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RESEARCH AND DEVELOPMENT BRANCH
DEPARTMENT OF NATIONAL DEFENCE
CANADA

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

DREO REPORT NO. 729
DREO R 729

ICE PRESSURES AT THE SHORE OF LINCOLN BAY

by

G.J. Irwin

PROJECT NO.
97-67-05

OCTOBER 1975
OTTAWA

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PUBLISHED OCTOBER 1975
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75-197

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Lines 4 and 5, page 9 should read

$$f = M_{\delta=o} z \left[\frac{M_{\delta=\phi}}{M_{\delta=o}} \right]^{\delta/\phi}$$

where M_δ is the ratio of rupture distance to depth of gouging.

In lines 3 and 14, page 17, substitute δ for ϕ.

75-214

ABSTRACT (U)

50// With increasing offshore activity in the Canadian Arctic Archipelago, there is a continuing need for more detailed knowledge of forces and pressures of pack ice acting in coastal regions. In July 1974 pack ice acting on the shores of Lincoln Bay, N.W.T. presented an opportunity for making an order of magnitude determination of sea ice pressure in the littoral zone. From considerations of ice uplift, block dimensions and density, moments in turning an ice block, and effort in ploughing beach material, horizontal pressures at the shore were calculated to be of the order of 0.1MPa. Such a value, if typical of impact pressures at a protected portion of the Ellesmere Island coastline, indicates that ice floes grounding on shore should pose little threat to many types of shoreline installation. //

RÉSUMÉ

L'accroissement des activités au large de l'Archipel Arctique canadien entraîne un besoin permanent de connaissances plus détaillées des forces et des pressions de la glace de banquise agissant sur les régions côtières. Au mois de juillet 1974, l'action de la glace de banquise sur les côtes de la Baie Lincoln, (T.N.-O.) a donné l'occasion d'établir l'ordre de grandeur de la pression de la glace de mer sur la zone littorale. Considérant le soulèvement de la glace, les dimensions et la densité d'un bloc de glace, les moments de rotation et l'effort de labourage du matériau de la plage, on a calculé que les pressions horizontales à la côte atteignaient quelque 0.1MPa. Si de tels résultats sont une indication typique des pressions de choc sur un secteur protégé de la côte de l'île Ellesmere, il semble que les glaces flottantes qui s'échouent sur le rivage ne présenteront que peu de danger pour de nombreuses installations côtières.

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INTRODUCTION

In order to gain some appreciation of the magnitude of ice forces and their distribution at shorelines in the Robeson Channel area, a study was carried out during the ice break up period of July 1974. One particular event conveniently lent itself to close scrutiny as channel ice moved into Lincoln Bay and pushed onto its shores with the rising tide.

The study stems from the foreseen need for the Department of National Defence to establish, as required, shoreline installations or docking facilities in the Canadian Arctic. It is expected that locations where there is a potential defence interest should be in areas where ice forces and pressures are relatively low. Ice forces on shore may be expected to have a wide variety of origins and a wide range of magnitudes. Thus the present work must be seen as merely a sample base-line investigation in a continuing effort to quantify ice forces at specific locations on the arctic coasts.

The scope of the study includes in situ measurements of the dimensions and density of ice blocks that push up on the shore with a view to determining shore-ice frictional resistance to ice movement, and the determination of beach material characteristics such as apparent friction and cohesion coefficients so as to estimate the bulldozing force of ice as it ploughs its way up the beach. For simplicity, SI units for force, pressure, and length are used throughout. Quoted sources using such units as pounds per linear foot or dynes per centimeter are thus converted.

There is a paucity of field data on sea ice pressures at the shoreline as well as reliable techniques of direct measurement. Kovacs and Mellor (1) from observations of ancient ice scoring in the Beaufort Sea, estimate force requirements of 1.3×10^6N. Parmerter and Coon (2) from a kinematic model of sea ice ridging predict instantaneous pressure peaks at 1.5×10^5N/m. Bridges, dams, or offshore structures are usually built to withstand an ice crushing strength of 2.7×10^6Pa or ice thrusts up to 6.8×10^5N/m in areas of fresh water ice (3). However, it is suspected that design pressures of this magnitude are unnecessarily high (4). Ice strengths are expected to be at least an order of magnitude higher than the pushing or driving pressures estimated for ice ridge building in the ice pack (2). Rogers et al (5) recently measured tidally induced ice stresses on the Chuckchi Sea coast up to 3.4×10^5Pa. However, driving pressures were not measured.

Defence operations at the arctic shore such as docking and ship off loading and the use of piers and buried acoustic cables should be unhampered as far as possible by natural ice forces. The forces of the pack ice zone per unit horizontal length at least as high as 10^5N/m may be expected to be transferred unabated to the shore. The length of fetch of the wind, the periods of open water followed by storms which help break up the ice pack, and the strong shear effects of passing ice floes and bergs as they are jammed against the shore, are all contributing factors to environmental damage at the shoreline.

BACKGROUND

Lincoln Bay (Figure 1) lies at the foot of the Hazen Plateau Division of the Central Ellesmere Fold Belt. The southern boundary of the bay, from point P west, consists largely of fine grained deep sea sediments, detrital siltstone, black or gray shales and weakly metamorphosed slates. This beach material is well graded with grain sizes ranging from 0.08 mm to 27 mm. East of point P the bay is bordered by steep skree slopes composed of course slabs of siltstone, shale, or slate varying in size between 0.1 m and 1 m.

During trips in the past two summers it was noticed that the south coast of Lincoln Bay is subject to significant ice action. This is evident from the numerous mounds of ploughed up beach material particularly at the jutting point P. (See also figures 2 and 3). Break up of ice in the Robeson Channel and the bays usually occurs during the month of July. It would be at this time that ice action on shores would be highly prevalent. Thus it was considered convenient to make a closer study of the Lincoln Bay area during this period.

The interior of Wrangel Bay by contrast to Lincoln Bay is relatively protected from ice action by a large promontory on its north side. As a result there was little evidence of ice push in this area despite the incidence of high gales up channel during summer periods of open water. The Canadian side of the Robeson Channel coast between the bays is open to very severe ice action at the ice foot for extended periods of time, particularly during the summer periods of break up and probably later during freeze up. This ice foot is perennial and protects the coast line from wave or ice action for most of its length. The ice foot terminates at the south cape of Lincoln Bay and recommences near the north cape. As a result of ice behaviour that is influenced by the presence of the coast line, there is a littoral zone adjacent to the ice foot which extends a distance of about 1 km across channel. Beyond this is the pack ice zone.

The particular ice pressures to be considered in Lincoln Bay are associated with a pressure phenomenon that occurred on July 19, 1974. The event was preceded by at least a week of completely open water in the bay and several days of persistent southerly winds gusting up to 20 knots. This was followed by a 180° change of wind direction on July 19. The wind change began at 11:00 GMT with the vector taking less than two hours to rotate from up channel, to east, to a steady direction down channel. The down channel or northerly wind direction then ranged in velocity between 6 to 16 knots for the balance of the day. Sometime after the change of wind, a portion of the ice pack moved steadily into the bay. This may have been associated with both a change in the internal forces of the pack as well as the approach of high tide. Ice action against the shore took place between 20:00 GMT, July 19 and 1:00 GMT, July 20, the time of the high tide peak. The ice topography established at that time maintained essentially that state (except for melting effects) for at least the following two weeks. The ice was in one case measured to move sporadically up the beach slope, i.e. in jerks that ranged between 0.6 and 1.7 knots. The ice in several cases rode up 30° slopes of the shore for distances of 1 to 10 m, scraping and pushing beach material before it. Extensive portions of the ice sheet moving on shore broke apparently to accommodate the slope of the shore as for example in figure 4.

The ice temperature was that for melting fresh ice, 0°C, while the salinity as expected was near 0 °/oo.

ON SHORE SEA ICE FORCES AND PRESSURES

BACKGROUND TO CALCULATIONS

In their description of the effects of ice floes and icebergs scoring the ocean floor, Kovacs and Mellor (1) consider three resisting forces: bottom friction (f_1); frictional forces due to passive or active earth pressure (f_2); and the bulldozing resistance (f_3). As ice blocks ride up on the beach, a fourth resisting force would be due to gravity (f_4). All of these should be calculable from the observations made at Lincoln Bay.

It is convenient to consider the ice pack as being in a state of steady motion, in general, as it moves into the bay until it is finally brought to rest at the shore. Isostacy is assumed to be operating initially. Upon touching the shore, a floe is pushed up the slope thus initiating the four resisting forces. The ice pack force (F) is in this case considered to be a reaction to the sum of the resisting forces mentioned above. Ridge building usually occurred remote from the shoreline and is not considered in the present calculations. The force of an active section of ice near the shore is the first item estimated. That dimension of an ice block most nearly normal to the ice pack force is designated the width and, in keeping with convention, is used for deducing force per unit of length. Taking into account the local ice thickness, an approximate ice pressure in the proximity of the shore is also calculated.

The force required to move floes against the friction of the beach (illustrated in figure 5) is given as

$$f_1 = F_v \tan\delta = \rho_w g u l w . \tan\delta \qquad \{1\}$$

where δ is the angle of ice-soil interface friction.

F_v is the portion of the weight of water displaced corresponding to the amount of uplift experienced by the floe

u is the uplift experienced by the floe

ρ_w is the density of sea water

g is the acceleration due to gravity

l is the length of a floe or ice block and is usually almost normal to the shoreline

w is the width or dimension of the grounded floe which is approximately parallel to the shoreline (normal to the ice pack force).

The component of the force of gravity down the slope of the shore would be:

$$f_4 = \rho_w g u l w . \sin\theta$$

where θ is the angle of inclination of the shore.

To determine the force of bulldozing as a floe ploughs its way up the slope, a model of bulldozing action must be assumed as is for example given in figure 6. The approach of Hettiarachi et al (6) for computing total draught (D) appears appropriate as it takes account of the gouging action and the surcharge weight of the ploughed material. See also Appendix A.

The draught as expressed in (6) and which is based on an equation by Reece (7) is:

$$D = (\gamma z^2 N_\gamma + CzN_C + C_a z N_a + qzN_q) \sin(\alpha + \delta) + V\tan\phi \qquad \{2\}$$

where ϕ is the angle of soil shearing resistance

N_γ, N_c, N_a and N_q are the Reece coefficients

z is the depth of gouging

γ is the soil density

q is the surcharge weight per unit fracture length

C is the apparent cohesion (units of pressure)

C_a is the soil interface adhesion (units of pressure)

α is the rake angle of the ice-soil interface

V is the reaction of the weight component W_1 of the surcharge normal to the shore surface (see figure 6).

The bulldozing force up the slope is

$$f_3 = Dw + Q\sin\theta$$

where Q is the weight of the ploughed soil.

The frictional force (f_2) acting on the vertical sides of a grounding floe may in the present case be considered negligible as the floes are usually rectangular and loading is frontal rather than lateral. Also the gouging depth is shallow.

An indication of the force in the ice field required to upturn large blocks of ice may be determined with the use of moments. Idealizing the shape of upturned ice blocks that were observed at the shoreline and assuming a pivot point an equation of moments may be set up. Figures 7 and 8 show two situations that were encountered during the ice pressure event.

In the first case (figure 7) the pivot is at hinge "A". Thus

$$\rho_i V'g\,(d - h/2\,\tan\theta')\cos\theta' \simeq F'h' \qquad \{3\}$$

where ρ_i is the density of sea ice

V' is the volume of the upturned ice block

θ' is the angle of inclination of the block

F' is the up slope component of the ice pack force

$2d$ and h are the length and thickness respectively of the upturned block

h' is the thickness of the pushing block

In the second case (figure 8) a wedge shaped block of ice is assumed to rotate at its centre of gravity as there was no translational motion yet slippage occurred at the base during the rotation.

Thus

$$F'(b/3 \sin\theta' - h/2 \cos\theta') = \rho_i g V' \tan\delta' \, (h/2 \cos\theta' + b/3 \sin\theta')$$

or

$$F' = \frac{\rho_i g \tan\delta' \, (h/2 \cos\theta' + b/3 \sin\theta')}{b/3 \sin\theta' - h/2 \cos\theta'} \cdot h\sqrt{s(s-b)^2(s-c)} \qquad \{4\}$$

where δ' is the angle of interface friction of ice and h, b and c are the block dimensions as given in figure 8.

$$s = \frac{2b + c}{2}$$

In what follows example calculations of ice force taken from specific instances where order of magnitude calculations were possible are presented.

EXAMPLE CALCULATIONS

EXAMPLE (1)

About 500 metres along the shore south east of point P (figure 1), a large sheet or block of sea ice was observed to have pushed up the shallow slope of the shore and at a right angle to the shoreline. The block is shown in the photos of figure 4 and 9. Large cracks opened up allowing the block to conform to the shape of the shore. The cracks are probably a consequence of the unevenly supported weight of the block which became uplifted. For purposes of calculation of the horizontal ice pack force required to produce this phenomenon a model is adopted as in figure 5. The shore is considered to extend from the point of initial impingement by the block as it moved toward the shore. The rectangular shape of the block is a convenient approximation and is assumed to extend back from the point of initial impingement as the block moves on shore. Assuming the block to be initially in isostatic equilibrium before impingement on shore, the following formula should hold:

$$\frac{H_k}{H_s} = \frac{\rho_i}{\rho_w - \rho_i} \qquad \{5\}$$

where H_k is the keel depth (submerged position of the block)

H_s is the sail height (above sea level)

ρ_i is the density of sea ice.

Also $H_k + H_s = h$

where h is the thickness of the block.

Thus
$$H_s = \frac{h(\rho_w - \rho_i)}{\rho_w}$$

and
$$H_k = \frac{h\rho_i}{\rho_w}$$

The portion of the vertical cross sectional area above the waterline is $H_s l$. Measuring a new cross sectional area above the waterline with the help of photos and in situ measurements, a value of uplift of the block in its final position on shore may be estimated.

The pertinent values used were:

width(w)= 36.6 m

length (l) = 34.3 m

thickness (h) = 6.97 m

angle of inclination of the shore (θ)

sea water density (ρ_w) = $1.03 \times 10^6 g/m^3$

sea ice density (ρ_i) = $0.830 \times 10^6 g/m^3$

As a result u = 2.25 m and the vertical weight is $ulw\rho_w = 2.3 \times 10^7 N$.

Experiments to be described later (Appendix B) suggest that very rough ice-soil interfaces were operating, making the apparent coefficient of friction, tan δ, a large value close to one. Considering the frictional and gravitational forces together and determining the horizontal resultant, the ice pack force is deduced as $2.6 \times 10^7 N$. This is an order of magnitude higher than that estimated by Kovacs and Mellor (1) and is probably due to the high values of u and tan δ used.

The force per unit width of the ice block is $7.1 \times 10^5 N/m$ and the corresponding pressure is $1.0 \times 10^5 Pa$. The force per unit of width is high compared to that of Parmerter and Coon (2) although the pressure is well below the expected crushing strength for non saline, high temperature ice (2) (8). See also Appendix C.

Relatively little ploughed shore material was observed south east of point P in Lincoln Bay. The bulldozing force on this shore is likely to be very small compared to the friction resistance and is therefore not included in the estimate of ice pack force.

EXAMPLE (2)

On the west side of P, the ice blocks were smaller and uniformly spaced. They pushed up decidedly more beach material as it was soft and of fine texture. In this case it was thought advisable to include a bulldozing resistance with the calculation of ice pack force. The dimensions of several blocks of similar size were measured and an average taken for the purpose of an order of magnitude calculation of force.

The average values used were:

width (w) = 3.4 m

length (l) = 13 m

thickness (h) = 1.4 m

inclination of shore (θ) = 6.6°

The uplift (u) was determined to be 0.43 m and the vertical weight acting on shore was 2.9×10^5N. Assuming as before that $\tan\delta = 1$ and that the block moved approximately normal to the shore line, then the frictional resistance of the beach is 2.9×10^5N and the force of gravity down slope is 3.3×10^4N.

To determine the bulldozing force required for a block of ice to plough its way uphill the following values of soil properties and ice push dimensions were used:

width (w) = 3.4 m

height (h_1) = 0.62 m (see figure 6)

thickness (h_2) = 0.58 m (see figure 6)

angle of shearing resistance (ϕ) = 45°

rake angle (α) = 90°

angle of soil interface friction (δ) = 18.4° (see appendix B)

apparent cohesion (C) = 1.58 kPa

soil interface adhesion (C_a) = 0.52 kPa soil density (γ) = 1.75 Mg/m^3

depth of gouging (z) = 10 cm

Thus the rupture distance, illustrated in figure 6 is

$$f = M_s \left[\frac{M_{\delta=\phi}}{M_{\delta=o}} \right]^{\delta/\phi} = 36.67 \text{ cm}$$

where m is the ratio of rupture distance to depth of gouging.

If the ice push is divided into two parts, then weight of soil per unit width is $W_2 = 3.88 \times 10^3$ N/m and $W_1 = 2.3 \times 10^3$N/m.

The total draught calculated from equation {2} is 1.0×10^5N uphill. Added to the other forces and converted to a horizontal ice pack force, a value of 4.3×10^5N is obtained. The force per unit width of ice block is 1.3×10^5 N/m while the pressure is 0.90×10^5Pa.

EXAMPLE (3)

An indication of the ice pack force required to upend or overturn large ice blocks at the shoreline by the thrust of ice from the bay may be obtained by moments as outlined in the previous section. One case shown in Figure 10 occurred near the foot of a stream located at A in Figure 1. This block rested at an angle of 40° from horizontal. From approximate dimensions of the block, 2.5 m x 8 m x 8 m, the weight was calculated to be 1.2×10^6N. Using a simplified system of moments, the horizontal force of the ice pack is 9.3×10^5N. The force per unit width in this location is about 1.2×10^5N/m and the corresponding pressure using the local ice field thickness of 3 meters is 0.39×10^5Pa. At the shoreline additional forces will of course be acting. The calculated pressure is in this case a minimal value.

EXAMPLE (4)

The method of moments was also applied to a wedge shaped block of ice just east of point P that was upended by pack ice pushing near its base. There being no translation, it was assumed the block was rotating on its centre of gravity. See figure 11. Using formula {4} and taking

$$\delta' = 45^{o}$$

$$h = 3.6 \text{ m}$$

$$b = 4 \text{ m}$$

$$c = 4.9 \text{ m}$$

$$s = \frac{2b + c}{2}$$

and $$\theta' = 66^{o}$$

a horizontal force of 9.5×10^{5}N is obtained. The force per unit width at the base of the overturned block is 1.9×10^{5}N/m while the associated pressure is 0.53×10^{5}Pa.

FORCE DISTRIBUTION AT THE SHORELINE

South-east of point P major pressure points on the skree slope were spaced by approximately 50 to 100 m. On the west of P, the ice blocks on the beach were numerous over a distance of 0.8 km and spaced regularly between zero and 5 m. Their angle of approach to the shore was often oblique as front faces made angles with the shoreline that varied between 0^{o} and 20^{o}. For present defence purposes, ice forces acting over a limited extent of shoreline, i.e. about the width of an ice block, must be considered significant. Averaged over much longer stretches of shoreline such ice forces will be less important.

CONCLUDING REMARKS

Summer ice impact pressures at the Lincoln Bay shoreline according to the few examples studied, approach a value of about 0.1 MPa. The observed gouging of beach material is only a few cm. If such observations are typical of similar occurrences in other years, then shoreline changes or damage by this means may not be significant. Offshore ice ridges that formed at the time of shoreline impact reached dimensions(about 2 m height x 4 meters breadth) that have been commonly observed at other times of year. Parmerter and Coon (2) have shown there is a limit height of ice ridges that depends on the pressure of converging ice sheets. Thus the magnitude of pressures associated with the July 19 phenomenon may not be unusual.

Precise measurements of ice-soil and ice-ice friction under a variety of environmental conditions should be made at coastal regions subject to impacting ice pressures. Friction and a more detailed knowledge of the cohesive properties of shore and beach soils is essential to precise determinations of shoreline forces and pressures. Continuous records of pressure sensing devices installed at regular intervals along shorelines and ice foots would provide supporting data and possibly useful tidal information (5).

APPENDIX A

SOIL FAILURE MODEL

If the vertical ice wall during ploughing of the beach is considered as a grouser without a top face then β, the characteristic angle of a plate grouser is zero. According to soil failure criteria set out by Harrison (9) and with the angular values for the present case (see diagram in Figure 12), an equilibrium soil wedge is expected. Along ab shear forces are only partially mobilized while along ac they are fully mobilized making ac a true failure plane. The degree of mobilization of shear forces at ab is measured by the ratio

$$\frac{\tan\delta}{\tan\phi} = \frac{C_a}{C}$$

where $\delta = \tan^{-1} \dfrac{\sin\theta'.\sin\phi}{1 - \cos\theta'.\sin\phi}$

and $\theta' = 2(\beta + \theta) - (90^\circ + \phi)$

If $\phi = 45^\circ$ then $\chi = 45^\circ$ from the diagram.

The cross sectional area of the radial zone may be obtained from

$$\frac{r_o^2}{2} \int_o^{\phi/2} e^{2\omega\tan\phi} d\omega$$

$$= \frac{r_o^2}{4\tan\phi} \left[e^{\pi/4} - 1 \right]$$

where $r_o = ac$

and ω varies from o at ac to $\phi/2$ at ad.

This expression is useful when deducing the total volume and weight of ploughed material.

APPENDIX B

BEACH EXPERIMENTS TO DETERMINE SOIL MECHANICAL PROPERTIES

In an effort to obtain an apparent coefficient of cohesion, C, and an apparent internal friction coefficient, tan δ, a series of ploughing experiments were conducted at Lincoln Bay. Steel dredgers in the shape of a grouser and top plate plus two side plates were used as the ploughing agent. These were pulled by an electric winch and cable with a dynamometer interposed (figure 13).

In one set of experiments, three sizes of dredger were loaded to varying amounts with beach material of varying granularity both wet and dry. The dredgers were hauled up a shallow slope near the water's edge on the beach (west of point P). The weight of soil per unit area normal to the surface was plotted according to the Coulomb equation against pulling or shearing force for the case of no gouging. See figure 14. Cases 1, 2 and 3 give abnormally high angles of internal friction (54° to 58°). Intercepts for 2 and 3 are negative or low possibly because the load was relatively dry. Case 4 yields a lower apparent friction value that may be applicable to the subsurface of the beach from which the load was taken. The lateral constraints of the dredgers may have had a significant effect on the results. The photograph in figure 15 shows an ice block after July 20 that had slid down a shallow slope under gravity indicating that ice-soil interface friction can be very low. Ambient temperature throughout the period of measurement was just above freezing.

The earth moving data that follows have been converted from units of the fps system to that of SI.

Table I

Dredger Dimensions

	Breadth (m)	Depth (m)	Height (m)
Small size	0.373	0.203	0.203
Medium size	0.304	0.304	0.304
Large size	0.759	0.304	0.304

RESULTS USING SMALL DREDGER

CASE 1. SIMULATED LOAD

The dredger load of beach material was similar to commonly observed ice push in the area, being moist and having a naturally occurring grain size distribution.

Beach angle of inclination (θ) = 10^o

Drag of dredger and scale system (P') ≈ 0

Area of base (A) = $0.0757\ m^2$

Table II

Load	Pull(P) on System (N)	Weight (W) of Dredger Plus Load (N)	Weight (W') of Dredger (N)	$\frac{P-W\sin\theta}{A}$ (kPa)	$\frac{(W-W')\cos\theta}{A}$ (kPa)
¼ charge	222	178	116	2.52	0.806
½ charge	355	240	116	4.14	1.62
full charge	511	365	116	5.91	3.23

$\tan\phi = 1.38$

$C = 1.58$ kPa

Note: $\frac{P-W\sin\theta}{A}$ is the shear pressure on the load and can be expressed as H/A

RESULTS USING LARGE DREDGER

CASE 2. SIMULATED LOAD

The load of beach material was moist and contained a grain size assortment similar to that commonly observed in the local ice push, i.e. 0.08 mm to 27 mm.

$\theta = 10^o$

Weight component of dredger plus drag of dredger system opposing motion (P') = 200 N

$A = 0.231\ m^3$

H/A is the shear pressure on the load $= \frac{P - P' - W\sin\theta}{A}$

Table III

Load	Pull (P) on System (N)	Soil Weight (W - W') (N)	H/A (kPa)	$\frac{(W - W')\cos\theta}{A}$ (kPa)
1/3 charge	667	351	1.75	1.50
2/3 charge	1.11×10^3	640	3.42	2.92
full charge	1.87×10^3	1.02×10^3	6.45	4.34

$\tan\theta = 1.6$, C is negative

CASE 3. LOAD OF DRY COARSE FRAGMENTS (>10 mm)

$\theta = 10^o$

$P' \simeq 200$ N The soil weight measurement was ommitted in error and was assumed to be approximately the same as that of the previous experiment.

$A = 0.230\ m^2$

TABLE IV

Load	Pull (P) on System (N)	P' (N)	H/A (kPa)	$\frac{(W - W')\cos\theta}{A}$ (kPa)
1/3 charge	467	351	0.794	1.50
2/3 charge	845	640	2.27	2.92
full charge	1.47×10^3	1.02×10^3	4.72	4.34

$\tan\phi = 1.38$, C is negative

CASE 4. DENSE WET LOAD OF FINE BEACH SUBSOIL (< 10 mm)

$\theta = 10^o$

$A = 0.230\ m^2$

$W = 200$ N

TABLE V

Load	Pull (P) on System (N)	(W - W') (N)	H/A (Pa)	$\frac{(W - W')\cos\theta}{A}$ (kPa)
1/3 charge	867	444	2.55	1.89
2/3 charge	1.18×10^3	903	3.55	3.85
full charge	1.85×10^3	1.37×10^3	6.08	5.85

$\tan\phi = 0.932$ $C = 0.414$ kPa

ADDITIONAL HAULING EXPERIMENTS

SOIL VS SOIL

In another experiment to determine approximate values of $\tan\phi$ and C for beach material, the small dredger was pulled up a 17.5° incline of the beach near point P. The depth of gouging was 7.0 cm and the ploughed soil weight was 187N when the pull force registered 890N. Employing a value of C equal to 1.13 kPa which is within the range of two graphical positive values (figure 14) and $\tan\phi = 1$, $\alpha = \beta = 90^\circ$, $\theta = 0^\circ$ and $\tan\delta = 0.333$ then using equation {4} for computing draught, the total bulldozing force is estimated to be 890N. The large pull force may therefore easily be explained for a moderately high value of C if $\tan\phi$ is also high.

ICE VS ICE

Experiments of winching ice, in an advanced stage of rotting, over the surface of a nearly level grounded floe were carried out. The medium sized dredger not touching the floe surface was placed behind the ice sample to be pulled horizontally. Forces of 845N and 979N were required to haul weights of 231N and 578N respectively. The surface friction of the ice apparently as a consequence of its slushy or rotten state is anomalously high when compared to published figures (10).

ICE VS SOIL

Calculations of ice-beach interface friction vary between 0.47 and 1. For calculations of maximum ice pack force it was decided to use $\tan\phi = 1$. Experimental results were highly inconsistent as is revealed in the following table:

TABLE VI

Pull Force (N)	Beach Angle of Inclination (degrees)	Weight of Ice (N)	Weight of Ice Push (N)	Angle of Interface Friction (degrees)
445	25.5	476	0	29
645	8	476	122	33
645	26	476	0	45
1.13×10^3	0	1.02×10^3	81	44
1.33×10^3	20	1.02×10^3	240	25

A contributing error in the determination of ϕ would have been in the estimation of the weight of ice push.

APPENDIX C

ICE DENSITY, SALINITY AND TEMPERATURE

This appendix is included as a source of supporting data. Ice density was taken as 0.83 Mg/m^3. This is an average of three determinations from newly grounded ice floes. Large cubes of about 0.1 m on a side were cut out of side faces of the floes with a chain saw and weighed on site within one day after the pressure event. Density determinations from smaller salinity samples taken six days after the event appear in Table VII to have an upper limit of 0.83 Mg/m^3. The samples were taken from a side face of a grounded floe designated as floe 1. Salinity was measured with a refracting salinometer. The low densities are indicative of increasing porosity with brine drainage.

TABLE VII

Distance from top surface of floe 1(m)	Density (Mg/m^3)	Salinity ($^o/_{oo}$)
0.15	0.535	0
0.38	0.606	1.6
0.46	0.760	1.6
0.91	0.828	1.6
1.2	0.681	1.1

Ice temperature was measured to be zero degrees centigrade on the top and side surfaces of grounded floes.

Other salinity determinations (Table VIII) taken seven days after the pressure event show evidence of brine drainage according to samples taken from vertical side faces of two grounded floes. This determination coincides in time with a series of determinations of crushing strength of prismatic samples (Table IX).

TABLE VIII

	Floe 2 at Lincoln Bay	Floe 3 at Lincoln Bay	Floe 4 on Ice Foot of Robeson Channel	Floe 5 at Lincoln Bay	
Distance from top surface(m)	Salinity ($^o/_{oo}$)	Salinity ($^o/_{oo}$)	Salinity ($^o/_{oo}$)	Distance from top surface(m)	Salinity ($^o/_{oo}$)
0	0	0	0	0	0
1	1.1	2.1	1.1	0.33	0
2	2.1	2.1	1.1	0.67	0
3	2.6	1.8	4.4	1.0	0
4	2.1	5.4	15.1		

STRENGTH OF GROUNDED ICE

Prismatic ice samples of low salinity between 1.6 and 0 $^o/_{oo}$ were tested vertically for crushing strength at Lincoln Bay seven days after the pressure event. The samples in situ had either a vertical or horizontal orientation. The fracture direction could be clearly identified only in five of the samples tested. In two cases fracture was vertical in samples that were vertical in situ probably because of the direction of candling (8). The rate of loading was greater than the required 0.5 MPa/s (8). The results are given in Table IX.

TABLE IX

Ice temperature = 0°C

Dimensions (cm)		Crushing Strength	In Situ Orientation	Fracture Direction
length	sides	(MPa)		
3.8	2.5 x 2.5	1.0	vertical	
5.3	2.5 x 3.6	1.2	vertical	
5.3	2.5 x 3.3	0.92	vertical	
5.0	2.6 x 3.3	1.2 to 1.3	vertical	
5.6	2.6 x 2.5	1.6	horizontal	
5.0	2.7 x 2.6	1.0 to 1.4	horizontal	
5.5	2.7 x 2.4	1.6	horizontal	45°
5.0	2.5 x 2.5	3.1	vertical	vertical
5.0	2.8 x 3.0	0.69	vertical	vertical
5.0	2.5 x 2.3	0.69	vertical	
4.8	2.5 x 2.2	0.86	horizontal	
5.0	2.4 x 3.0	0.841	horizontal	
3.9	2.5 x 2.8	2.8	horizontal	
4.7	3.0 x 2.6	1.3	horizontal	45°
5.8	2.7 x 2.8	1.2	horizontal	
5.8	3.2 x 3.6	0.68	horizontal	45°

The arithmetical average crushing strength is 1.3 MPa. Also there is no perceptible strength difference between in situ vertical and horizontal samples.

Brine volume, ν_b, being over 500 °/oo at 0°C thus $\sqrt{\nu_b} \simeq 0.7$ (11). Where $\sqrt{\nu_b} > 0.6$, compressive strength reaches some low limiting value (8). When $\sqrt{\nu_b} > 0.4$, ring tensile strength reaches a limiting value of 0.66 MPa (8) and cantilever strength 0.20 MPa. Limiting strength for other forms of testing of samples are as low as the estimated pressures at the Lincoln Bay shoreline and are about an order of magnitude lower than those given in Table IX. There may be a size effect that makes small samples stron However, it is expected that the crushing phenomenon of high temperature ice during summer in the Robeson Channel is less frequent than breaking in flexure

ACKNOWLEDGEMENTS

Thanks are due to Mr. G. St. Germain who, using facilities of Algonquin College, Ottawa, Ontario carried out the seive analysis of beach material from Lincoln Bay. The author also thanks Dr. T. Frisch of the Geological Survey of Canada, who supplied descriptive information concerning the siltstones, shales and slates found at Lincoln Bay; and Mr. J. Keys from whose experimental results for the Robeson Channel, some wind velocity data was taken.

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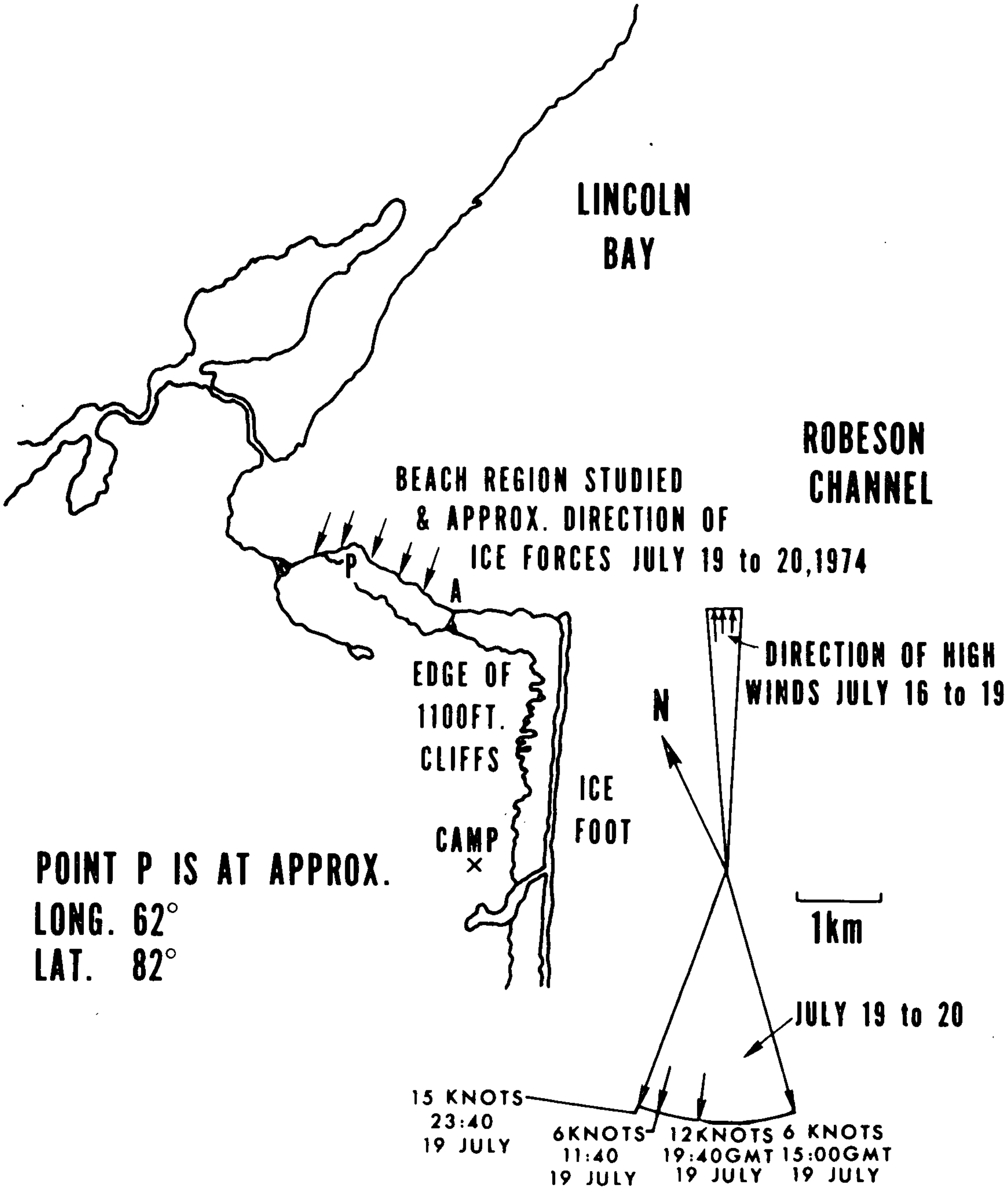


Fig. 1 Sketch of Experimental Site on Lincoln Bay

Fig. 2 Grounded Ice on Lincoln Bay West of Point "P"

Fig. 3 Grounded Ice at Lincoln Bay, South-East of "P". Ice Pushed Up Bank Some 8 Metres.

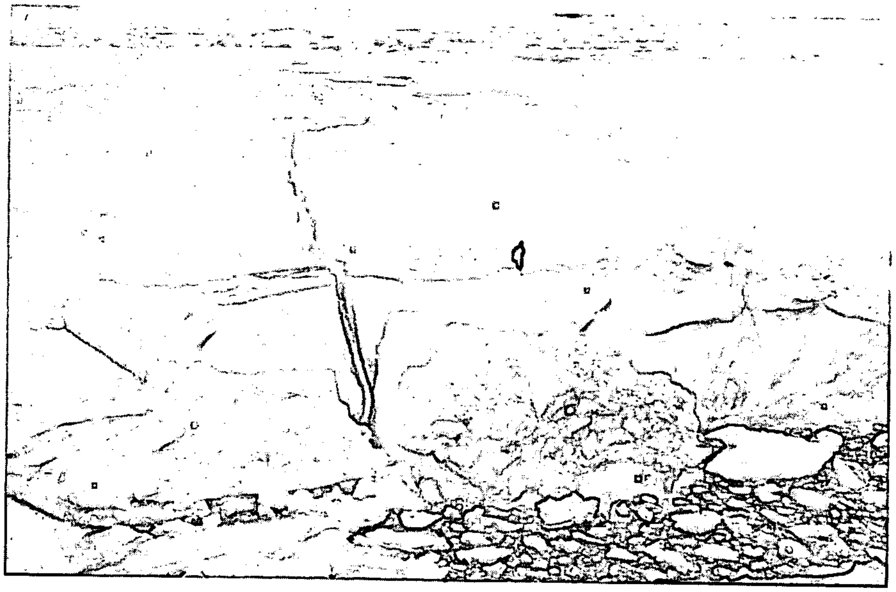


Fig. 4 Portion of Grounded Massive Ice Block at Lincoln Bay

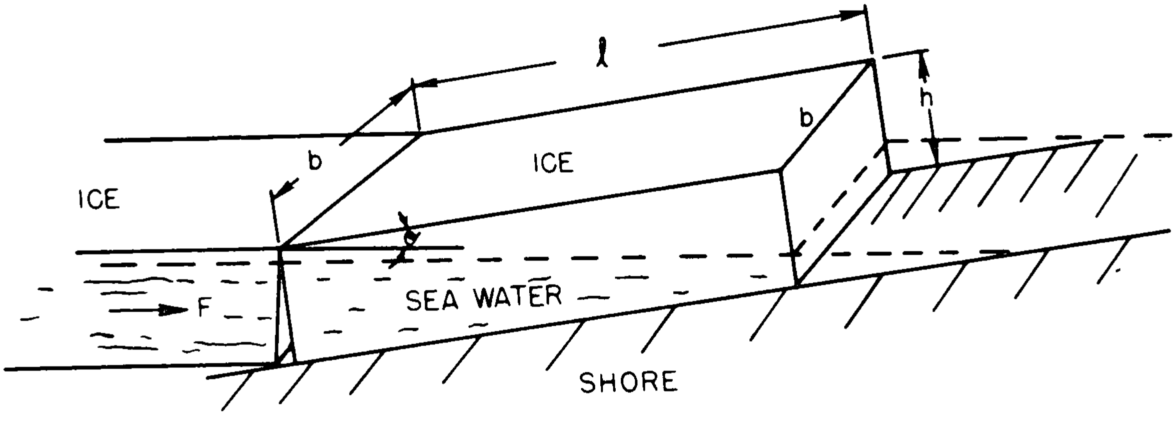


Fig. 5 Diagramatic of Ice Block Moving On Shore

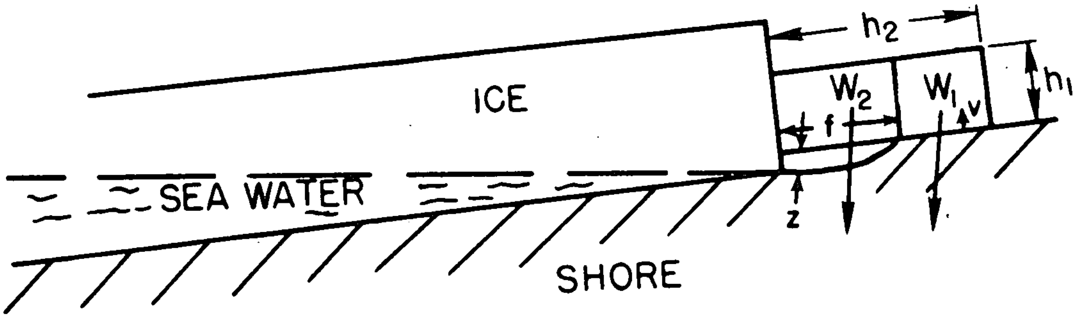


Fig. 6 Diagramatic of Ice Block Moving On Shore and Ploughing Up Beach Material

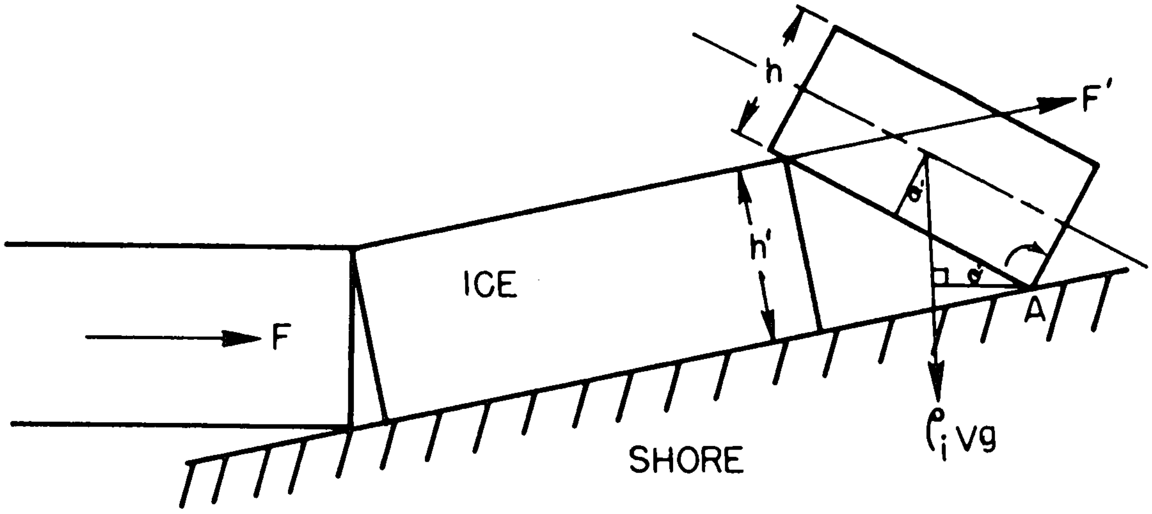


Fig. 7 *Diagramatic of Ice Block Overturning Another on the Slope of the Shore.*

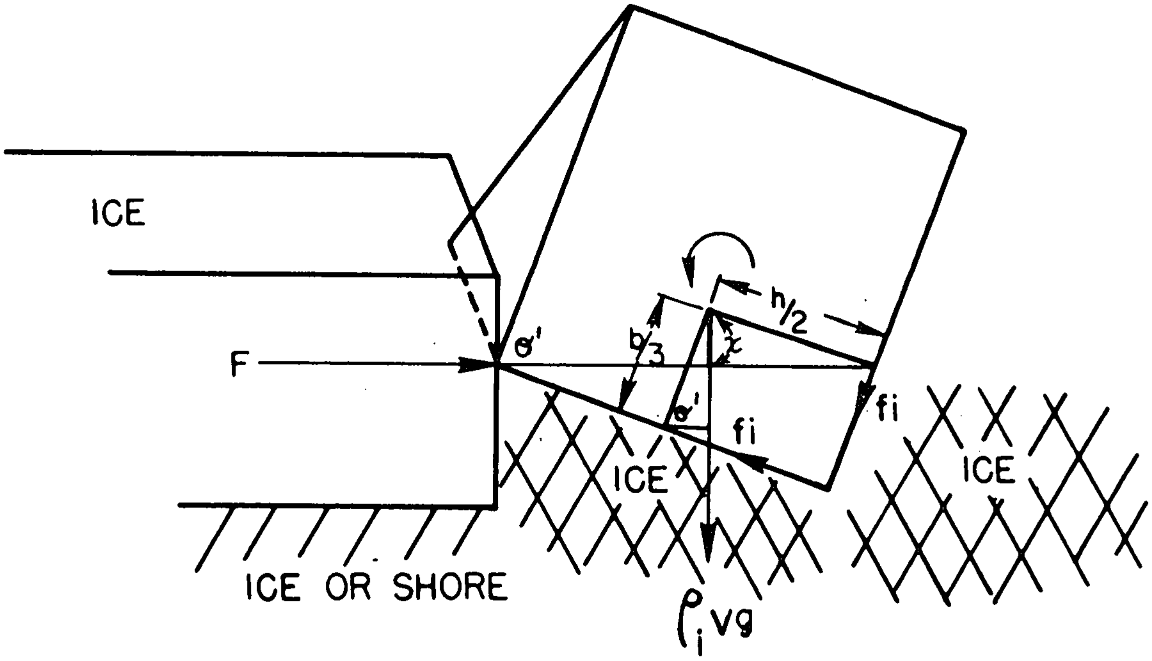


Fig. 8 *Diagramatic of Ice Block Rotating on Grounded Ice*

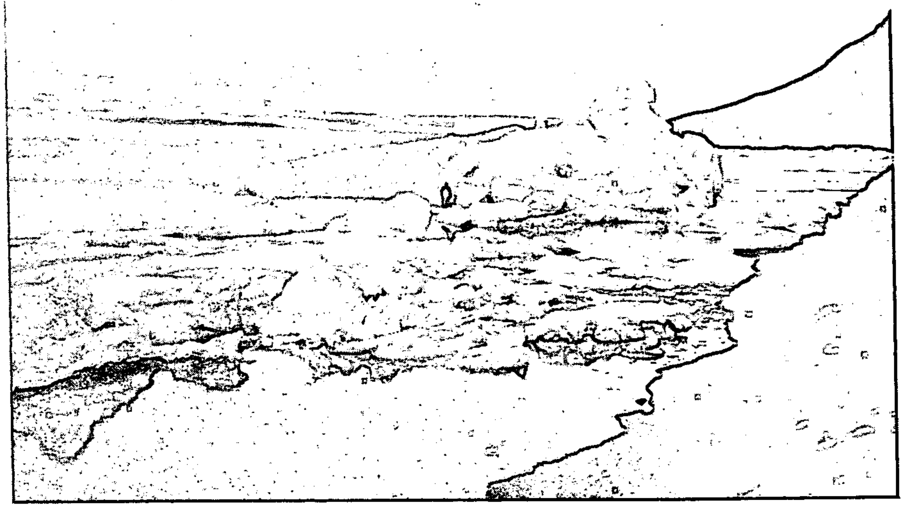


Fig. 9 "Side" View of Massive Block **at** *Lincoln Bay. (See Figure 4)*

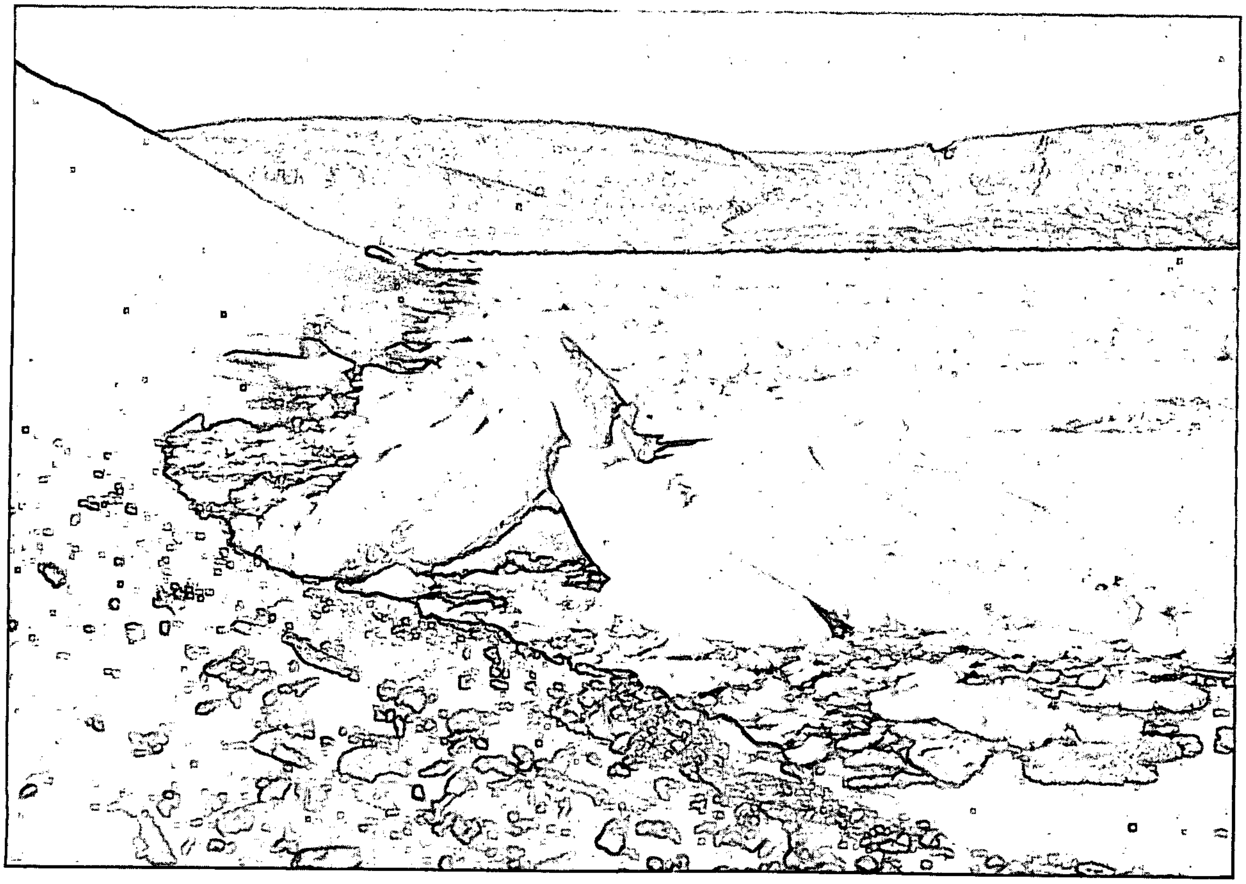


Fig. 10 Ice Block Upended Near "A" in Figure 1 on Lincoln Bay

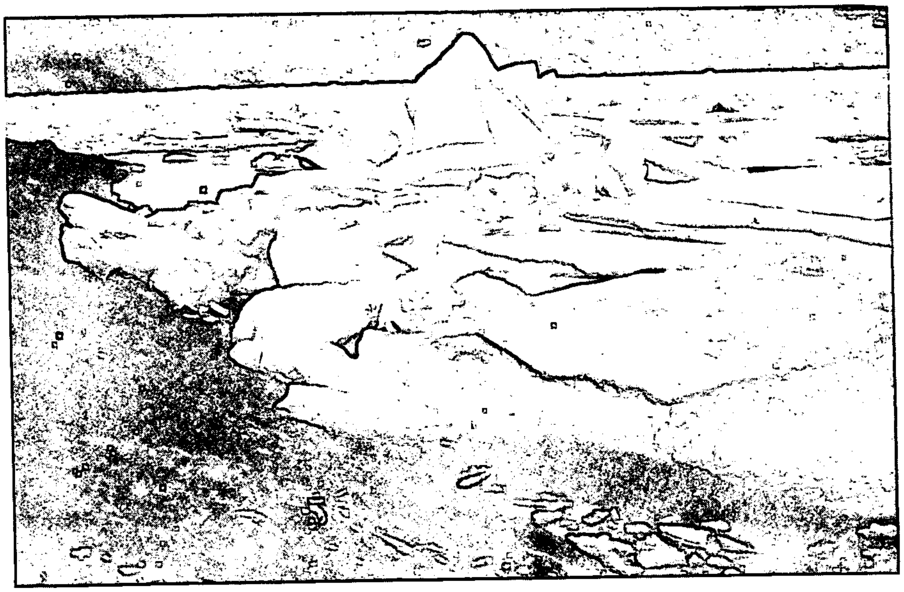


Fig. 11 Wedge Shaped Ice Blocks Just After Rotation

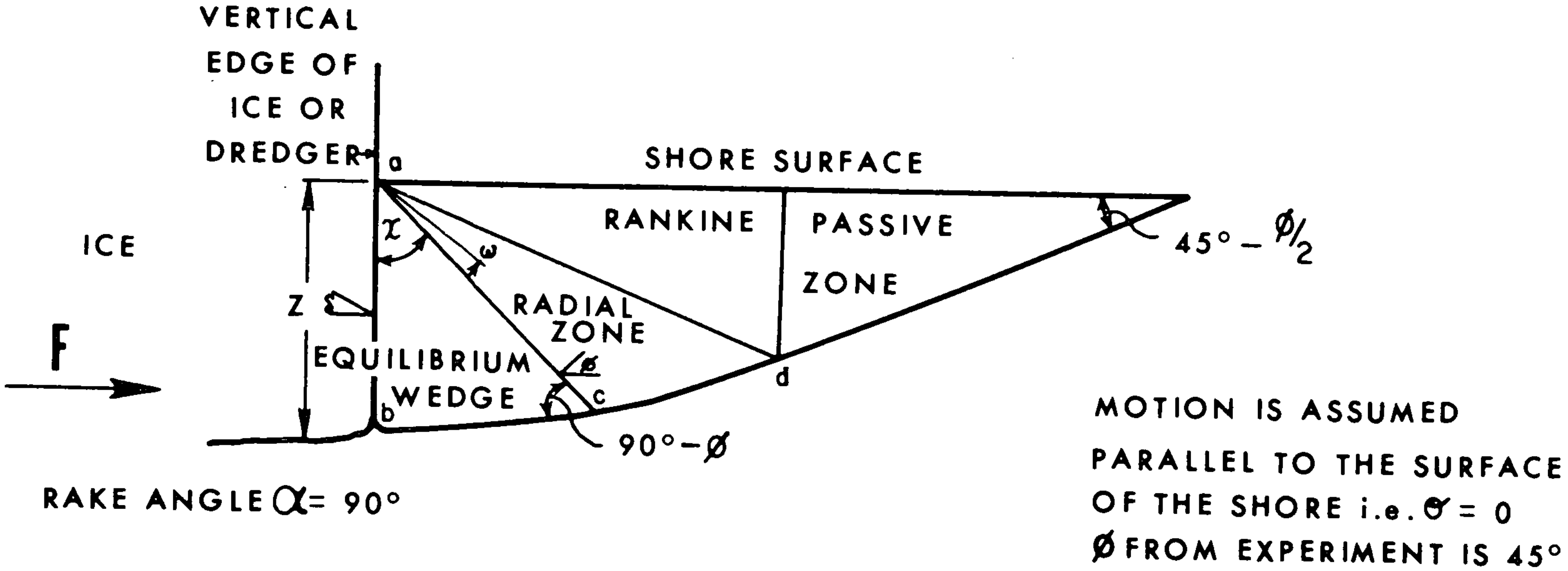


Fig. 12 Soil Failure Model in Cross Section

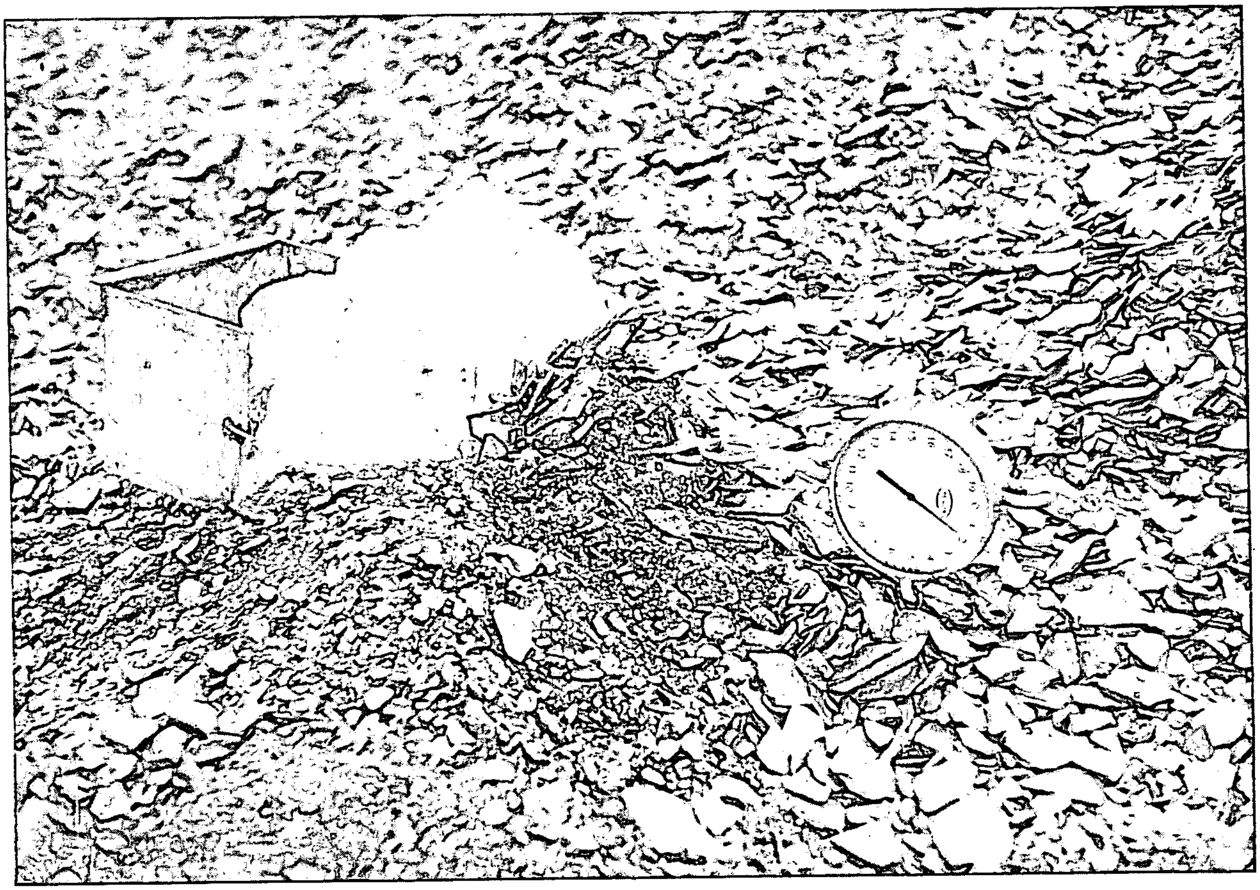
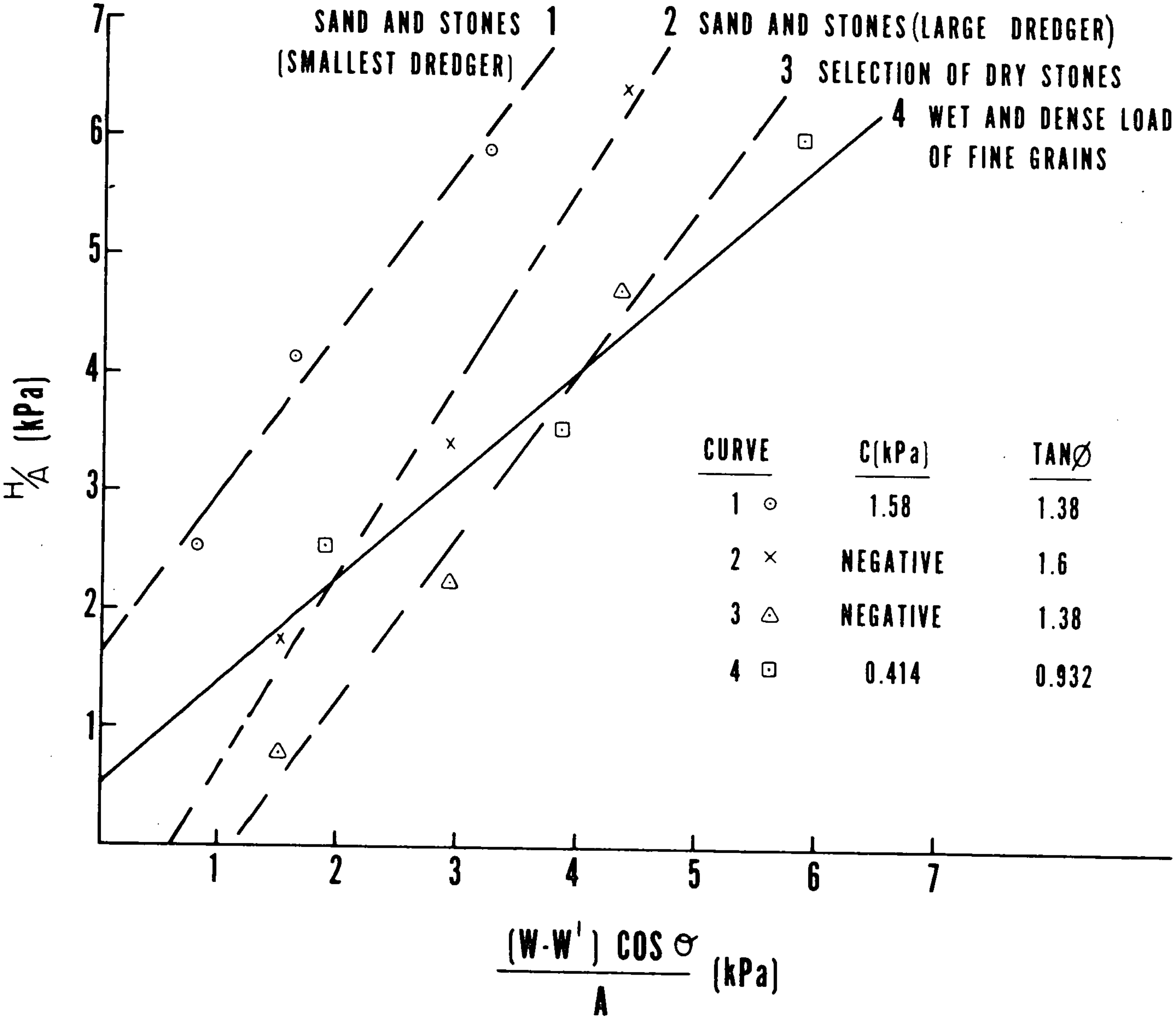


Fig. 13 Experimental Combination of Dredger, Sample Ice Block and Dynamometer Used at Lincoln Bay



CURVE	C(kPa)	TANØ
1 ⊙	1.58	1.38
2 ×	NEGATIVE	1.6
3 △	NEGATIVE	1.38
4 ⊡	0.414	0.932

Fig. 14 Determination of Apparent ϕ and c

Fig. 15 Grounded Ice that Apparently Slid Back Down Slope a Few Days After the Pressure Event

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1. ORIGINATING ACTIVITY Defence Research Establishment Ottawa National Defence Headquarters, Ottawa, Canada. K1A 0Z4	2a. DOCUMENT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. DOCUMENT TITLE

ICE PRESSURES AT THE SHORE OF LINCOLN BAY

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

5. AUTHOR(S) (Last name, first name, middle initial)

Irwin, Gerald J.

6. DOCUMENT DATE August 1975	7a. TOTAL NO. OF PAGES 34	7b. NO. OF REFS 11
8a. PROJECT OR GRANT NO. 97-67-05	9a. ORIGINATOR'S DOCUMENT NUMBER(S) 729	
8b. CONTRACT NO.	9b. OTHER DOCUMENT NO.(S) (Any other numbers that may be assigned this document)	

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With increasing offshore activity in the Canadian Arctic Archipelago, there is continuing need for more detailed knowledge of forces and pressures of pack ice acting in coastal regions. In July 1974 pack ice acting on the shores of Lincoln Bay, N.W.T. presented an opportunity for making an order of magnitude determination of sea ice pressure in the littoral zone. From considerations of ice uplift, block dimensions and density, moments in turning an ice block, and effort in ploughing beach material, horizontal pressures at the shore were calculated to be of the order of 0.1 MPa. Such a value, if typical of impact pressures at a protected portion of the Ellesmere Island coastline, indicates that ice floes grounding on shore should pose little threat to many types of shoreline installation.

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Sea ice force
Sea ice pressure
Shoreline
Ice push
Ploughing
Beach
Shore
Interface friction
Coefficient of cohesion

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PROJECT NO: 97-67-05

TITLE: Ice Pressures at the Shore of Lincoln Bay

AUTHOR: G. J. Irwin

DATED: October 1975

SECURITY GRADING: UNCLASSIFIED Initial distribution: November 1975

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