cap sites in Greenland and Antarctica are given. It is usually difficult to make meaningful measurements of vertical strain in the unrestrained tunnels of ice cap stations because of thermal disturbance, irregular overloading by surface snow drifting, and periodic maintenance cutting. However, observations at the "new" Byrd Station in Antarctica (Mellor and Hendrickson, 1965) showed that tunnel closure rates were consistent with calculated values for $\dot{\varepsilon}_{zz}$ when temperature corrections were applied and adjustments for additional load were made. Values of $\dot{\varepsilon}_{zz}$ calculated from eq 5 give the minimum strain rate which can be expected; at Byrd Station tunnels of the typical "cut-and-cover" type closed vertically at rates from 15% to 16% higher than the calculated rates adjusted for temperature change.

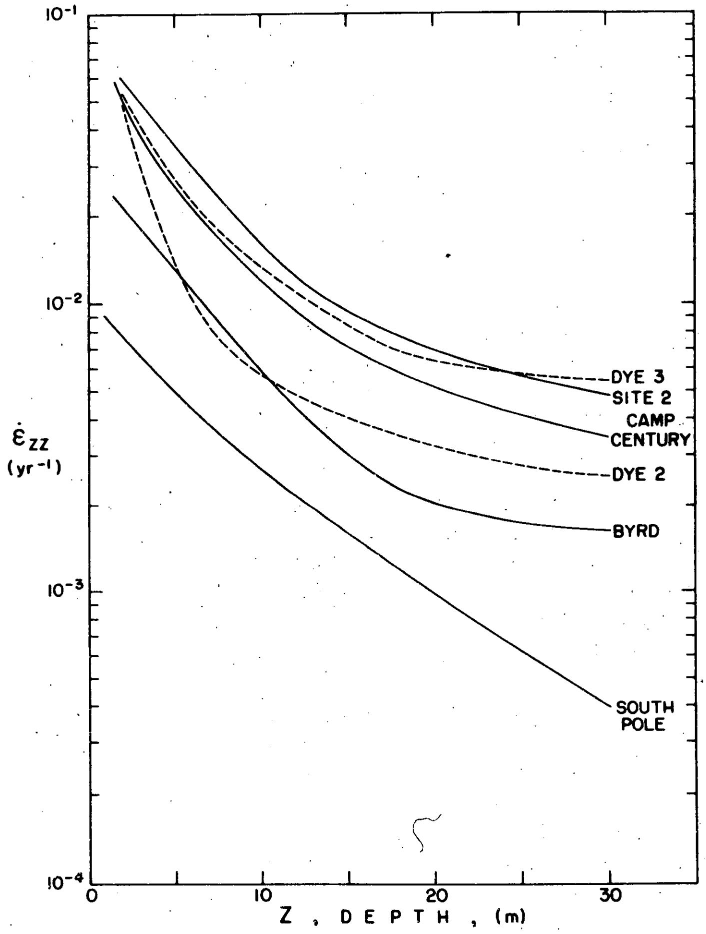

Figure 2. Representative values of vertical strain rate $\dot{\varepsilon}_{zz}$ for ice cap sites in Greenland and Antarctica.

Vertical strain of the ice cap snow has an important effect on completely buried rigid structures: since vertical dimensions of the structure are fixed while the vertical thickness of horizontally adjacent snow layers is decreasing, peripheral shearing of the snow imposes stresses on the structure. Thus any attempt to compute structural stresses purely from body-force considerations could be misleading; it is necessary to assess the strain rate and estimate the resulting stresses via the constitutive equation for dense snow.

STRAINS IN THE HORIZONTAL PLANE

When coordinate directions are suitably chosen, i.e. with the x-direction along the resultant line of ice flow, there is no systematic combination of factors tending to produce shear strains in the horizontal plane. However, the general flow direction will not necessarily coincide with a principal strain direction and significant values of $\dot{\varepsilon}_{xy}$ might be experienced locally, e.g. near the edge of an "ice stream." A likely cause of such shearing would be bed slope transverse to the flow direction, and at a construction site these cross slopes could be detected by detailed measurement of ice depth, preferably by radio sounding.

With the lateral components $\dot{\varepsilon}_{xx}$ and $\dot{\varepsilon}_{yy}$, which in most cases ought to be principal strain rates, the situation is different. Looking at eq 8, $\dot{A}/\bar{\rho}h$ is systematically positive in the accumulation zone, and $(u_x/h)(\partial h/\partial x)$ is also systematically positive over sufficiently large distances in the x-direction. The magnitudes of these two terms tend to increase as the margins of the ice cap are approached, as there is generally an increase in $\dot{A}$, u_x, and $-\partial h/\partial x$, as well as a decrease in h. Thus all structures built upon or within the ice cap are expected to be affected by these components of lateral strain, and some means of assessing probable magnitudes of the effects ought to be provided for the designer.

For practical purposes it seems reasonable to consider a simplification of eq 8 based on certain assumptions. For an idealized ice cap site it might be assumed that $\partial u_y/\partial y$ is very small, so that plane strain conditions prevail with $\dot{\varepsilon}_{yy}$ zero. It might also be assumed that the ice cap is neither growing nor shrinking at a significant rate, i.e. $(1/h)(\partial h/\partial t)$ is more than an order of magnitude smaller than $\dot{A}/\bar{\rho}h$. For central regions of Greenland and Antarctica it also seems justifiable at first sight to neglect the term (u_x/h) $(\partial h/\partial x)$, since it will usually be more than an order of magnitude smaller than $\dot{A}/\bar{\rho}h$. However, this last assumption cannot be sustained when the peripheral zones of the ice cap are under consideration, as $(u_x/h)(\partial h/\partial x)$ becomes comparable to, or larger than, $\dot{A}/\bar{\rho}h$ in those regions.

There are now available the results of observations on three major structures on the Greenland Ice Cap, and these can be used to check the response of structures to ice cap strains in the horizontal plane. The radar station N-34 in northwest Greenland was instrumented at the time of its construction in 1953 (Hansen, 1955) and after a period of observation its performance was analyzed (Mellor, 1964). Observations continued up to August 1965. The radar stations DYE-2 and DYE-3 in southern Greenland were instrumented at the end of construction in 1960, and results of the continuing program of observation are now appearing (Reed, 1966; Reed and Vanden Hoek, 1966).

At N-34, angular measurements in the complex of tubular steel undersnow tunnels indicated that the original rectangular plan form defined by the four corners of the complex was deforming slowly into a parallelogram at an angular rate of approximately 5 minutes of arc per year. The direction of the extending diagonal (221°) coincides almost exactly with the direction of ice movement (218°), and it is expected to be close to a principal direction for ice cap strain. Since the observation points define a figure which is almost square, the other diagonal lies close to the remaining principal direction. Unfortunately, no precise linear measurements were taken, but after consideration of the structural connections it is concluded that the deformation pattern is consistent with a strain rate of $+7.2 \times 10^{-4}$ yr^{-1} along the extending (221°) diagonal and a strain rate between zero and -7.2×10^{-4} yr^{-1} along the other (303°) diagonal.

An abortive experiment at the same site in 1954-55 (Bader et al., 1955) gave some independent indications of ice cap strain rates there. A 40 ft long strain gage in the east-west direction showed a strain rate averaging $+6.8 \times 10^{-4}$ yr^{-1} over a $9\frac{1}{2}$-month period, while an identical gage in the north-south direction appeared to settle to about the same rate after 2 months of initial erratic behavior. These limited data suggest a principal strain direction along the 225° azimuth, and a sum of principal strain rates amounting to $+13.6 \times 10^{-4}$ yr^{-1}.

At DYE-2 and DYE-3, angular and linear measurements were made inside the complex undersnow structure of columns and trusses which transmits the weight of the large elevated radar building (120 ft square, 150 ft high overall) and its attached antennas to the foundation pads (footings). The bearing surface of the foundation system is almost 60 ft below the snow surface at time of writing, and the corner columns define a figure which approximates a 120-ft square. Since the main connections of the columns and trusses are released annually to permit jacking and leveling of the building, elastic strains induced in the structure by lateral ice cap strains are relieved periodically and the footings and column bases are thus substantially free to follow displacements of the ice in which they are embedded. At both stations a consistent pattern of distortion is observed. The originally square array of columns is slowly deforming into a rhombic pattern; the angular deformation rate at DYE-2 is 0.7 minutes of arc per year, and at DYE-3 it is 3.0 minutes per year. At the same time the side lengths of the original squares are changing, with one pair of opposite sides lengthening and the other pair shortening at rates on the order of 10^{-4} yr^{-1}.

At DYE-3 the ice flow direction, assumed to be orthogonal to surface contours, is within a few degrees of the azimuth of the extending diagonal of the substructure (63°), and strains in the diagonals are principal strains. Analysis of the structural deformation gives a strain rate in the flow direction of $+3.00 \times 10^{-4}$ yr^{-1}, and a strain rate along the contour direction of -5.04×10^{-4} yr^{-1}.

At DYE-2 the orientation of the structure is not simply related to directions of principal strain in the ice cap. Analysis of the pattern of structural distortion gives the azimuth of the principal extensive strain as 288°, which can probably be accepted as the flow direction since estimates of the ice flow direction made from contour data range between 290° and 296°. The principal strain rates obtained from analysis of structural distortion are $+1.67 \times 10^{-4}$ yr^{-1} in the flow direction and -3.87×10^{-4} yr^{-1} in the cross-slope direction.

If these structural deformations actually reflect ice cap strains, as seems likely in view of the coincidence of principal directions for both structural and ice cap straining, the plane strain assumption proposed earlier is unsupportable, even though it appears very reasonable at first sight. Nevertheless, it is of interest to compare the extensive strain rate $\dot{\varepsilon}_{xx}$ predicted by the steady-state, plane strain simplification* of eq 8, i.e. $\dot{\varepsilon}_{xx} = \dot{A}/\bar{\rho}h$, with the strain rate $\dot{\varepsilon}_{xx}$ for the structures. In Table I it can be seen that $\dot{A}/\bar{\rho}h$ is in very close agreement with the structural measurements for $\dot{\varepsilon}_{xx}$ at both DYE sites, while at N-34 it amounts to about one-third of the observed value for $\dot{\varepsilon}_{xx}$. There is, then, perhaps some empirical justification for using the very simple formula for estimation of the magnitude of longitudinal strain rate at sites in the central regions of ice caps.

Table I.

Station	Strain rates of structures		Site data relevant to eq 8					
	$\dot{\varepsilon}_{xx}$ (yr^{-1})	$\dot{\varepsilon}_{yy}$ (yr^{-1})	$\dot{A}/\bar{\rho}$ (m ice yr^{-1})	h (m)	u_x (m yr^{-1})	$\frac{\partial h}{\partial x}$	$\dot{A}/\bar{\rho}h$ (yr^{-1})	$\frac{u_x}{h} \cdot \frac{\partial h}{\partial x}$ (yr^{-1})
N-34	$+7.15 \times 10^{-4}$	Between zero and -7.15×10^{-4}	0.47	1630 (1)	36 (2)	$\approx(-2 \times 10^{-3})$ (3)	$+2.88 \times 10^{-4}$	$\approx(-4.4 \times 10^{-5})$
DYE-2	$+1.67 \times 10^{-4}$	-3.87×10^{-4}	0.309	1850 (4)	$\sim(50)$ (5)	$\approx(-7 \times 10^{-3})$ (4)	$+1.67 \times 10^{-4}$	$\sim(-2 \times 10^{-4})$
DYE-3	$+3.00 \times 10^{-4}$	-5.04×10^{-4}	0.505	1730 (4)	$\sim(50)$ (5)	$\approx(-4 \times 10^{-3})$ (4)	$+2.92 \times 10^{-4}$	$\sim(-1 \times 10^{-4})$

Data sources:

(1) Estimated from nearby seismic soundings by Roethlisberger et al., 1965.
(2) Determined by U.S. Army Map Service using repeated first order astronomical fixes over a 7-year period.
(3) Estimated from seismic data by Allen and Miller, 1954.
(4) Estimated from regional data on bed and surface relief by Holtzscherer, 1954 and Mock and Ragle, 1963.
(5) Inspired guess (based on data for Station Centrale - Mock, personal communication, and Hofmann, 1964).

In Table I an attempt has been made to compile all site data relevant to eq 8, but when these data are substituted it becomes clear that the observed structural strains are incompatible with the predicted sums of strains if it is assumed that steady-state conditions prevail. There is, of course, no good reason for believing that the dimensions of the ice caps are perfectly stable, but this question of glacier mass balance will be pursued in a separate paper.

CONCLUSIONS

In the design of engineering structures for ice caps it is necessary to take complete account of the ice cap strain field. The effect of the vertical component of strain on deformable structures has long been appreciated, but its influence on the loading of buried rigid structures is less well understood. Vertical strain rate can be calculated from readily obtainable site

---

*This simplified relationship was deduced earlier by Nye (1957).

data. Strain rates in the horizontal plane are comparatively low, but over a period of years the accumulated strain can produce measurable distortion of structures and induce severe stressing in unrelieved elastic structures. In very long structures, such as pipelines or cables, horizontal strains are a major consideration. The magnitude of one of the principal strain rates in the horizontal plane appears to be well indicated by measurable site parameters, while the other principal strain rate can perhaps be assumed to be of the same order of magnitude with the sign indicated by surface contour data.

Although longitudinal strain rate in the ice cap appears to be indicated nicely by snow accumulation rate and ice thickness, the agreement between observation and simple theory may be partly fortuitous. When considered in detail, the present results seem to be inconsistent with an assumption that the Greenland Ice Cap maintains a steady-state surface profile.

LITERATURE CITED

Allen, C.F. and Miller, S.W. (1954) "Seismic measurements on the Greenland Ice Cap" in Operation Ice Cap 1953, Stanford Research Institute for U.S. Army Transportation Corps.

Bader, H. (1960) Theory of densification of dry snow on high polar glaciers, U.S. Army Snow, Ice and Permafrost Research Establishment (USA SIPRE), Research Report 69.

__________ (1962) Theory of densification of dry snow on high polar glaciers II, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL), Research Report 108.

__________; Waterhouse, R.W.; Landauer, J.K.; Hansen, B.L.; Bender, J.A. and Butkovich, T.R. (1955) Excavations and installations at SIPRE test site, Site 2, Greenland, USA SIPRE Report 20.

Hansen, B.L. (1955) Instrumentation of ice cap stations, USA SIPRE Technical Report 23.

Hofmann, W. (1964) Die Geodätische Lagemessung über das Grönlandische Inlandeis der Internationalen Glaciologischen Grönland-Expedition (EGIG) 1959, Meddelelser om Grønland, Bd. 173, no. 6.

Joset, M.A. and Holtzscherer, J.J. (1954) Détermination des épaisseurs de l'inlandis du Greenland, Rapports Scientifiques des Expéditions Polaires Francaises N III 2, Annales de Géophysique, vol. 10, no. 4.

Mellor, M. (1964) Undersnow structures: N-34 radar station, Greenland, USA CRREL Technical Report 132.

__________ and Hendrickson, G. (1965) Undersnow structures: Byrd Station, Antarctica, USA CRREL Technical Report 138.

Mock, S.J. and Ragle, R. (1963) Elevations on the ice sheet of southern Greenland, USA CRREL Technical Report 124.

Nye, J.F. (1957) The distribution of stress and velocity in glaciers and ice sheets, Proceedings of the Royal Society, A, vol. 239, p. 113-133.

LITERATURE CITED (Cont'd)

Reed, S.C. (1966) Performance study of the Dewline ice cap stations, Greenland, 1963, USA CRREL Special Report 72.

__________ and Vanden Hoek, A.M. (1966) Engineering performance of Dewline ice cap stations, Greenland, USA CRREL Technical Note (unpub.).

Roethlisberger, H.; Bentley, C.R. and Bennett, H. (1965) Movement studies by seismic soundings on the Greenland ice sheet 1956-59, USA CRREL Research Report 161.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
ICE CAP STRAINS AND SOME EFFECTS ON ENGINEERING STRUCTURES

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Technical Report

5. AUTHOR(S) *(First name, middle initial, last name)*
Malcolm Mellor and Sherwood Reed

6. REPORT DATE December 1967	7a. TOTAL NO. OF PAGES 14	7b. NO. OF REFS 14

8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. DA Task 1V025001A13001 d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report 202 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U.S. Army Cold Regions Research and Engineering Laboratory Hanover, N.H.

13. ABSTRACT

The components of strain for the upper layers of ice sheets are given in terms of ice flow velocity and snow accumulation rate. Methods of estimating the components of strain rate which are necessary for design of engineering structures are outlined, and representative measured values are given. The relation between observed structural deformation and ice cap straining is discussed.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT.	ROLE	WT	ROLE	WT
Ice cap strains						
Foundations						
Structures						