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Unbonded single-wire gages establish strain rates in Alaskan glaciers

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ABSTRACT—Natural scientists and engineers are continuing to seek an understanding of the mechanism of flow and deformation of glaciers. A necessary component of this exploration is the accurate determination of strain rates in glacier ice. The purpose of this investigation was to develop a strain-measuring method which is dependable and precise under difficult field conditions.

The measuring technique which was developed uses unbonded electrical-resistance strain gages which consist of single strands of 5-mil Constantan wire 10-ft long. Six gages are embedded in the glacier-ice surface in the form of two delta rosettes in order to obtain strain at a point with some redundancy of data in this two-dimensional problem. The rigid-body rotation of the gage anchor posts was measured by sensitive inclinometers in order to assess the effect of pressure melting on the strain data. The data are interpreted using cross-correlation and best-fit programs to yield maximum shear-strain rate and average normal-strain rate.

Strain readings were conducted over a period of eight days on the Ptarmigan Glacier near Juneau, Alaska. The maximum shear-strain rate at the surface ranged from 0.25 to 1.2 × 10^{-6}/hr., which agrees with estimates derived from known flow rates. The wire gages were found to adhere to the ice well enough to make the gage anchor posts unnecessary—pressure melting is therefore insignificant. A tolerance of ±6.0 microstrain was determined for the strain gages.

Introduction

The flow mechanism of glacier ice is today one of the significant unanswered questions in natural science. Geologists, glaciologists, geophysicists, physicists, and mechanicians have, for the past two or three decades, been studying the properties of glacier ice[1] and the forces at work on glaciers, as well as the response of glaciers in the form of flow and mass transport.[2-6] Others have been employing rheological concepts to formulate theoretical models of simple glaciers.[7-8] Eventually, it is hoped, there will result an even more complete theoretical model of glacier systems which agrees with and explains the divergent behavior of these complex systems as studied and measured in nature.

One important aspect in the larger problem is the precise experimental measurement of strain rates in existing glaciers. Such data are needed to guide the thinking of theoreticians as well as to check the predictions of their models.

The classical method of surface-strain measurement is to set stakes in the ice and determine the strain history through periodic measurement of the distance between pairs of stakes.[5,9] The stakes are ordinarily set up in a diamond configuration, with each gage length recommended to be approximately equal to the ice thickness; in a valley glacier, the ice is typically 200-1200-ft thick. A steel surveyor's tape is used for the distance measurements. The strain is obtained by computing the change of distance and dividing by the original distance.

While this method is simple and straight-forward, its precision is impaired by several factors. One basic problem results from the low sensitivity of the tape. Large gage lengths and long periods of time are required to obtain deformations great enough to be read. The overall average strain rate which is obtained ignores important short-term phenomena such as diurnal variations. Given the fact that the flow rates of temperate glaciers may exceed 1 meter/day,[3] the motion of the gage site during the measuring period is too great to be ignored, as is commonly done. The variations of technique and ambient conditions which may occur over the several weeks or months of reading further decrease precision. Physical access to the stakes is necessary, and ablation will cause the stakes to loosen and tilt.

Consideration of these factors as well as others leads to the conclusion that the taping method can, at best, yield an approximate average value for glacier strain rate. A new and more precise method is called for.

Factors Affecting Choice of Technique

In order to establish accurately the surface strain rates in glaciers and to assess high-frequency phenomena such as daily variations, the apparatus should have a sensitivity of approximately 10 micro-

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strain. $(\mu\epsilon)$ The shape of a glacier, its bottom contour, and the presence of crevasses cause strain gradients. Gage lengths of not more than 10 meters were deemed necessary in order to reduce gage length error to an acceptable level with the expected strain gradients.

The environmental conditions in glaciated regions are major factors. The weather is often rainy and windy with poor visibility. The logistics of glacier research require that the equipment be light in weight, portable and rugged. Electrical equipment should be battery powered, although ambient conditions are such that battery life is short. Solar radiation even on cloudy days is intense and soon melts the ice immediately adjacent to objects embedded in the ice surface. Thus, posts or stakes tend to become loose in a short time unless protected by some sort of cover. During the summer, the ice near a glacier surface is saturated with water. It is also at the melting temperature, so it is very sensitive to pressure melting and regelation. Areas of interest are often heavily crevassed. Since the ice is relieved of stress near a crevasse, the presence of these cracks or fissures places limits on site location and gage length. Also, much of a glacier is covered by old snow or firn which is granular, wet, soft and of little interest in this study except that it limits access to the ice.

Basic Instrumentation

Given the conditions discussed above, embedded wire resistance strain gages were chosen as the best transducer. The gages used were made from 10-ft (3 meters) lengths of 5-mil Teflon-coated Constantan wire. Constantan was chosen because its gage factor remains nearly constant under elastic and plastic strain. Teflon provides good electrical and radiation insulation as well as abrasion resistance. Adhesion of the insulated wire to the ice was not a factor since anchor posts were to be used. The gage wires were stretched between posts anchored in the ice to form two delta rosettes and the whole setup covered with firn.

Since the gage wires had a resistance of about 120Ω, conventional strain-gage instrumentation could be used. For these experiments, a BLH Model N indicator was used for readout. Instrument zero and temperature compensation were achieved by sealing two gage lengths of wire in a plastic box and burying it with the gage system. One of these wires served as a compensating gage while the other was used as a zero-strain active gage. To assure minimum lead-wire effects, all leads were 20-gage copper in 25-ft lengths.

A 10-day minimum gaging period was anticipated; so a commercial switch-and-balance was not adequate. A sealed terminal and switch box was built around a 12-position rotary switch. This switch provided one position for zero, eight channels for active strain gages, and two for inclinometers. A 59,880-Ω resistor in series with a momentary-contact switch was placed across the compensating arm as a calibration check.

The anchor posts were made from 4-in. PVC tubes (schedule 40 DWV pipe) 40-in. long with Plexiglas caps on top and bottom to exclude water. Plastic was chosen because of its low weight and low thermal conductivity. The pipe provided large

Fig. 1—View of upper Ptarmigan Glacier from west edge. 0 = gage site. X = site of camp 17, Juneau icefield

diameter (low contact pressure) and relatively large section stiffness.

Although the 5-mil gage wire produced a maximum lateral force of only 0.5 lb on the anchor posts, it was necessary to assess the degree to which pressure melting affected strain data by allowing the posts to rotate in the ice. In order to measure the rigid-body rotation, inclinometers were placed inside two of the posts.

The conditions of equilibrium suggest that an anchor post will rotate about a point approximately 14 in. upward from the bottom. With this assumption, it was projected that 1 microradian of relative rotation between two posts would produce 2 $\mu\epsilon$ of error in gage reading; so, sensitive inclinometers were needed. Those used were made by suspending 4-1/2-in. pendulums from the top covers of the anchor posts. Each pendulum was constructed of 10 mil × 1/4-in. shim stock with a 0.04-lb lead weight at the end. Two semiconductor strain gages (BLH SPB 3-07-35) were installed on each pendulum 1/4 in. from the fixed end. The inclinometers were immersed in 20-weight oil for damping. Calibration was carried out at 35°F, with an optical indexing head having a least reading of 5s. The inclinometers proved to be linear in the calibration range of ±15 deg. The calibration factors for the two devices, found through the use of a least-squares best fit, were 10.5 and 11.2 microradian/$\mu\epsilon$ or 2.15 and 2.30 s/$\mu\epsilon$.

Site Location and System Installation

The Ptarmigan Glacier (Figs. 1 and 2) on the Juneau icefield was chosen for the first studies because of its nearness to Juneau, Alaska, the availability of a permanent base camp with good logistical support, and because this glacier has been extensively studied in the past. The Ptarmigan Glacier is approximately 2-1/2-miles long, 1/2-mile wide, and 400-ft thick. The site was about 200 yards from the edge in a region where the firn cover was 40-in. thick. The site was over 175 ft. from the nearest crevasse. A schematic of the gage site is shown in Fig. 2.

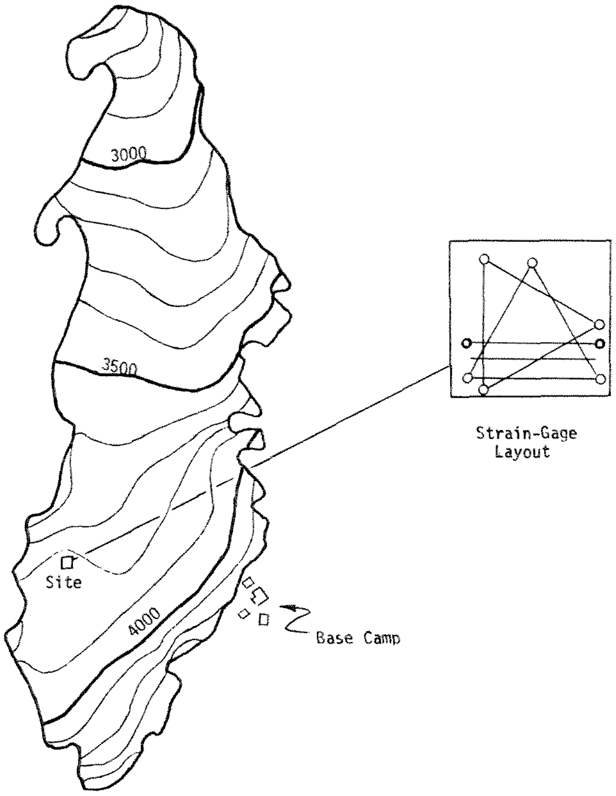

Fig. 2—Map of Ptarmigan Glacier showing rosette location and orientation

A pit 12-ft square was dug through the firn to the ice surface. Holes of 5-in. diameter and 40-in. deep were drilled in the ice to form two equilateral triangles 125 in. per side. The triangles were oriented so that normal strain could be measured on axes having 30-deg separation from 0 deg through 150 deg. Holes were also drilled for the pressure-melting evaluation. The run-off water on the glacier surface quickly filled the bore holes.

The 4-1/2-in. O.D. plastic posts were filled 2/3 full with dry ice and inserted in the bore holes; the dry ice served as a heat sink to freeze each post in place (it was later found that an ice-salt mixture in the posts provided a sufficient heat sink). After the dry ice had dissipated, the gages were attached by their lead wires to the cover plates on the posts. A prestrain of about 1500 $\mu\epsilon$ was induced in each gage at the time of attachment in order to allow for compressive strain rates. Six gages were employed on the two delta rosettes, one additional gage was installed without anchoring it to the posts, and one more gage was placed for the pressure-melting evaluation. Figure 3 shows a portion of the gage installation before covering.

Fig. 3—Top of anchor post with gages and leads attached before covering with snow

Following gage installation, the layout was carefully covered by about 40 in. of protective firn. Two

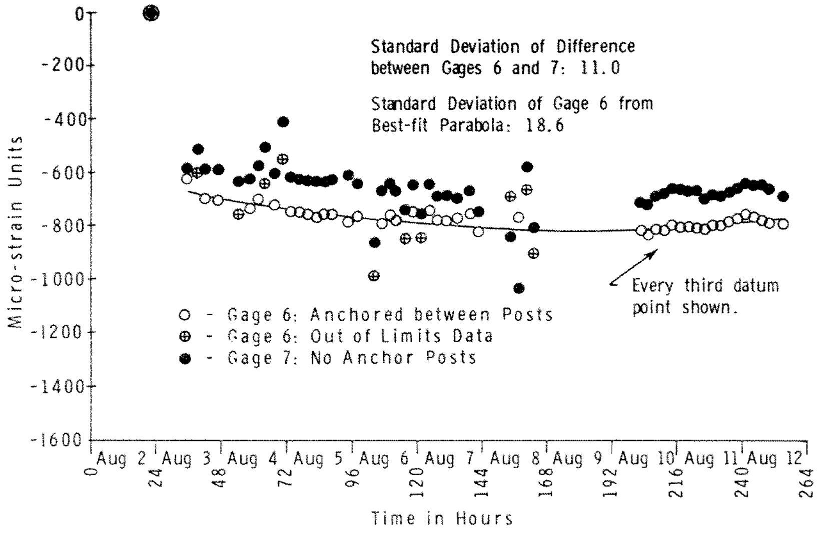

Fig. 4—Net strain data from gages 6 and 7

tarps were placed over the snow to retard ablation. The first cover was dark-green, 6-mil polyethylene to stop short-wave radiation. Long-wave radiant-energy effects were retarded by yellow 3-ounce nylon coated with polymer.

Because of failure of the gage which was installed to evaluate pressure melting, it was necessary to repeat this phase of the experiment. The setup was identical, with only 2 posts containing the inclinometers being installed with one gage wire.

A second strain-measurement experiment was conducted on the Cathedral Glacier near Atlin, British Columbia, Canada. Methods and apparatus were essentially as described above. The data from the Cathedral studies will not be considered in this paper.

Data Acquisition

Original plans were to camp at the gage site and collect data hourly. Extremely wet and windy conditions made it necessary to conduct operations from a base camp 1/2 mile away. The indicator was kept at the base camp and carried in a plastic bag to the gage location every three hours for a reading. The standard internal-battery pack of the type N indicator failed in a short time, and a new one was improvised of 10 alkaline D-cells which were taped to the indicator. Although the indicator was exposed only while taking readings, it soon started to behave erratically because of moisture. This condition caused data collection to be temporarily halted on the sixth day. With improved weather on the seventh day, data acquisition was begun on an hourly basis and continued for two days.

Analysis of Results

The strain-indicator readings were estimated to the nearest 5 $\mu\epsilon$. Since net strain is the gage reading less the zero reading, the theoretical RMS standard error of the indicator in this application was 7.1 $\mu\epsilon$.

The pressure-melting experiment produced some unexpected results. The strain rate between the posts was essentially constant at -0.2 $\mu\epsilon$, or about twice the theoretical instrument value. The inclinometer on one post revealed no rotation after the first 30 hr, and the other inclinometer indicated an inward rotation of about 4.5 microradians/hr. After 90 hr, both posts started a rapid inward rotation. It was later discovered that the rocks holding the covering tarps in place came to rest against the posts (it must be recalled that this is a rerun of the melting experiment). The strain gage did not indicate any change in its normal trend.

An extra strain gage had been embedded without anchor posts parallel to one of the rosette gages in the strain experiment. Figure 4 shows that both gages responded identically after extraneous data are removed. The standard deviation on the difference between the two gages was 11 $\mu\epsilon$.

The experiments discussed in the preceeding two paragraphs suggest that the gage wires become bonded to the ice. This result is important in that it implies that the anchor posts serve no purpose and are not required for embedded-strain-gage installations in temperate glaciers having snow or firn cover.

Figure 4, which has already been mentioned, is quite typical of the raw data obtained for all gages in the Ptarmigan Glacier study. Clearly, the data exhibit considerable scatter during the six-day period of poor weather. Study of the scatter suggests that it results from the following four causes:

1. About 20 hr are required for the gages to become bonded to the ice. There is a large and meaningless indicated strain during this initial settling period.
2. Much of the scatter occurs between midnight and 6:00 A.M., when observers tend to be less alert.
3. If the scattered points are corrected by adding or subtracting either 2000 $\mu\epsilon$ or 100 $\mu\epsilon$, these points fall within normal experimental limits. This observation suggests that the strain indicator was misread. Such mistakes are easy to make with the model N indicator. The coarse balance is especially tricky because of parallax. This problem is magnified when reading by lantern light on a stormy night. A relevant fact is that ice-

field personnel who were untrained in experimentation aided in this project by taking several of the readings.
4. The indicator was behaving erratically during the wet weather.

Even with the scatter present in the data, there appears to be a diurnal variation of strain rate. The analysis of diurnal variations is the object of subsequent studies. This variation was ignored in the analysis of trends and average strain rates discussed here, but it certainly increases the standard deviations.

Plots of the outputs of all six rosette gages suggest a parabolic relationship with time for the period of the test. In order to establish best values for the strain rates, the net strain data were fitted with parabolas using a least-squares computer program. The standard deviation for the gages was from 12.3 to 21.5 $\mu\epsilon$. This standard deviation includes the apparent diurnal variation. By subtracting instrument error and the daily variation, a tolerance of ±6.0 $\mu\epsilon$ was determined for the strain-gage transducers. The time-derivatives of the parabolic curves were best-fitted into the strain-transformation equations to establish the rate of average normal surface strain and the maximum shear-strain rates. The results are plotted in Fig. 5. The maximum shear-strain rate ranged from 0.25 to 1.2 $\mu\epsilon$/hr. This value is quite low, and initial reaction is that the experiment failed. However, data obtained from annual photographs show that average gross-flow rate at the gage site on the Ptarmigan Glacier amounts to only about 0.03 ft/day. From this flow rate, one may calculate an approximate anticipated shear-strain rate of 1.6 $\mu\epsilon$/hr.[5,7] This crude estimate agrees as well as can be expected with measured values. It seems that a rather dead area of the glacier was chosen for the gage site. Thus, by accident, the experiment served as an especially severe test of the technique. The evidence demonstrates that the embedded strain gages did yield a valid measurement of surface strain rate.

Summary of Conclusions

1. The embedded-strain-gage technique is valid, simple and useful for measuring surface strain rates in glaciers.
2. The anchor posts are not necessary when the gages are made of 5-mil Constantan wire embedded in the ice under snow or firn cover.
3. The BLH Model N is not adequate for the rugged field conditions encountered. Sealed weatherproof instrumentation is required. Telemetric data acquisition is advisable.
4. Shear-strain rate for the chosen site on Ptarmigan Glacier ranges from 0.25 to 1.25 $\mu\epsilon$/hr. at the time of the test.
5. There is an apparent daily variation in glacier strain rate.

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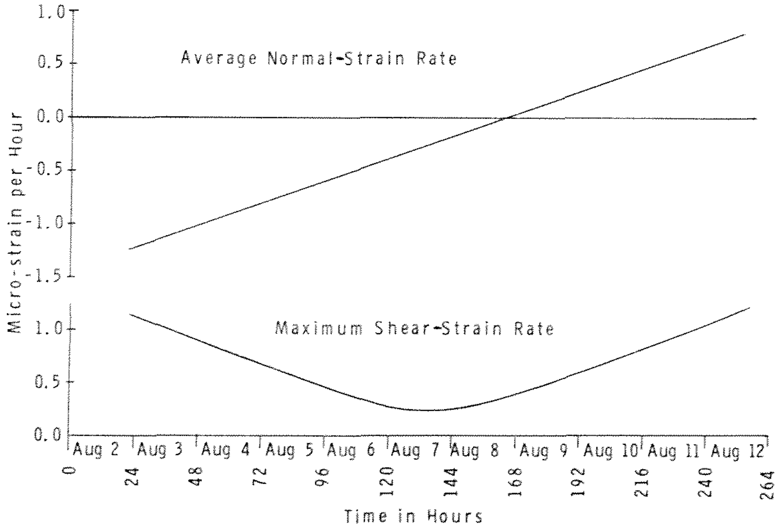

Fig. 5—Average normal-strain rate and maximum shear-strain rate