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Publisher’s version / Version de l'éditeur:

Canadian Geotechnical Journal, 25, 4, pp. 726-734, 1988-11

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Reprinted from
Canadian Geotechnical Journal
Vol. 25, No. 4, November 1988
p. 726-734
(IRC Paper No. 1578)

NRCC 30047

Canada

Field measurements of stresses and deformations in a first-year ice cover adjacent to a wide structure

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Received August 4, 1987

Accepted April 14, 1988

Ice cover movements and stresses were measured near Adams Island from November 1984 to May 1985. The average horizontal movement rate was 0.1 m/day. Global compressive and tensile strains were less than 1 and 4%, respectively. Strain rates (measured over 1−2 month periods) were of the order of 10^{-9} s^{-1}. Maximum stresses and forces in the ice cover were 500 kPa and 400 kN/m, respectively.

Key words: ice movements, ice stresses, ice forces, Canadian Arctic Ocean.

Les mouvements et les contraintes dans les couverts de glace ont été mesurés près de l'île Adams de novembre 1984 à mai 1985. La vitesse moyenne du mouvement norizontal était de 0.1 m/jour. Les déformations globales en compression et traction étaient respectivement moins de 1 et 4%. Les vitesses de déformation mesurées au cours de périodes de 1−2 mois étaient de l'ordre de 10^{-9} s^{-1}. Les contraintes et forces maximales dans le couvert de glace étaient respectivement de 500 kPa et 400 kN/m.

Mots clés : mouvements de la glace, contraintes dans la glace, océan Arctique canadien.

[Traduit par la revue]

Can. Geotech. J. **25**, 726−734 (1988)

Introduction

The design of offshore structures in many Arctic regions requires a knowledge of the behaviour of the ice cover as it impinges on wide obstacles. Some information on expected loads due to first-year ice is now available from monitoring programs carried out in the Beaufort Sea (e.g., Metge 1976; Semeniuk 1977; Pilkington *et al.* 1983; Johnson *et al.* 1985). Those field programs were focused on ice force measurements; information on the corresponding ice conditions, movements, and deformation is limited. Consequently, the data are insufficient to develop an understanding of ice cover behaviour.

To date, attempts to model ice interaction with structures have used ice properties obtained by testing small samples to solve an indentation problem. Ralston (1978) developed an upper bound plastic limit solution. Ponter *et al.* (1983) and Bruen and Vivatrat (1984) used creep equations for ice. A review article by Sanderson (1984) gives an evaluation of the various models. More recently, Shyam Sunder (1986) used a fracture criterion in conjunction with a viscoelastic model and thus incorporated a "scale" factor.

However, an actual ice cover usually includes numerous irregular features (rafted ice, ridges, cracks, and open leads) and experiences locally a number of nonsteady (sporadic) and three-dimensional deformation modes. The deformation history of different parts of the ice cover may vary as well. As a result, considerable uncertainty regarding the validity of the above continuum models exists. Full-scale measurements are still needed to guide the development of appropriate models.

The present paper reports on studies undertaken as a part of the Adams Island project. Ice cover behaviour near a natural island was monitored in order to develop an understanding of the interaction between floating ice covers and wide structures. Ice movements, properties, and stresses, water current, tide, and meteorological conditions were measured over three winters. Frederking *et al.* (1984, 1986*a*, *b*) reported on the results obtained each winter. The objective of the present paper is to present in greater detail the results obtained from the 1984−1985 measurements. Attention will be focused on ice cover deformation and stresses in the vicinity of the island. At length scales of a few hundred metres, which are pertinent to the present situation, the driving forces acting on ice (e.g., wind and water current drag) have negligible effects on the equilibrium (balance of momentum). Only ice cover movements, deformation, and stresses need to be considered.

The site

Adams Island is located in Navy Board Inlet at its intersection with Lancaster Sound (70°45′N, 81°30′W) about 3 km east-northeast offshore of Borden Peninsula. The map in Fig. 1 shows the location of the island, which is approximately 200 m in diameter and has steep rocky sides reaching 20 m above water level. The seabed is relatively steep with a maximum slope of approximately 1 vertical : 2.5 horizontal to the southeast and a minimum of 1 vertical : 20 horizontal to the northwest. Water depth in the vicinity of the island reaches 400 m.

Freeze-up usually begins in October and the ice remains landfast until May. The ice is predominantly first year with a few frozen-in multiyear floes. The ice cover moves mostly to the north out from Navy Board Inlet. Icebergs often freeze in the ice a few kilometres north of the island at the boundary of Lancaster Sound.

Measurements

An array of prism reflectors mounted on wood stakes was placed around the island during the first visit to the site, 5−19 November 1984. Ice thickness was 0.25−0.30 m at the beginning of that period. A second array was placed near the shore

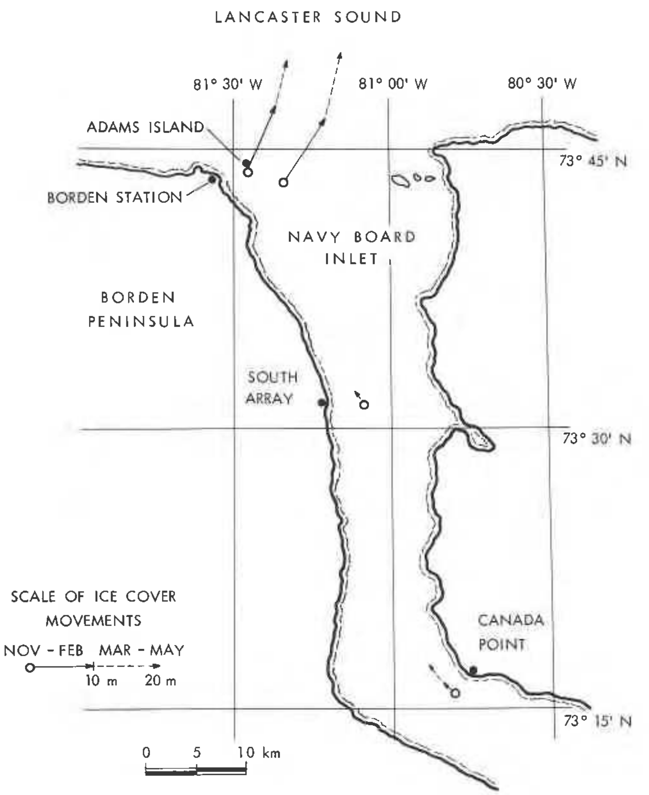

FIG. 1. Adams Island area and Navy Board Inlet, 1984−1985 season.

at Borden Station and a third one was placed about 60 km south of the island. Locations of the reflectors were surveyed from fixed points on the island or the shore using an electronic distance measuring (EDM) instrument (Wild DI 20) and a theodolite (Wild T-2). The measured locations were accurate within approximately ±20 mm. Ice movements were determined from repeated surveys of the reflectors. Surveys were conducted at 1 or 2 day intervals during three occupations: 5−19 November 1984, 28 February − 16 March 1985, and 13−21 May 1985. Movements of the ice cover were also monitored continuously using a wire line device manufactured by Arctec Canada Ltd. Two wires were wound over pretensioned reels that were housed in a box on the ice. The wires passed through a vertical grease-filled tube and were anchored on the seabed. A schematic diagram of the setup is shown in Fig. 2. The changes in wire length were recorded at 15 min intervals from 14 November 1984 to 19 May 1985 except for a break of about 2 weeks in February.

Several stations were set up on the ice cover around Adams Island to measure air temperature and wind speed, direction, and profile. At one station, at Canada Point, a thermocouple probe placed in the ice cover measured ice temperatures at the surface and 0.25, 0.5, 1.0, 1.5, and 2.0 m below the ice surface.

Normal stresses in the ice were measured along the south side of the island using six flat 1 × 1 × 0.025 m panel transducers (''IDEAL'') manufactured by Terrascience Systems Ltd. Each panel consists of a number of strain-gauge-monitored elements placed between two thin stainless steel plates. The panels are sectioned to separately measure the average normal stress on two horizontal strips, each 0.5 m high.

Six panels were installed along a line 75 m long at a distance

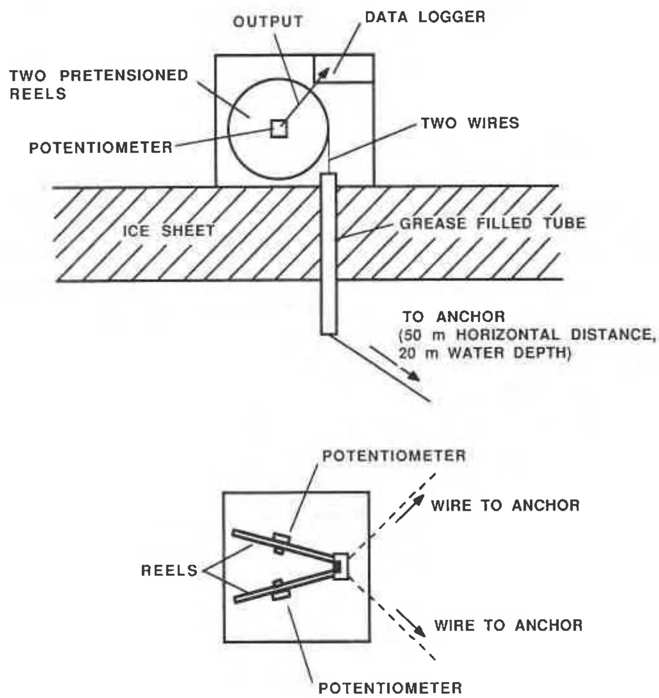

FIG. 2. Schematic diagram of the wire line system.

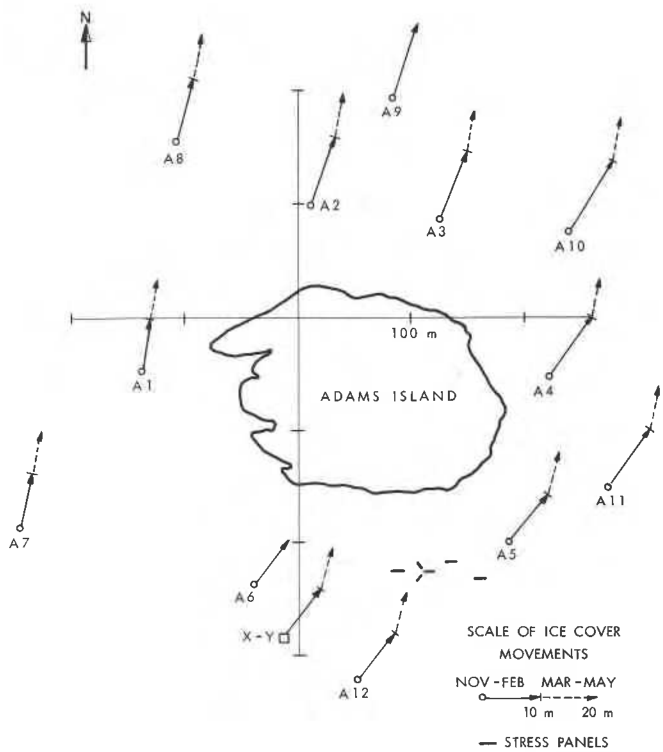

FIG. 3. Horizontal movements of the ice cover and locations of stress panels adjacent to Adams Island, winter 1984−1985.

of 75 m from the island and parallel to its shore. Three of the panels were arranged in a rosette in order to determine the principle stresses. Slots (approximately 0.3 m wide) were cut in the ice and panels were frozen in them in November 1984. Owing to problems with the data logger, recording did not start until 25 April. The signals were scanned and recorded at 15 min intervals until 19 May 1985. Locations of stress sensors,

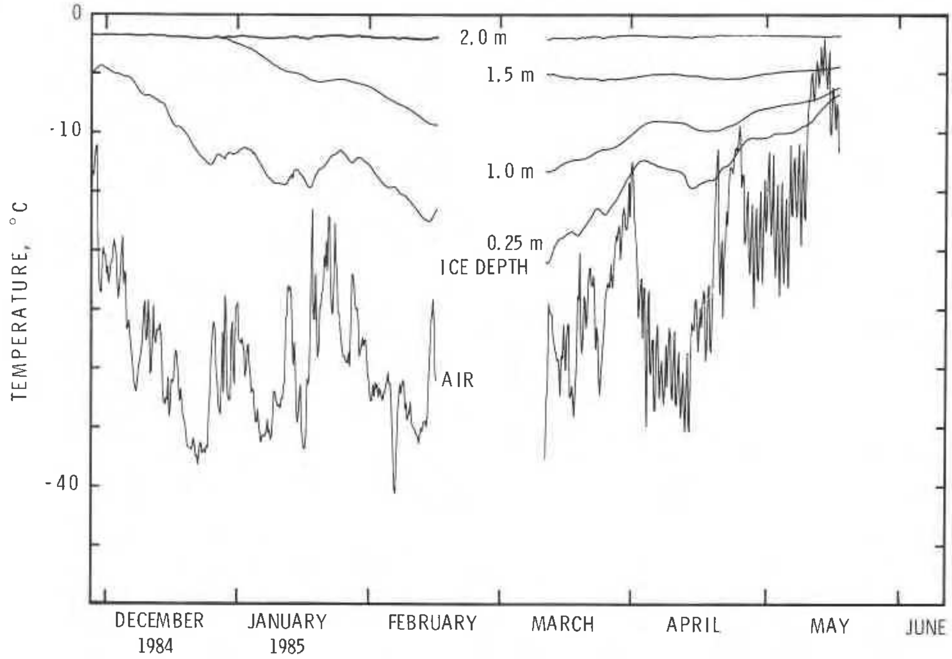

FIG. 4. Air and ice temperatures at Canada Point.

survey reflectors, and the wire line box are shown in Fig. 3.

Eight biaxial stress sensors were also deployed in November 1984 around the southern and western sides of the island. These are cylindrical (50 mm diameter) vibrating wire gauges supplied by IRAD Gage (type VBS-3). They measure principal stresses in the plane of the ice sheet and were installed at a depth of 0.2 m. Records were obtained at 4 h intervals from 21 November to 4 December 1984. Seven more sensors were installed in March 1985 to encircle the island and records were obtained from 14 March to 6 April 1985. Additional records at half hour intervals were obtained from 15 to 18 May 1985. All these records have been corrected for the effect of temperature and long-term drift. A thermistor is included in the gauge and the temperature data are applied to a correction algorithm. Zero stress readings were taken before installation in the ice and again after removal. These known points were used to make a linear adjustment to correct for long-term zero drift.

Ice cover movements

Movements, determined from repeated surveys of the reflectors, from November 1984 to February 1985 and from March to May 1985, are shown in Fig. 3. The average rates were 0.12 m/day and 0.081 m/day for the two periods respectively. The total movement from November to May was about 18 m in a generally northerly direction. Movements near Borden shore were similar. An array 60 km south of Adams Island, at Canada Point, moved at slower rates of approximately 0.05 m/day and 0.02 m/day during the November–February and March–May periods respectively. There, the total movement was about 5 m to the northwest. Ice thickness increased from 0.25–0.30 m in November 1984 to 1.5 m in March and 1.75 m by May 1985. Air and ice temperatures at various depths measured at Canada Point are plotted versus time in Fig. 4. The gap in the record was due to limited storage capacity of the logger. Ice thicknesses inferred from the ice temperature profiles agree with the measured ice thicknesses.

Details of the movement rates of reflector A12, which was

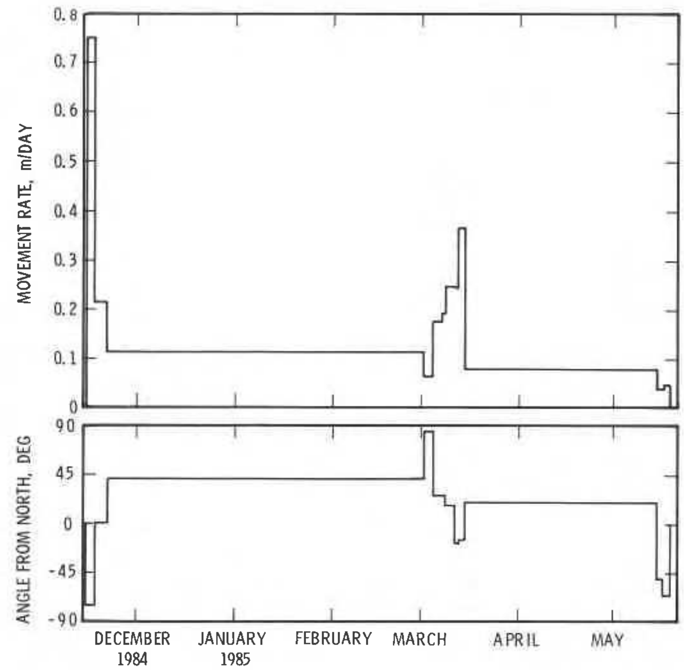

FIG. 5. Movement rate and direction south of the island (reflector A12).

located south (upstream) of the island, are shown in Fig. 5. As expected, rates measured over 1 or 2 day intervals were higher than the average values mentioned above and movement directions fluctuated. Given the accuracy of the surveys, movement rate error could be as high as 0.04 m/day over a 1 day interval.

The wire line device was intended to provide a more frequent record of ice movement. The lengths of the two wires can determine the location of a point on the ice sheet if the vertical motion is negligible. Because of the large tidal range (up to 1.9 m), an additional condition had to be used in order to determine ice movements. In one method, the records were

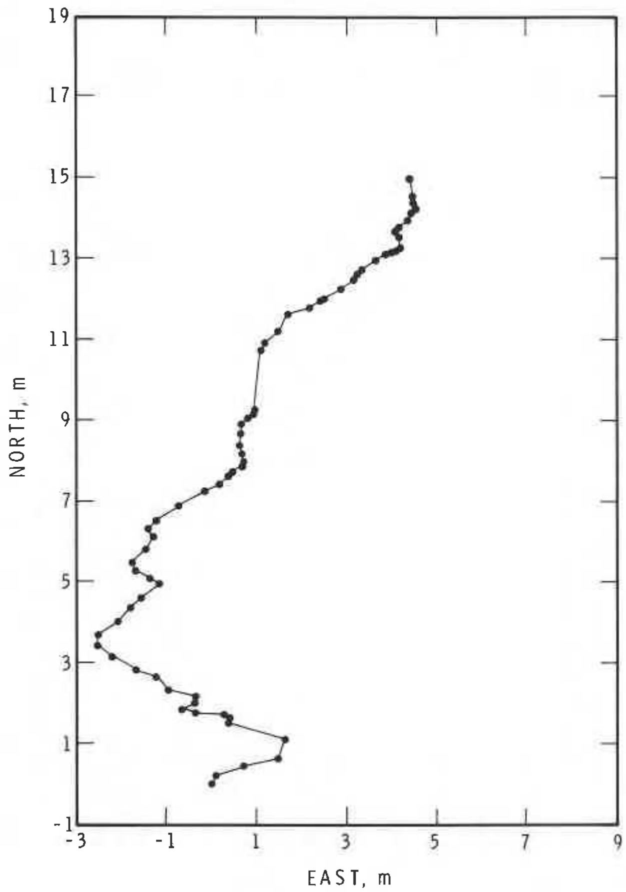

FIG. 6. Displacement of the wire line box from November 1984 to May 1985.

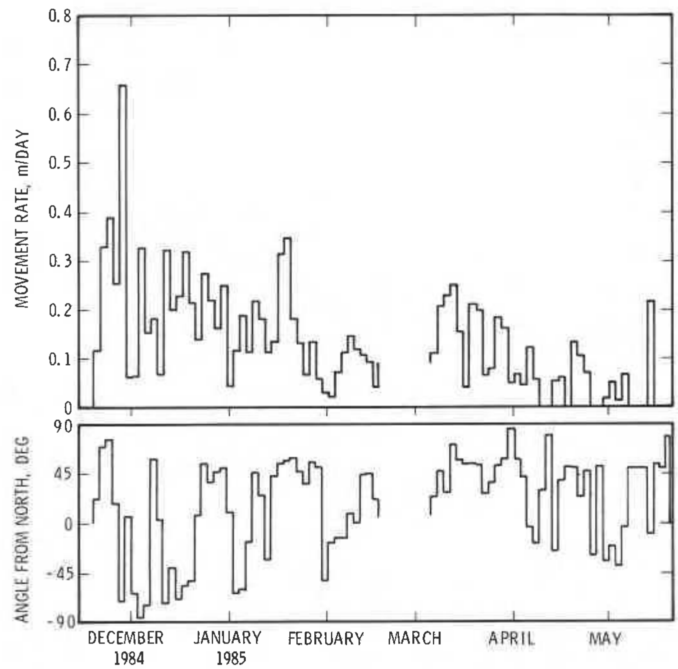

FIG. 7. Movement rate and direction of the wire line box.

averaged over 48 h periods and thus the vertical tidal movement was eliminated. In the second method, measured tide elevations were used together with wire length changes. The wires assumed to extend in straight lines between the box and the anchors. At each time step, the component of horizontal displacement (in the vertical plane of the wire) was calculated from the change in wire length. The two horizontal displacement components were used to calculate the magnitude and direction of the total horizontal ice movement.

The above two methods gave almost identical results when calculations were made at 48 h intervals. Results obtained for shorter intervals using the second method (employing tide data) showed a spurious cycling movement was not observed from frequent surveys of some reflectors. The drag force on the wire due to water current, which has a strong tidal component (Frederking *et al.* 1986*a*), probably caused the cyclic change of wire lengths, which coincided with the tidal frequencies. Estimates of wire extension due to drag force fluctuations were of the order of 0.1 m (using wire tension of 13 N, diameter of 1.6 mm, length of 50 m, and water velocity of 0.3 m/s). Therefore, it was concluded that the device cannot dependably measure ice movements at intervals as small as a few hours. Movements and movement rates calculated using 48 h averages are shown in Figs. 6 and 7. There were no noticeable erratic movements from the general direction, as can be seen from Fig. 6. The rates, shown in Fig. 7, followed a decreasing trend with progression of the season similar to that observed from the surveys (e.g., Fig. 4) and caused probably by the increase in ice thickness. The average rates are approximately 0.2 m/day from December to February and 0.1 m/day from March to May, which are higher than the values calculated from surveys. This is expected because reflectors are assumed to move in straight lines between surveys.

Surveys indicated a large easterly movement in November 1984 that was not detected from the wire line system. However, the results appear to agree for the period from December to April. It is not clear, as well, if the wire line system malfunctioned during the late April–May period, because the rates became very small. One wire (which extends nearly to north-northwest) did not move except for small sudden jumps during that period. Consequently, there is some uncertainty regarding the corresponding results.

Ice cover deformation

Movements of the ice cover obtained from the surveys were used to calculate the strains and strain rates over lengths of several tens of metres. At this scale, deformation may be considered two dimensional. The linear strain between two reflectors was taken as the change of length divided by the original length measured in November 1984. This choice of original length is somewhat arbitrary because the ice cover has no clear natural or undeformed state. The use of a different reference length such as the current length would give similar results because of the relatively small values of strains. Groups consisting of three reflectors were used to calculate the linear strains along the sides of triangles. These in turn were used to determine the magnitude and direction of the principal strains, which may be considered as average values over the area of a triangle. The principal strain rates were calculated in a similar manner from the linear strain rates, which were taken as the rate of change of length (between two reflectors) divided by the original length.

Calculations were done over triangles surrounding the island. The total principal strains from November to March and from November to May are shown in Fig. 8. Compressive strain was considered negative and is shown in Fig. 8 with

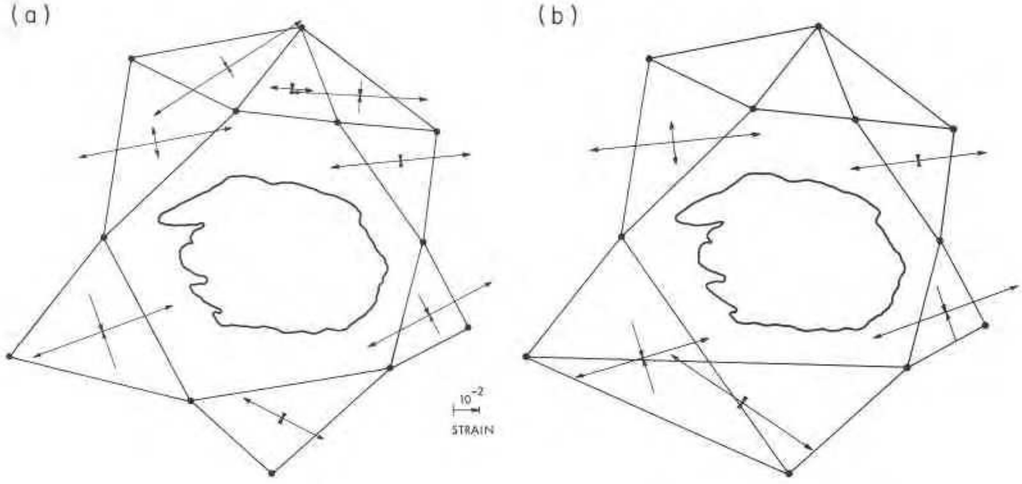

FIG. 8. Principal strain calculated from ice displacements: (*a*) from November 1984 to March 1985; (*b*) from November 1984 to May 1985.

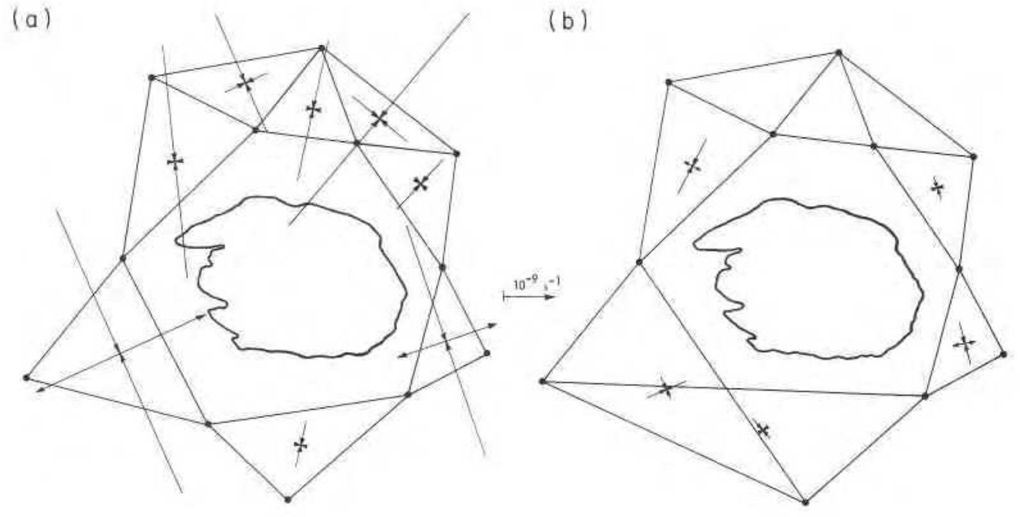

FIG. 9. Principal strain rates: (*a*) from November 1984 to March 1985; (*b*) from March 1985 to May 1985.

arrows pointing inwards. Calculations for triangles involving reflector A6 stop in February because in March the reflector was pushed against the rubble. The strains shown in Fig. 8 indicate that the change from March to May was small compared with that taking place from November to March.

Strain rates were calculated between each pair of successive surveys. The principal strain rates from November to early March and from late March to May are shown in Fig. 9. The values presented in Fig. 9 are those calculated between the last survey in November and the first survey in March, and between the last survey in March and the first survey in May. Therefore, those values do not correspond to the total strains (between the first and last surveys) shown in Fig. 8.

The magnitudes of the major principal strain rates from November to March were of the order of 10^{-9} and 10^{-10} s^{-1} from March to May, and also had a large north–south components. The strain rates shown in Fig. 8 are mostly compressive. The tensile strains, which appear prominent in Fig. 8, mostly occurred early in November and were measured by the initial surveys. Details of the development of the strains and strain rates over the season are given in Figs. 10 and 11, for triangles south and west of the island. Strains in other parts of the ice cover around the island followed trends similar to those in Figs. 10 and 11 with maximum values less than 4%. The strain rates showed some scatter especially over short durations (1 or 2 days). They also changed from tension to compression (or from compression to tension) at times. Strains and strain rates further south from the island (at Canada Point) were relatively small (Table 1), likely because the ice cover did not encounter a nearby obstacle. There, the strains and strain rates were almost negligible between March and May.

Stress measurements

Principal stresses measured at 0.2 m depth in the ice using biaxial gauges are available for the period from 22 November to 4 December and from 14 March to 7 April. Results from a location south of the island (near the flat panels, see Fig. 3) are shown in Fig. 12. Stresses during the November–December period were relatively low with an average of 100 kPa and a maximum of 200 kPa. Stresses increased by the March–April period to reach a maximum of 450 kPa and displayed a pronounced cyclic behaviour. Results from the later period show values and patterns similar to those obtained using flat panels during the April–May period.

Results from the centre and west panels for 26 April – 19

TABLE 1. Principal strains and strain rates south of Adams Island at Canada Point

Date	Principal strain			Principal strain rate		
	Major	Minor	Angle*	Major	Minor	Angle*
1984-11-10	0.0	0.0	0.0			
1985-02-28	0.77×10^{-2}	-1.16×10^{-2}	−25.8	1.22×10^{-9}	-0.81×10^{-9}	−25.8
1985-05-20	0.78×10^{-2}	-1.22×10^{-2}	−27.2	0.10×10^{-9}	-0.29×10^{-10}	−23.3

*Degrees clockwise from north.

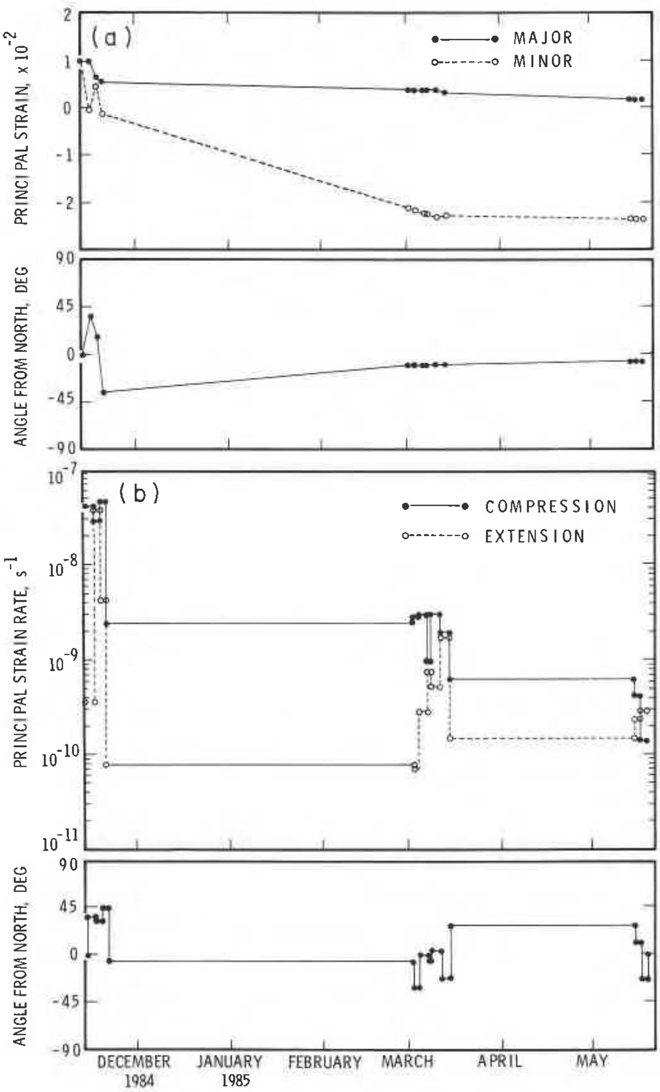

FIG. 10. (*a*) Principal strains south of the island; (*b*) principal strain rates south of the island.

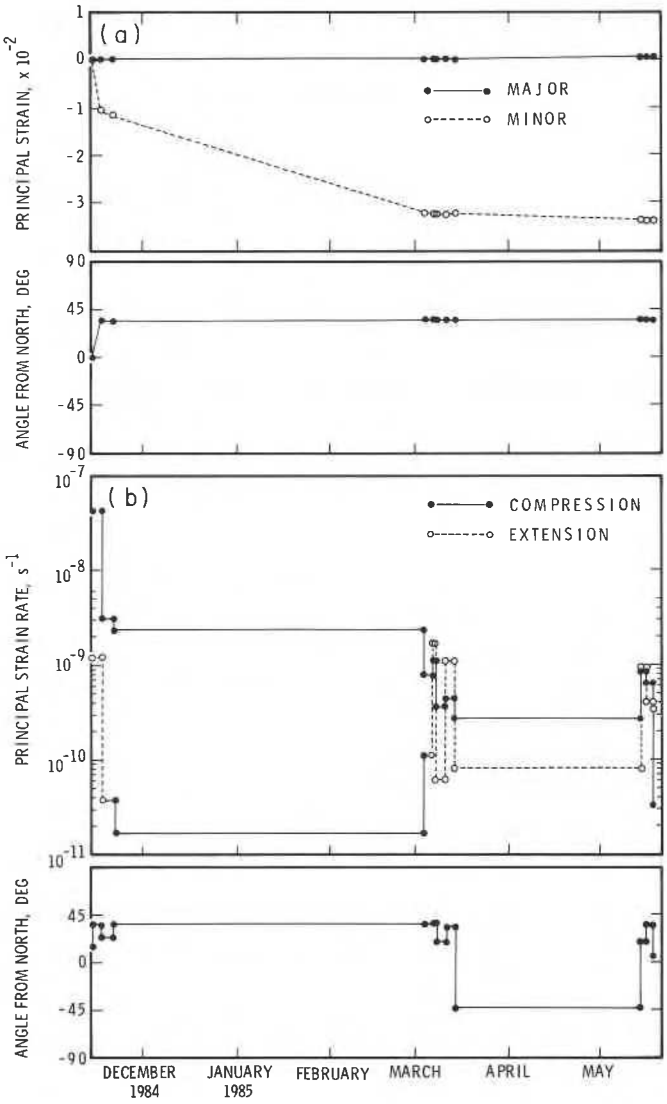

FIG. 11. (*a*) Principal strains west of the island; (*b*) principal strain rates west of the island.

May are shown in Fig. 13. The maximum stresses were 500 and 350 kPa at the two locations respectively. All panels measured lower stresses at the 0−0.5 m depth than at the 0.5−1.0 m depth of the ice sheet. Vertical stress profiles measured during the 1983−1984 winter (Frederking *et al.* 1986*a*) show that stresses are relatively small below the 1 m depth (and correspond to less than 10% of the total force acting over the full ice depth). Measured ice temperature profiles at Canada Point, and during the 1983−1984 season, showed a rapid increase with depth below 1 m. The "weaker" warmer ice in the lower part of the ice sheet is assumed not to support appreciable stress. Detailed discussion of this assumption was given by Frederking *et al.* (1986*a*). Based on that earlier result, stresses below the 1 m depth are neglected. Therefore, forces per unit length in the ice sheet were calculated from stresses measured over the top 1 m of ice thickness.

Principal forces, shown in Fig. 14, were calculated from the rosette of three panels. Both the magnitude and direction of the principal forces were cyclic with a period of approximately 12.5 h, which coincides with tidal frequency. The output of all panels underwent similar periodicity in unison. Magnitude of the forces also increased with increasing tidal range. Forces

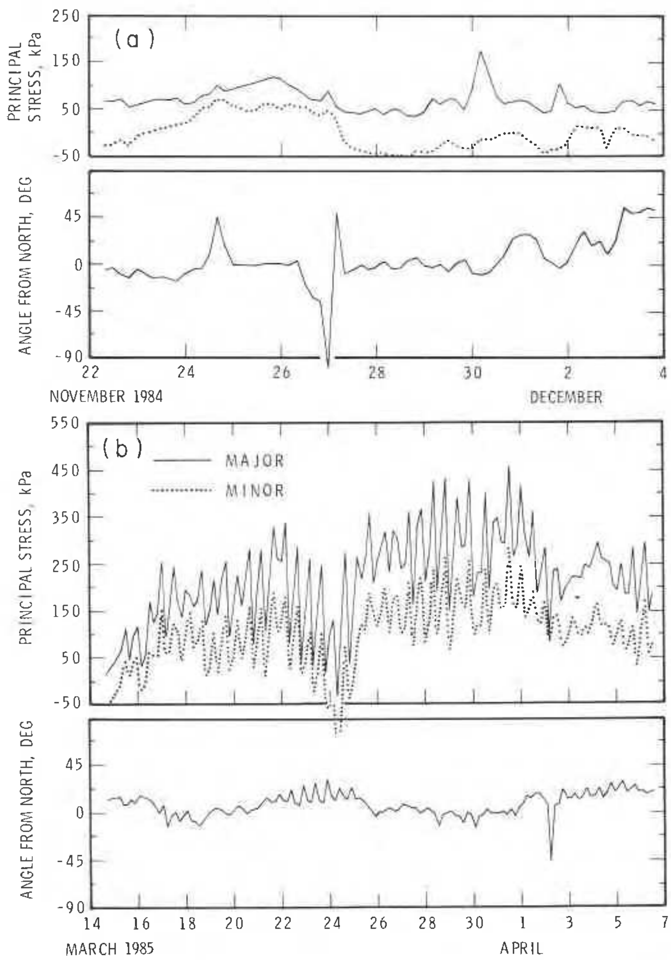

FIG. 12. (*a*) Principal stresses south of the island from biaxial sensors, November–December 1984; (*b*) principal stresses south of the island from biaxial sensors, March–April 1985.

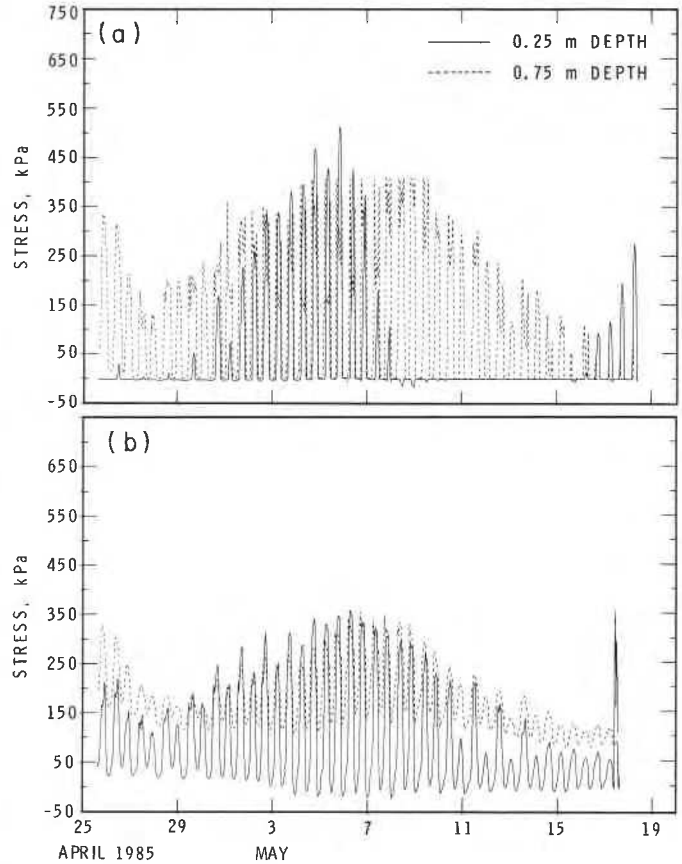

FIG. 13. (*a*) Stresses measured by the centre panel, south of the island; (*b*) stresses measured by the west panel, south of the island.

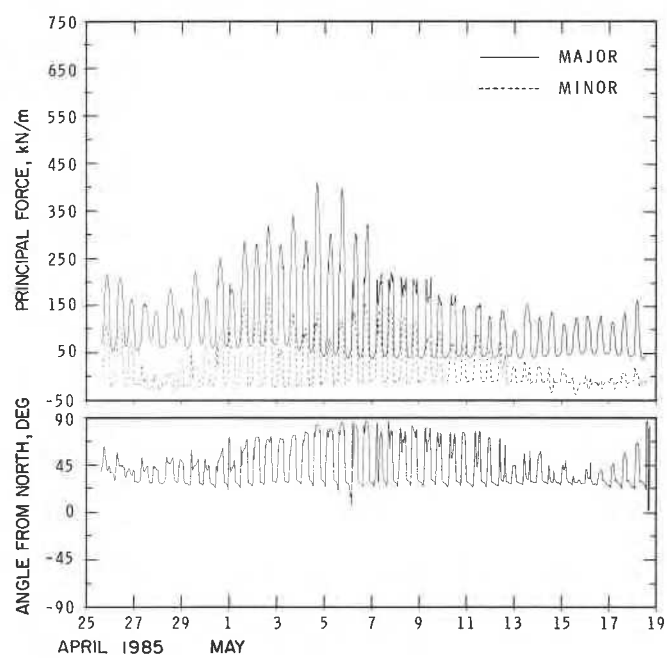

FIG. 14. Principal forces in the ice cover at the panel rosette.

and relative water levels during 3 and 4 May 1985 are shown in Fig. 15. These indicate that high forces coincide with low water levels. Although water current measurements were not successful, owing to loss of equipment, previous measurements by Frederking *et al.* (1986*a*) indicate that the current at that location is primarily tide driven. Thus, water drag could be cyclic and might have caused the stress fluctuations. Another possible reason for the apparent correlation between stress and tide could be the rocking movement of ice blocks that form at the shores of the inlet. This was referred to as "tidal jacking" and discussed in detail by Frederking *et al.* 1986*a* (see also Frederking and Kakawo 1984).

Discussion

Recorded ice cover movements past the island showed no erratic jumps. The rates depended on the frequency of measurements; high rates were observed over short durations. Still, the average rates decreased from 0.12 to 0.081 m/day as ice sheet thickness increased from 0.25 to 1.75 m. Although no estimates of the driving forces acting on the ice cover were made, it appears (Frederking *et al.* 1986*a, b*) that no significant changes in wind or water current drag took place with progression of the season. Stress measurements indicate that forces were relatively small during November–December, then increased to reach their maximum values by March and remained unchanged afterwards until May. Thus the decrease of movement rate was likely caused by increasing ice cover "resistance" rather than a decrease in the driving force.

Principal strains calculated over triangular areas surrounding

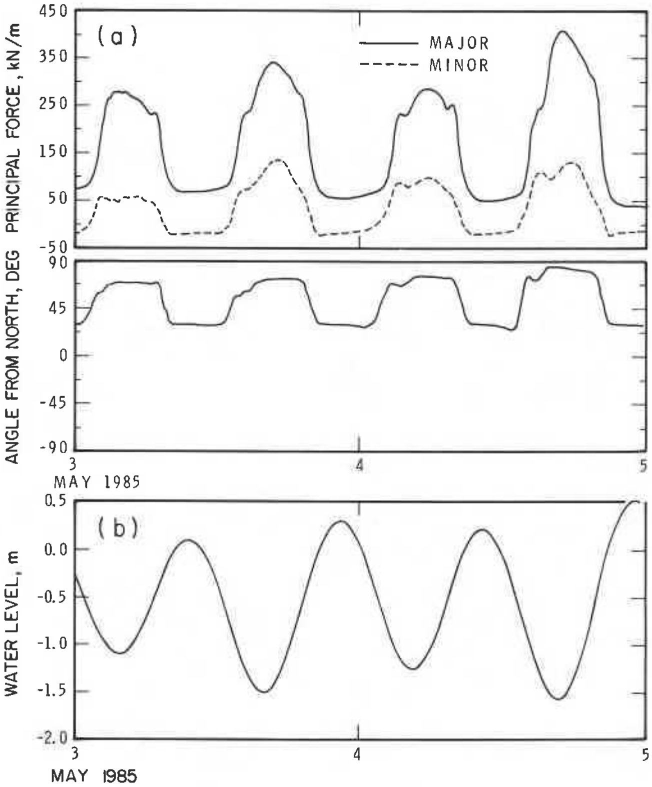

FIG. 15. (*a*) Principal forces, 3–4 May 1985; (*b*) water levels, 3–4 May 1985.

the island displayed consistent trends. Tensile strains had a maximum of 4% and were always higher than compressive strains, which had a maximum of 1%. Directions of the major principal strain were mostly to the north-northwest. The above values include ice cover deformation by cracking, opening of leads, ridging, and rafting, in addition to the local deformation of the ice. Thus it may be concluded that most of the global deformation was due to opening of leads and to a lesser extent ridging and rafting . Most of the tensile strains, however, occurred in early November. Later in the season strains became predominantly compressive and decreased with time. This can be seen from Fig. 8, where principal strain rates starting from late November are plotted. The development of strains with time, shown in Figs. 9 and 10, also illustrates that the relatively large tensile strains occurred only early in the season.

Strain rates measured over 2 day intervals fluctuated more, and were approximately an order of magnitude larger than those measured over 2 or 3 month periods (see Figs. 9 and 10). Those fluctuations were caused by actual ice cover movements and not measurement errors.

Maximum strain and strain rate measurement errors can be estimated by considering that survey accuracy of a reflector's location is within 20 mm. For a length of 100 m, which is typical of strain triangles, the maximum strain error would be 0.2×10^{-3}. The strain rate error decreases with increasing durations between measurements. The error for a 2 day interval, based on the above strain error (0.2×10^{-3}), would be 10^{-9} s^{-1}.

Strain rates, as expected, decreased with the decrease of movement rate. Most of the strain rates for the November–March period were in the range of four to five times those for the March–May period. The corresponding average ice thicknesses were 0.88 m (increasing from 0.25 to 1.5 m) and 1.6 m (increasing from 1.5 to 1.75 m), giving a ratio of 0.53 between the two periods. The average movement rates were 0.12 and 0.081 m/day respectively, giving a ratio of 0.67.

A reference strain rate (e.g., Sanderson 1984), often used for indentation problems, can be calculated by dividing the movement rate by the island's diameter (200 m). The average reference strain rates for the above two periods would be 7×10^{-9} s^{-1}. The corresponding maximum measured principal strain rates at the island are 3×10^{-9} and 0.5×10^{-9} s^{-1}; that is, they are of the same order as the reference strain rate.

Deformation south of the island in Navy Board Inlet (at Canada Point) is expected to be typical of ice cover behaviour away from obstacles. The maximum major principal strain was 0.8% and maximum major principal strain rate was 0.1×10^{-9}s^{-1}.

Stresses measured by flat panels and biaxial cylindrical sensors were in the same range, with maximums under 500 kPa. Estimated maximum force was 400 kN/m just south of the island. Unlike strains and strain rates, which were measured over length scales of the order of the island's diameter, stresses were measured locally over much shorter lengths. However, records from the various sensors acted in unison; no sporadic (or so-called ''nonsimultaneous'') behaviour was detected. Stress distributions also appear to be spatially smooth, which indicates that those stresses may be close to the global values (over long length scales).

The present measurements are not suitable for direct derivation of the appropriate constitutive equations for the ice cover. They can be used best as references to verify the results of modelling assumptions. The currently available idealized two-dimensional indentation solutions (mentioned in the Introduction) cannot account for many features of ice cover behaviour (e.g., stress cycling, opening of leads, and out-of-plane deformation). They can, however, be adjusted to fit certain ''averages'' or ''smoothed values'' of the measurements. Trying to fit the foregoing results to a simple continuum solution is beyond the scope of the present study. Such an attempt here would obscure the significance of the observations.

Conclusions

Measurements of landfast ice cover movements and stresses were conducted at Adams Island in Navy Board Inlet. Movements were consistently to the north with very small fluctuations at a rate of approximately 0.1 m/day.

Global strains and strain rates were calculated over lengths of the order of the island's diameter. The maximum compressive and tensile strains from November 1984 to May 1985 were less than 1 and 4% respectively. Most of the tensile strains were caused by the opening of leads in early November. Compressive strains became dominant from late November until May.

Strain rates, measured over 2 and 3 month intervals, were of the order of 10^{-9} s^{-1}. This is also in agreement with the reference strain rate, taken as the movement rate divided by the island's diameter. Strain rates measured over 2 day intervals fluctuated, and were an order of magnitude larger than those measured over 2 and 3 month intervals. Movement rates and strain rates both decreased with progression of the winter season.

Local stresses measured using two types of sensors had a maximum of 500 kPa. Estimated maximum force was

400 kN/m. The mean values were approximately half of the above maximum. The stresses exhibited a cyclic behaviour that depends on the tide. There was no evidence of nonsimultaneous or sporadic stresses around the island.

The preceding observations describe some aspects of ice cover interaction with wide structures. The problem is very complex and includes many intricate processes. Several subjects, such as the relationship between global and local stresses and ice deformation, still require further study. It should be noted that the present results are valid for a limited range of conditions (for example movement rates) beyond which they should not be extrapolated.

Acknowledgements

The financial support of the Panel on Energy Research and Development is gratefully acknowledged, as is the logistic support provided by the Polar Continental Shelf Project. The use of the facilities at Borden Station owned by the Canada Department of Fisheries and Oceans, and technical support in the field provided by the Arctic Research Establishment, Pond Inlet, greatly facilitated the work. Assistance in preparations and in the field provided by P. Jochmann and W. Neper of Hamburgische Schiffbau-Versuchsanstalt GmbH. (HSVA), J. D. Neil, Technical Officer, National Research Council of Canada, A. H. Headly, Atmospheric Environment Service, Environment Canada, and C. Labine, Campbell Scientific, Edmonton, Alberta, is gratefully acknowledged. Financial support of the German Ministry of Research and Technology made possible the participation of HSVA in the project.

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