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THE INTERACTION BETWEEN ICE AND COASTAL STRUCTURES

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Abstract - Two subjects are dealt with. One is piling up ice on shores and coastal structures. The other is the "beach ice" phenomenon occurring in Alaska.

1. PILING UP ICE ON SHORES AND ON COASTAL STRUCTURES

The part of the ice/shore and ice/ shore-structure interaction which has particular interest in this section is the piling up of ice on or in front of a shore or shore-structure.

The forces which cause piling up of ice are due to winds and currents. Wave forces are only in action when the belt of ice in front of the shore-structure is so narrow that waves penetrate through the belt without losing all their energy by damping effects.

The shear force by wind may be written:

$$T_w = \frac{1}{3600} \cdot u_w^2 \ (kp/m^2), \text{ when } u_w = \text{wind velocity in m/sec}$$

The current force on ice may be written:

$$T_c = \frac{1}{4} \cdot u_c^2 \ (kp/m^2), \text{ when } u_c = \text{current velocity in m/sec}$$

As an example, an ice cover extending 100 km out from the coast or from a coastal structure acted upon by winds of 30 m/sec (10 Beaufort) or a current of 1 m/sec, will be driven against the coast or against the structure by a force of 25 tons per meter ice front causing a compressive stress of 12.5 kg/cm² with an ice thickness of 20 cm. Assuming a compressive strength of 8.8 kg/cm² (125 psi), this pressure will cause the ice sheet to break by vertical deflections, crushing or in case of less extensive structure (width < $15 \cdot t_{ice}$)

by splitting. As a result, shores and coastal structures may become exposed to ice pilings, the extent and geometry depending upon depth, frontal slope and roughness, ice-structural characteristics etc.

Piling up of ice was investigated by examining field data in Scandinavia and in the United States. Some qualitative laboratory experiments were also undertaken.

Field data from Scandinavia

Nordre Røse Lighthouse is located in the Sound between Sweden and Denmark at Copenhagen. A cross section is shown in Fig. 1. The dashed lines indicate the design before the reconstruction in 1893. This lighthouse was exposed to considerable ice piling in 1892 and in 1956. In 1892 the ice reached an elev. of ab. 10 m above sea level (Fig. 2) and in 1956 an elev. of ab. 8 m. Ice first filled up the platform just above sea level. This resulted in a nearly straight ice slope from the water line up to the top of the deck upon which the ice piled up easily. The resulting slope of underlying ice was somewhat steeper than the slope was before the reconstruction. This together with "the delay" due to the platform caused less piling on the lighthouse than before the reconstruction.

Fig. 3 (March 1963) shows ice climbing the 1:2 slope rubble mound breakwater at Knudshoved ferry-port on the Great Belt in Denmark. Maximum elevation of the ice was ab. 8 m. The ice caused considerable damage to the armour layer. Knudshoved was also exposed to ice piling in February 1941, when the ice climbed the breakwater up to elevations of ab. 8-9 m. The ice floes were ab. 0.4-0.5 m thick and up to 20 m floes were found on the lee-side of the breakwater. Many ports which occasionally are subjected to strong ice drift, have experienced that ice does not climb vertical faced structures if the depth in front of them exceed ab. 5 m. An example of ice piling in front of a vertical structure is shown in Fig. 4, the Port of Hälsingborg on the Øre-sound between Sweden and Denmark. The depth in front of this breakwater varies from 6 to 11 m.

In the Danish seas, particularly at the Øresund, (sound between the Danish island Seeland and the southernmost Swedish province Skaane), ice piling of ab. 10 m or more takes place as a result of wind and current action, particularly at sloping shores, while ice piling hardly ever occurs at vertical walls if the water is not very shallow in front of them. A typical example of ice piling on a sloping shore is shown in Fig. 5, which is from the shore near Hamlet's castle KRONBORG, at the entrance of the Sound in Denmark.

Fig. 6 shows a 5-6 m high ice piling which according to P. Tryde, Techn. University of Denmark, built up in ½ hour in the Sejrø Bay, the island of Seeland, Denmark (1956).

Field data from Lake Superior

At Duluth, Lake Superior, northeasterly winds cause westward ice drift. When the ice runs aground on the shore or is stopped in front of coastal structures, it builds up pressure ridges above the surrounding field usually at some distance from the point of contact. Storms may form more ridges in front of the first ridge. Before Lake Superior froze over during the 1966/67 winter season, a total of three ice-ridges developed west of the Superior Entry. Surveys revealed that ice climbed to 9 m elev. on a rock reef with slope 1:5 to 1:10 (Fig. 7). The actual thickness of the ice from bottom to crest of ice pile may have been of the order 9 to 12 m. Ice pilings of various heights were observed on all slopes. Vertical walls however, did not cause ice pilings.

Summary of results of field observations

Based upon observations in the field the following general conclusions may be drawn:

(a) Sloping shores and structures favor ice piling. As a result of wind and current forces, ice may pile up to elev. of 10 to 15 m above still water level.

A berm or platform incorporated in the structure caused somewhat less ice piling than a corresponding straight rubble mound mainly due to the "delay" obtained in filling up the platform with ice.

(b) Vertical walls do not favor ice piling. If the depth in front of the structure is sufficient the ice does not climb but is rather forced down. When depth in front of the structure including any filling e.g. in the form of a rock mound was more than 5 m, no piling up took place in most cases, but with 4 m depth piling occurred at Nordre Røse and at Hals Barre Lighthouses in Denmark. This does not allow the conclusion that 4 to 5 meters is a "critical depth". Such depth must depend upon the actual exposure. Cases mentioned in this paper are examples on medium to heavy situations. In Lake Superior ice ridges formed at depths up to approx. 4.5 to 5.5 m which is in agreement with the experience from Denmark.

LABORATORY EXPERIMENTS

An effort was made to produce a realistic model of ice piling on an unyielding boundary. Tests were run in a 1:30 scale hydraulic model based on Froude scaling. The hydraulic forces, water movement and the dynamics of the individual ice floes therefore were scaled correctly as the density of the model ice was the same as for natural ice. The break up of big ice floes and the climbing of ice on structures not only depends on the geometrical conditions (depth in front of the structure and the slope of the structure) but also on the strength of the model ice. Attempts were therefore made to produce the strength of the model ice to the scale of the hydraulic forces. It was difficult to scale other properties such as elasticity and friction adequately. The ice produced consisted of paraffin, oil, charcoal and sand and in accordance with the 1:30 model scale, the compressive strength varies from 0.8-2.0 kp/cm^2, and the tensile strength from approximately 0.5-1 kp/cm^2. It was neither particularly adhesive nor remarkably brittle.

The model tests were carried out in a 60 cm (18 m prototype) wide flume. The length of the ice cover was 7 m (210 m in the prototype). A slab was used as an imitation for a coastal structure or a beach.

Producing ice piling in a laboratory by means of wind or current shear stresses however, requires a much longer flume than was available. A simulation of the conditions in nature was aimed at by pushing the steel slab against the ice sheet. A fixed structure at the other end of the ice field formed an unyielding boundary.

Two sizes of ice floes were used as shown in Table 1.

Table 1

Ice data	Thickness of ice model (Prototype)	Size of ice floes model (Prototype)
Test 1	1.5 cm (0.45 m)	80-100 cm^2 (ca. 10 m^2)
Test 2	2.5 cm (0.75 m)	0.3-0.6 m^2 (270-540 m^2)

With the smaller ice floes it was very difficult to get any particular ice piling because they started rotating before any considerable horizontal force in the ice sheet built up. Thus a barrier or a ridge formed in front of the sloping structure and occasionally also somewhere between the limiting boundaries as well. In case of the larger rectangular ice floes, however, the ice sheet was more stable. As the width of the two ice floes placed side by side in the flume was slightly less than the width of the flume, side friction effects were negligible.

Although friction between the ice floes and the steel slab was rather high, ice pilings occurred for slopes as steep as approx. 30 degrees. For steeper slopes the ice floes rotated in front of the structure forming a similar ridge as mentioned above. For vertical boundaries, however, the ice sheet did not buckle although a slight crushing was observed at the boundaries.

To get ruptures of the ice sheet due to vertical deflections maximum length of the ice floes that could be produced was still far too small. It is necessary to produce a homogenious and nonfissured well defined model ice to get fully realistic tests. The tests however, described prototype conditions qualitatively right.

DISCUSSION ON ICE PILING

The reason why ice does not pile up to "infinite height" probably is the same as the reason why a bulldozer regardless of how powerful it is can only pile rubble up to a limited height. Consider a slope or pile of ice blocks of relatively regular size and weight. These blocks rest on a layer of similar type ice blocks or plates. Each block is now replaced by a spring which represents the mass of the ice blocks and its "possibility for movement". This is indicated in Fig. 8 by two different signatures for the same spring. It may be noted that the coefficient of elasticity of the "armour layer" of ice (E_S) is not directly related to ice properties but to the porosity of the ice mound or rather to the possibility for movement of blocks. This in turn is related to the geometry of the ice blocks and to the friction between the blocks in all directions. Considering forces parallel to the slope the following force balance equation may be written assuming blocks of similar material characteristic, but of varying overall "elasticity coefficient" or "possibility for movement", the same slope angle α but with friction angle ϕ depending upon "local circumstances".

$$P/\cos\alpha = \underset{(a)}{\Sigma_1^n w \sin\alpha} + \underset{(b)}{\Sigma_1^n E_S \,\Delta s} + \underset{(c)}{\Sigma_1^n w \cos\alpha \,\mathrm{tg}\, \phi} \qquad (1)$$

It is clear that as P does not increase infinitely there must be certain limits for the number of blocks which it is able to move when forces by "elasticity", gravity and friction shall all be overcome. This means that there is an upper limit called u (upper) for n determined as

$$P_{max/\cos\alpha} = \underset{(a)}{\Sigma_1^u w \sin\alpha} + \underset{(b)}{\Sigma_1^u E_S \,\Delta s} + \underset{(c)}{\Sigma_1^u w \cos\alpha \,\mathrm{tg}\, \phi} \qquad (2)$$

As members (a) and (b) of eq. (1) increase with α while members (c) decrease it is obvious beforehand that the max climbing elevation is not related to a certain angle of the slope but that ice strength, block and mound characteristics incl. the geometry of ice blocks and the permeability of the mound are important parameters. If the ice is very strong, it is able to transfer a higher force at point A in Fig. 8 without being crushed. At the same time it will however, tend to break in larger pieces and the mound, which results from such ice, may therefore tend to have more voids. This situation may finally decrease members (b) while at the same time a higher degree of irregularity of the mound may tend to increase members (c).

The ice which causes piling is usually limited in thickness to less than 1 meter and most of it is less than 0.5 meters. Its moment of resistance therefore is limited. According to ref. (3), referring to Russian authors (Korzhavin et al), the length of the block before breaking can only be approx. three times the thickness of the ice.

The thickness of the ice in a piling therefore has an influence on the geometry of the piling. Considering again Fig. 8; When relatively small ice blocks pile up, the pile will tend to be rather dense (less voids). Consequently it includes many "springs" with a relatively "even" spring constant as well as friction coefficient. The pressure transferred from the ice field to the pile is absorbed gradually by "spring" and friction action with the result that it vanishes in the upper part of the pile. Consequently there is an upper limit for the elevation of the pile. When this elevation has been reached, the pile does not increase in height, but in width. The slope angle needless to say, has an influence on the pile up, but as slope angle decreases, friction increases while spring forces may decrease. Larger (and thicker) blocks cause spring action to become more irregular due to larger voids making the surface of the mound rougher, increasing friction forces. The result is that the pile will tend to get wide rather than high (compare Fig. 3 from Knudshoved ferry port, Denmark to Fig. 5 from Kronborg, Denmark).

The final geometry of the pile, en gros as well as en detail, must be considered as an integrated result of maximazation of forces Σ F in eq. (2) and experience so far is that for slopes of approx. 1 in 1 to 1 in 2 the max pile up normally is of the order of 8 to 10 meters (25 to 35 ft). It should be noted however, that the structural slope is not identical with the ice slope when ice rests on ice and ice may creep up higher on gentle slopes before ridges form by buckling.

The situation described above is comparable to piling by a bulldozer of very rough, large size material e.g. heavy concrete rubbish or broken road pavement. The pile tends to be wide and relatively low because a number of vertical pieces in the pile present hindrances to further increase in elevation. Contrary smaller size e.g. structural rubbish of smaller size, brick and concrete may be pushed up as high as horsepower permits, still without having the dozer climbing the pile itself.

Allen's formula based on theory published by the National Research Council of Canada in November 1970 (ref. 1) gives the relation between height of ice h, effective ice pressure p, ice thickness T, density of broken ice in pile ρ, coefficient of internal friction within the ice pile f, and slope angle β

$$h = \sqrt{\frac{2\ p\ T}{\rho\ (1 + \frac{f}{\tan\beta})}} \qquad (3)$$

According to this expression the height of the ice piling increases with increase of the pressure exerted by the ice and with increasing slope angle. It decreases with the density of the broken ice in the pile and with increase of friction.

Allen's theory may present an oversimplification however, as ρ, f and β are not independent. With a decrease in ρ due to higher permeability caused by larger blocks, f may increase and the combined result may be a decrease in h with a decrease in ρ causing an increase in f. This is probably what happens in the case of large thick blocks. Furthermore when piling has started the structural slope angle may become immaterial as explained earlier.

From the above mentioned it is obvious why ice does not pile up in front of a vertical wall. All forces exerted on ice by water and wind are horizontal forces. Vertical forces are gravitation only. Complex vertical forces however, develop when ice starts buckling. Probably due to friction buckling never seems to start right at the vertical wall but at a certain distance from it. At the wall itself where ice may have been crushed, it will rather tend to be forced down against buoyancy forces than to be lifted up against gravity. With increasing thickness of the crushed ice possibilities for piling up vertically increase as a slope gradually may develop above the ice field. When the layer of ice at the vertical wall has reached down to the bottom, ice can only climb up as reaction to the pressure exerted upon it. This is undoubtedly the reason why ice never seems to pile up at vertical walls in deep water while it may pile up in shallow water. It may however, develop one or more ridges at a certain distance from the wall. Furthermore ice ridges form in deep water when floes are forced against each other.

An obstruction like a lighthouse placed on a caisson in relatively shallow water like Fig. 1 may initiate piling on either side particularly if it is located in an area with rather strong currents or in areas where currents and winds sometimes blow in the same direction. Comparing the earlier mentioned expressions

$$T_{wind} = \frac{1}{3600} u_w^2 \ (kp/m^2) \text{ and}$$

$$T_{current} = \frac{1}{4} u_c^2 \ (kp/m^2)$$

One has for a 30 mph wind (~50 km/h = 14 m/sec)

$$T_{wind} = \frac{1}{3600} \cdot 14^2 = 50 \text{ kp per meter}$$

and for a 2.5 knot current = 1.2 m/sec = 4 ft/sec
assuming a 1 km ice cover:

$$T_{current} = 360 \text{ kp per meter}$$

or a total of approx. 400 kp per meter. This force may push a 1 ton ice floe up a 1 in 3 slope while it will probably not cause any crushing against a vertical wall. If water is rather shallow as e.g. in the case of a lighthouse built on a shoal, ice piling may start building up on either side of the obstruction "widening" its effect considerably beyond its geometrical limits. This has been observed at many offshore lighthouses e.g. at Nordre Røse (Figs. 1 and 2).

2. BEHAVIOR OF BEACH ICE, KNIK ARM, ALASKA

In Cook Inlet, Alaska, particularly in its innermost parts, the Turnagain Arm and the Knik Arm, two entirely different types of ice occur. One is the normal ocean or sea ice which results from freezing of undercooled surface water at rest. This process sometimes is advanced in fiords due to freshwater run off causing lower salinity or even a freshwater sheet in the upper surface layers. Such ice may occur in very large floes. In case of an almost full ice cover as found in most parts of the Arctic Ocean the thickness of the ice excluding ridges may be up to 7-8 ft with open cracks resulting from shear forces by currents and/or winds. In the Cook Inlet large ice floes of 0.5 to 1 million square meters, 1.5-3.5 ft. thick may also occur but generally speaking floes are much smaller. Fig. 9 shows an airial photograph from the inner part of Cook Inlet at Anchorage (Febr. 1971). These floes often consist of a number of broken ice floes of smaller size frozen together at slack water periods. Max size may be a few thousand m^2. Geometrically there is a tendency for all floes to be elliptical with a smooth periphery and no protruding corners. The strong tidal currents carry them back and forth and rub and crush them up against each other which results in a "practical floe geometry" offering maximum resistance to crushing, shearing and bending in almost any situation. These "thin" floes tend to float with their longest dimension parallel to the stream lines which tendency may be noted from Fig. 10 in front of the area just below the shoals in Knik Arm. It is demonstrated somewhat clearer in Fig. 9 in the vicinity of the Anchorage Harbor where ice floes have jammed closest to shore in a random pattern tending to fill all "voids" as much as possible, while closer to the middle part of the Arm floes, can move more freely and orient themselves as described above just like a vessel would tend to do. The driving force for the blocks is shear stresses by tidal currents. When ice floes meet an obstruction the ice breaks up. The mode of failure such as buckling, crushing, bending and splitting is governed by the relationship between structural geometry and ice thickness. A considerable amount of literature is available on this topic e.g. published in the Proceedings of the IAHR Ice Symposium in Reykjavik, Iceland, 1970. Ref (7) by C.R. Neill, summarizes the results of field experiments on bridge piers subjected to pressure by 3 ft ice by stating that the upper limits range from 8.4 to 17.6 kg/cm^2 or 120 to 250 lbs/sq in. Similar figures are revealed from results of ultimate strength analyses of old piers which have been subjected to heavy ice forces but are still standing. Peyton (ref. 8) mentions results of field tests at platforms in Cook Inlet. It was observed that the failure mode of the ice is direct compression. No significant tension cracking of the ice floes occurred. The most interesting results of test pile studies were that the largest ice forces occurred when the ice velocity was very low or almost zero causing ratcheting failure. The actual rate of loading for this type of failure was somewhere between 0 and 50 ft per minute while normal high velocity failure might have been as high as 600 ft per minute. Field samples were collected and direct compression strengths were determined over a range of load rates and temperatures. Highest failure strength was approx. 300 psi. (approx. 22 kg/cm^2) for a very low load rate. At more normal load rates of 6,000 to 8,000 psi/min failure strength was approx. 120 psi or 8 to 10 kg/cm^2.

The flexural strength of ice investigated e.g. by Assur (ref. 2) and Frankenstein (ref. 4) is of the order of 2.5 to 7.5 kg/cm^2.

The other type of ice which occurs in Cook Inlet and particularly in the Turnagain Arm and the Knik Arm is "beach ice". Figs. 11 and 12 show ice formations on the beaches of Turnagain Arm. Beach ice is formed on shores subject to high tidal fluctuations, in the above mentioned cases 20 to 30 ft. Fresh-water flow across the beach from wells and creeks moving on the top of the salt water favours the development. The beach ice thickens gradually, the max thickness depending upon the tidal range and upon the structural characteristics of the ice. Snow added to the top may freeze to (weak) ice also. Beach ice also forms on offshore shoals (see Fig. 13 from Knik Arm). When it breaks loose it floats away (Fig. 14), and may run aground on shoals or on beaches further away. Examination of a great number of airial photos reveals that most blocks are rectangular in shape or perhaps triangular or trapezoidal. Most blocks cover areas $< 50\ m^2$ but a few are larger. 50 to 100 m^2 blocks are not uncommon and a very few seem to be 150 m^2 and 250 m^2.

With respect to thickness actual observations demonstrate common thickness of 1.5 to 2.5 m but a few may be much thicker. Theoretically they may become as thick as the tidal fluctuation minus 10% (snow ice on the top disregarded). It is of interest to consider the process which is responsible for the breaking loose of blocks. One may consider two different possibilities. One is breakdown by buoyancy (uplift) forces due to submergence of the block at high tide (Fig. 15). The other is breakdown by gravity forces at low tide following erosion of the beach making the block cantilever out (Fig. 16).

Counting on an overall specific gravity of ice of approx. 0.9 grams/cm^3 the buoyancy force directed upward at flood tide is only approx. 10% of the gravity force directed downward at low tide. Erosion by currents and perhaps minor wave action however, does not start until the beach ice has reached a certain thickness which is able to concentrate current action and cause scour or until reflection from the front side of the block has become so severe that erosion results in front of the beach ice block. As long as the beach ice is thin it may break down by uplift forces (Fig. 15) but as it gets thicker it is undoubtedly the gravity forces caused by erosion which carry the main responsibility for ruptures (Fig. 16). This is in fact also revealed by Figs. 11 and 12 from the Turnagain Arm.

Consider the situation in Fig. 11 where cracks may have formed by creeping in the beach ice at rather regular intervals. Experience comprising examination of field data incl. airial photos shows that floating beach ice occurs in relatively squared blocks. If one assumes various thicknesses of blocks one may compute the relation between thickness and length perpendicular to the shore line assuming ultimate strength of 25 ts/m^2 and 50 ts/m^2 (Table 2).

Table 2 Distances (depths) of ruptures from front side in beach ice for various thicknesses of blocks and ultimate flexural strengths of 2.5 kg/cm^2 and 5.0 kg/cm^2. Areas of blocks assume squared blocks.

Thickness	Depth of block for 25 ts/m^2	Area of block	Weight	Depth of block for 50 ts/m^2	Area of block	Weight
	m	m^2	ts	m	m^2	ts
1 m	2.9	8	7	4.1	16	14
2 m	4.1	16	30	5.8	34	62
3 m	4.9	24	65	7.1	50	132
4 m	5.7	32	115	8.2	67	242
5 m	6.3	40	180	9.1	83	372
6 m	7.0	49	265	10.0	100	540
7 m	7.6	58	365	10.8	116	730
8 m	8.2	67	480	11.6	134	960
9 m	8.6	74	600	12.2	150	1200

Based on field observations all dimensions indicated in Table 2 seem to be realistic. It may therefore be assumed that block ice is formed first by adding successive layers of ice, next by ruptures resulting from erosion by currents possibly combined with wave action causing the beach ice to cantilever in a similar way as observed at calving of glaciers (ref. 9). In the case of wave action it is possible that vibration (fluctuating uplift forces) may play a role for the breakdown thereby causing blocks of lesser size to develop (ref. 9).

From airial photographs it was noted however, that some ice blocks had triangular and a few had trapezoidal shape just as a corner had broken off a rectangular block. Such blocks may have ruptured from a free corner of the beach ice.

The momentum along the rupture line is:

$$M_B = \frac{1}{12} \rho_{br} L^2 \qquad \text{when } \rho_{br} = \gamma h_{br}$$

γ = specific gravity of ice
h_{br} = thickness of block
L = length of free sides of the triangular block

One has: $h_{br} = \frac{\gamma (L^2)}{2 \rho_{br}}$

Table 3 gives values of L for various thicknesses h_{br} of the beach ice from 1 m to 9 m for γ=900 kp/m³, σ_{br}=2.5 kg/cm² and 5.0 kg/cm².

Table 3 Relation between block thickness and block length for γ=900 kp/m³, σ_{br}=2.5 kg/cm². Figures for σ_{br}=5.0 kg/cm² in paranthesis.

H meters	L meters	Area m²	Weight ts
1 m	8 (11)	30 (60)	25 (55)
2 m	11 (15)	55 (110)	100 (200)
3 m	14 (19)	90 (180)	240 (480)
4 m	16 (22)	120 (240)	440 (880)
5 m	18 (25)	150 (310)	700 (1400)
6 m	19 (27)	180 (360)	1000 (2000)
7 m	21 (29)	210 (420)	1300 (2700)
8 m	22 (31)	240 (480)	1700 (3500)
9 m	23 (33)	520 (1050)	4200 (8500)

The figures of Table 3 are also realistic. Triangular blocks as mentioned above have been observed although not as large as the larger sizes of Table 3. Probably due to cracks in the beach ice perpendicular to the shoreline triangular blocks with sidelines as long as those indicated in Table 3 do not develop. Also the 5.0 kg/cm^2 ultimate strength is probably high while the 2.5 kp/cm^2 gives more reasonable dimensions of blocks.

Floating beach ice functions as current tracers and indicate boundary flow phenomena including consecutive boundary eddies and standings waves (Fig. 17) and meanders (Fig. 18).

Examination of photos in detail revealed that ice blocks may travel with any side parallel to the current. Due to their thickness they are undoubtedly moving slower than the surrounding surface waters because surface water velocities are a little higher than velocities 8-12 ft or more below the surface. This will give rise to drag forces on the upper part of the block which are never distributed symmetrically on the block and consequently must cause some tendency to turning and yawing perhaps even rotation. This is a very important fact to consider because in computing forces the geometry of the block greatly influences the "added mass" coefficient, which for sway (broadside) collision e.g. with a bridge pier may rise above 2 for sway collisions of rectangular blocks. For a surge collision it may be 0.5-1. The actual force depends highly upon impact time which means ice properties. A very short impact time e.g. of 0.1 sec duration could cause at least 5 times higher impact force than a 0.5 sec impact time. Ice will be crushed in the impact and cracks may develop through part of the block which will have a decreasing effect on the impact ("shock") pressure. The beach ice blocks at Cook Inlet as described above are "laminated" which makes a rather strong ice.

Consider as an example a rectangular ice block with sidelines a, b and c. This block collides with an obstacle e.g. a bridge pier. During the collision the following situations may occur:

Obstacle and block collide vertical face to vertical face. Assume that pier is rectangular sideline "d" $< a < b$. Weight of ice block is γ abc, crushing strength is X kg/cm^2. Approach velocity is 10 ft/sec. Added mass coefficient equals 1.5 (sway collision) or 0.5

(surge collision).

The force exerted upon the obstacle during the collision depends upon the "penetration time" and the crushing strength X kg/cm^2. According to experience X may preliminarily be set to 5 kg/cm^2.

If the ice moves very slowly crushing strength increases but momentum probably decreases due to the low velocity.

Impact X equals the change of momentum, $Fdt = mv_1 - mv_2$.
Assuming that the dimensions of the iceberg a = 20 m, b = 10 m and c = 6 m, one has for sway-motion:

$$Fdt = \frac{2.5 \cdot 20 \cdot 10 \cdot 6 \cdot 1.0}{10} \cdot 3 = 900 \text{ tons} \cdot \text{sec}$$

For surge-motions:

$$Fdt = \frac{1.5 \cdot 20 \cdot 10 \cdot 6 \cdot 1.0}{10} \cdot 3 = 540 \text{ tons} \cdot \text{sec}$$

For a 0.5 sec collision one gets 1800 tons for sway-motion and 1080 tons for surge-motion, but energy absorbtion during the impact may reduce these forces to half of these values or less than that. Crushing of the ice decreases impact forces. If the ice crushes during the impact, pier diameter should not exceed the following values:

Sway-motion: $\frac{1800}{d \cdot 6} > 50 \text{ tons/m}^2 \quad : d < 6 \text{ m}$

Surge-motion: $\frac{1080}{d \cdot 6} > 50 \text{ tons/m}^2 \quad : d < 3.6 \text{ m}$

The importance of streamlining is therefore obvious. From Korzhavins formula (ref. 6) one gets:

$$H = I \cdot m \cdot k \cdot d \cdot t \cdot \sigma_{cr}$$

when
H = horizontal force
d = pier diameter
t = thickness of ice
σ_{cr} = crushing strength of ice
$I = 1 + 4 / \exp\sqrt{d/t}$

$m = 0.6$ for a 45° angle but 0.81 for a 120° angle
$k \approx 0.6$

For a 6 m pier diameter and $\sigma_{cr} = 50$ tons/m^2 one gets $\underline{H \sim 1.600 \text{ tons}}$
For a 3 m pier diameter $\underline{H \sim 970 \text{ tons}}$

In either case forces would be approximately 35% higher for a less streamlined 120° nose angle.

As it may be noted from Fig. 19 block geometry and its relation to pier size and geometry must have an important influence on impact forces.

It is contradictory to field experience to assume that the ice block has fully vertical sides and equally unlikely that the block would hit the pier symmetrically.

A not vertical side collision and an unsymmetrical collision is considered. One can estimate the impact during roll by considering the translatoric kinetic energy as well as the rotational kinetic energy. The translatoric kinetic energy is given by

$$E_k = \tfrac{1}{2} Mv^2$$

This energy may be reduced by the rotational energy which results from an impact as shown in Fig. 19

$$E_R = \tfrac{1}{2} Iw^2$$

when I is the moment of inertia around the point of impact and w the angular velocity of the block when it rolls after impact.

The total impact energy therefore is

$$E_T = E_K - E_R = \tfrac{1}{2} Mv^2 - \tfrac{1}{2} Iw^2$$

This in turn means that a second impact occurring when the block has turned may be more severe than the first impact but in all cases the max translatoric impact will be reduced even though reduction may be of the order 10-20% only.

It is highly unlikely, however, that the block hits the obstacle symmetrically and the slightest deviation from the symmetrical will decrease the impact. The impact will be reduced in a similar way as in the case of berthing of a vessel. Fig. 19 shows such situation. The iceberg may have a rotation just before impact, but most likely the angular velocity will be so small that it may be ignored for force calculation.

The expression for impact energy is:

$$W = \tfrac{1}{2}\, m\, u_o^2\, \frac{k^2 + r^2 \cos^2\gamma}{k^2 + r^2}$$

when k = radius of gyration
r = distance from the centre of gravity to the point of impact
γ = the angle of the velocity vector with the line joining the centre of mass and the point of impact

It may be seen that impact energy in all cases is reduced.

In the case considered above radius of gyration is:

$$k = \sqrt{\frac{a^2 + b^2}{12}} \sim 6.5 \text{ m}$$

Comparing an unsymmetrical impact with a symmetrical impact one gets

$\gamma = 60^o$, $r/k = 1.1$ W = 800 tons m
$\gamma = 45^o$, $r/k = 1.1$ W = 970 tons m
$\gamma = 0^o$, $r/k = 0.8$ W = 1350 tons m

One may ask: What is the practical possibility of a fullfledged impact with vertical plane faces of ice up against vertical faces in the pier and in addition a fully symmetrical blow. The answer is that this case will hardly ever occur. The icebergs hardly ever have a fully vertical plane face. The collision therefore causes local crushing and cracking increasing energy absorbtion as well as impact time. Most of the bergs have trapezoidal cross section and as mentioned earlier, float like vessels with the widest part up parallel to the current. In impact this will result in considerable reduction of impact energy thereby of impact force. Finally a fully symmetrical blow is highly unlikely. In almost all cases impact forces will be reduced by a combination of energy absorbtion in the ice (perhaps 50%) and energy absorbtion by roll and by unsymmetrical impact. A minimum of 50% reduction and in most cases considerably more may be counted on any time. From a practical point of view a reasonable design procedure therefore seems to include the following steps:

(1) Secure data on the frequency of occurrence of blocks of certain size ranges. Use airial photos taken at various periods preferably during the time when the number of ice blocks is maximum.

(2) From airial photos find the "density" defined as $\frac{\text{area of ice cover}}{\text{area of water}}$ in the channels through which ice and water flows and where bridge piers may be placed.

(3) Draw streamlines on blow-ups of the airial photos from either side of the pier. Find the number of collisions e.g. per tidal cycle of block sizes recorded from the photos and extrapolate by means of knowledge about frequency of occurrence of block sizes and density.

(4) Find the relative occurrence of various positions of blocks compared to the centerline of the pier remembering that the pier will be hit by all blocks within the width 2D+d when D is block size (max side line) and d = pier diameter.

(5) The momentum equation Kdt = dB gives the impact when added mass, impact velocity and (estimated or experimented) impact time, energy loss (experiments) and position of block in relation to pier is known. Impact is reduced by roll and unsymmetrical blows.

The design should probably consider:

(a) Very infrequent occurrences of impact of very heavy blocks (e.g. 1,000 to 2,000 ts). To increase energy absorbtion in such cases a fender e.g. a pipe, a rubber fender or similar may be placed in the "nose" of the pier. (Fig. 20) Design criteria could be ultimate strength times a minor safety factor.

(b) In the case of more frequent occurrence of relatively heavy blocks the allowable strength criteria may be used.

An independent fender system ("ice breaker cells", ref. 5) or a sloping structure may needless to say be considered also but it may be difficult and expensive to arrange when water is deep and/or tidal range is high as it is at Anchorage.

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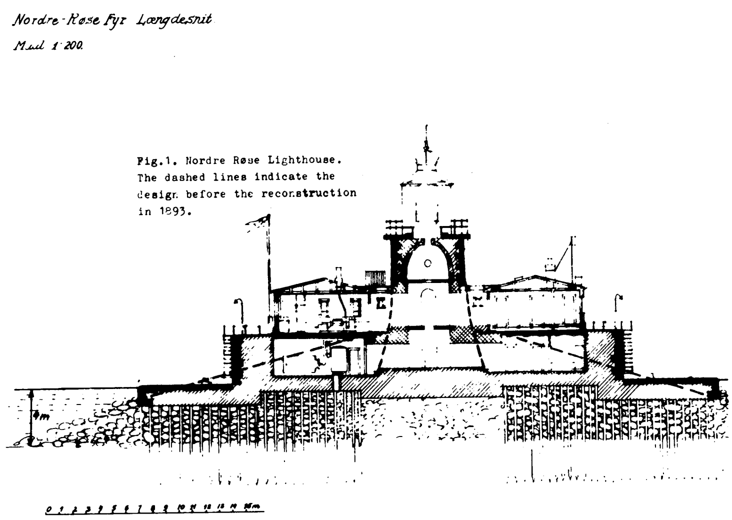

Fig. 1. Nordre Røse Lighthouse
The Øresund, Denmark

Fig. 2. Ice piling at Nordre Røse Lighthouse
The Øresund, Denmark

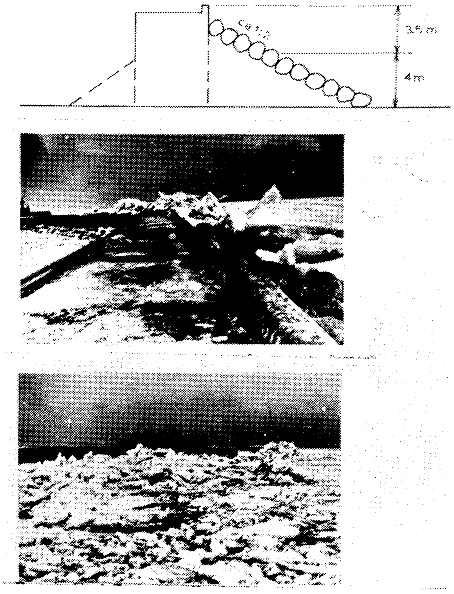

Fig. 3. Ice piling at Knudshoved ferry port
The Great Belt, Denmark

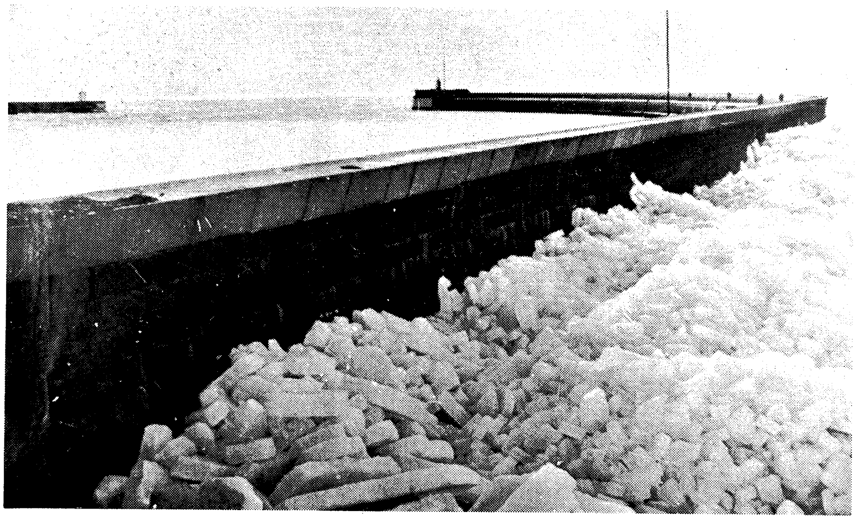

Fig. 4. Ice at the vertical side breakwater at the port of Hälsingborg, The Øresund, Sweden

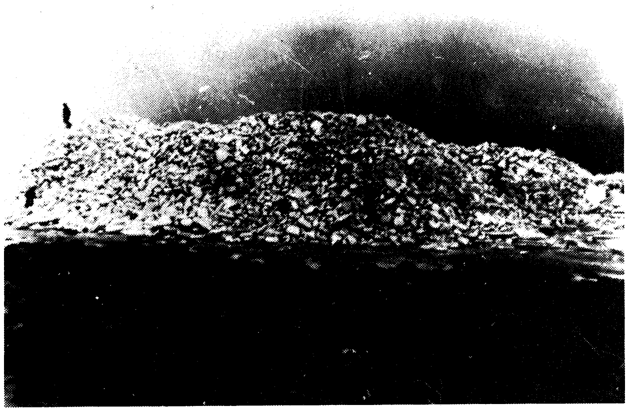

Fig. 5. Ice piling on the shore at Kronborg, The Øresund, Denmark

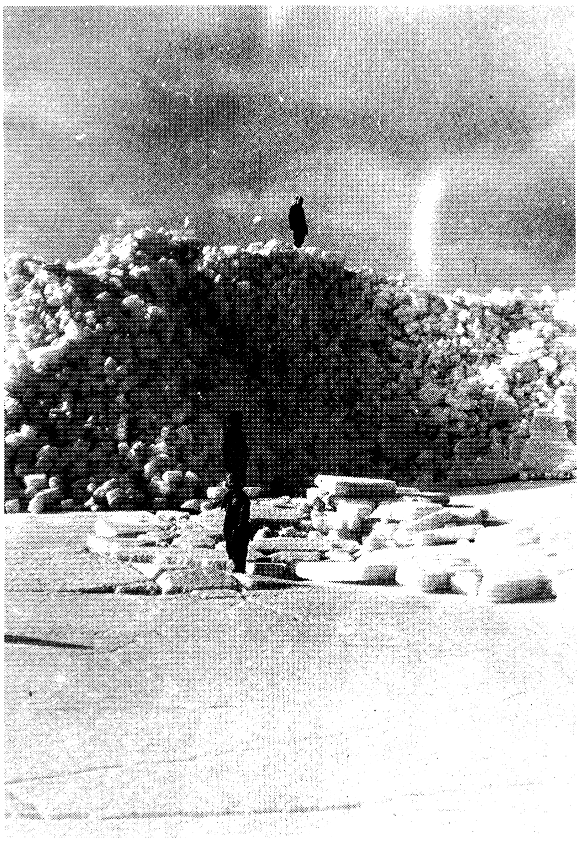

Fig. 6. Ice piling at Sejrø Bay, Denmark

Fig. 7. Ice piling in Lake Superior at Duluth, Minnesota

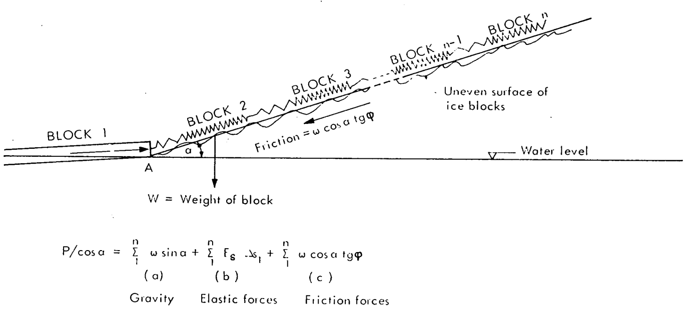

Fig. 8. Ice piling - schematics

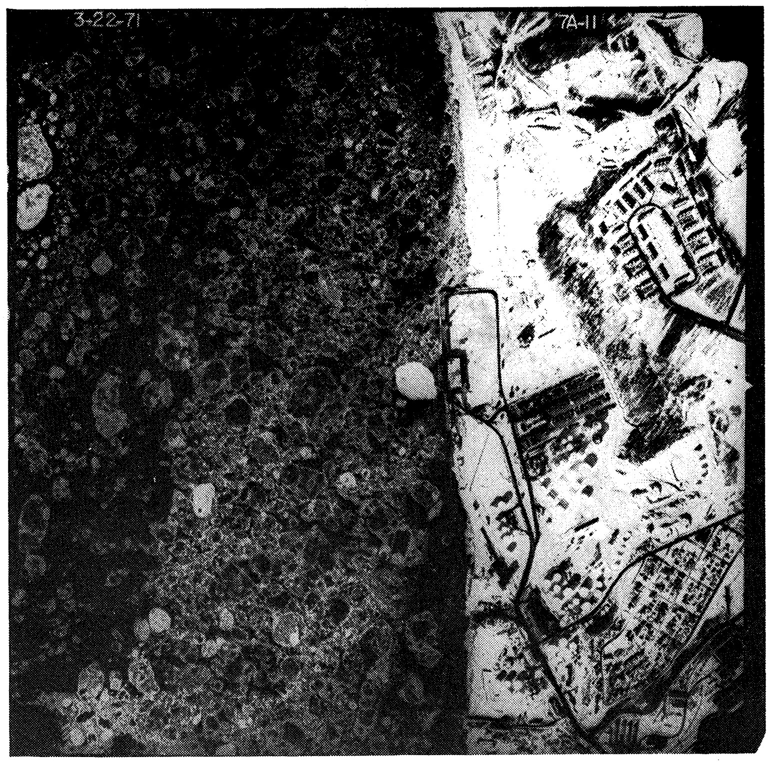

Fig. 9. Ice floes at Anchorage, Alaska

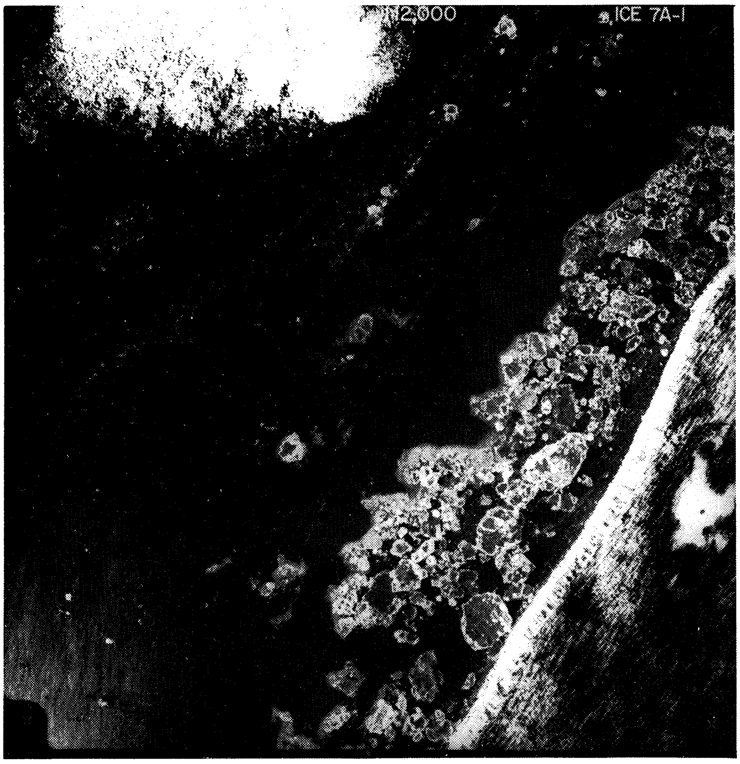

Fig. 10. Ice floes in Knik Arm, Anchorage, Alaska

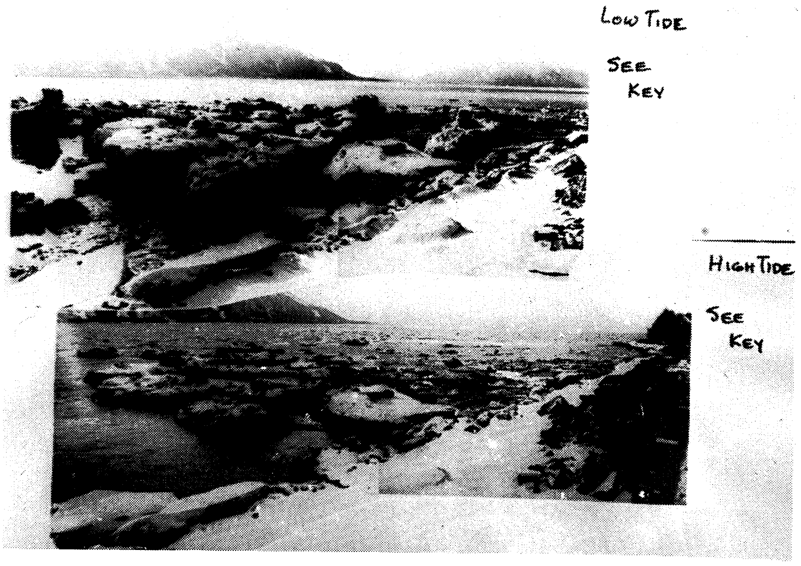

Fig. 11. Beach Ice at Turnagain Arm, Anchorage, Alaska

Fig. 12. Beach Ice at Turnagain Arm, Anchorage, Alaska

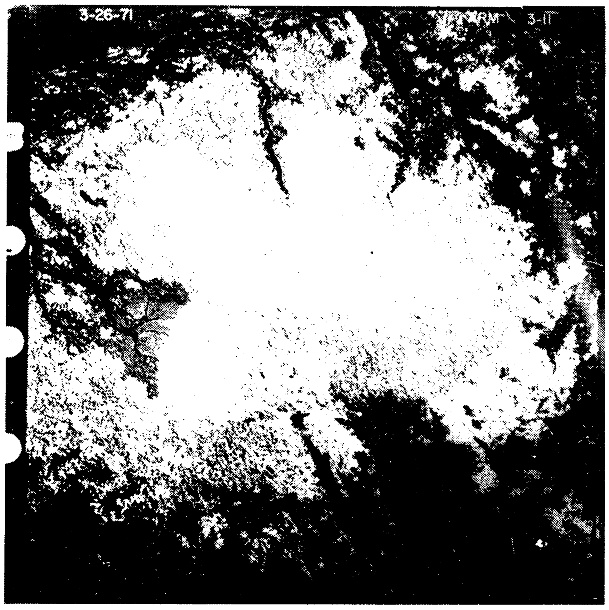

Fig. 13. Beach Ice formation on shoals Knik Arm

Fig. 14. Floating Beach Ice at Knik Arm

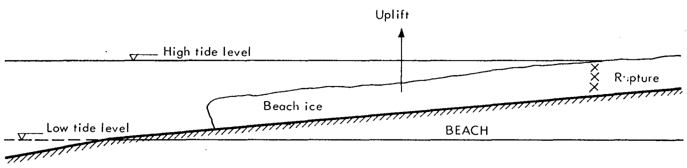

Fig. 15. Beach Ice, schematics

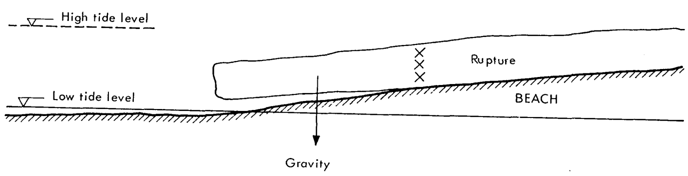

Fig. 16. Beach Ice, schematics

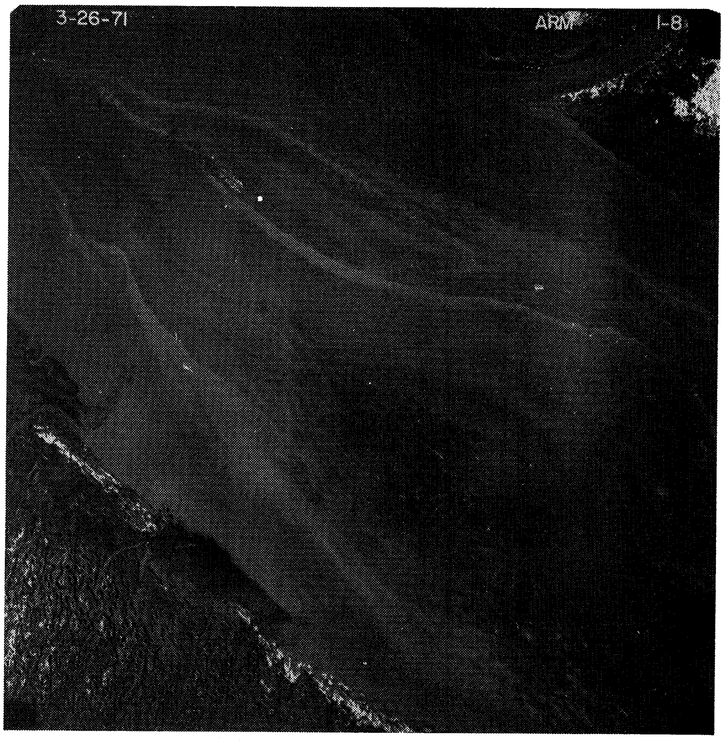

Fig. 17. Grounded and floating beach ice in currents, Knik Arm

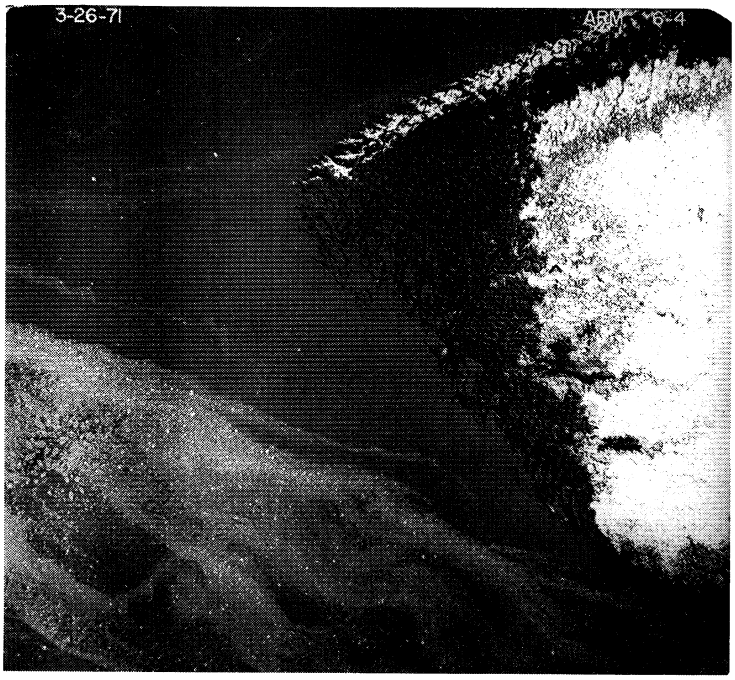

Fig. 18. Grounded and floating beach ice in currents, Knik Arm

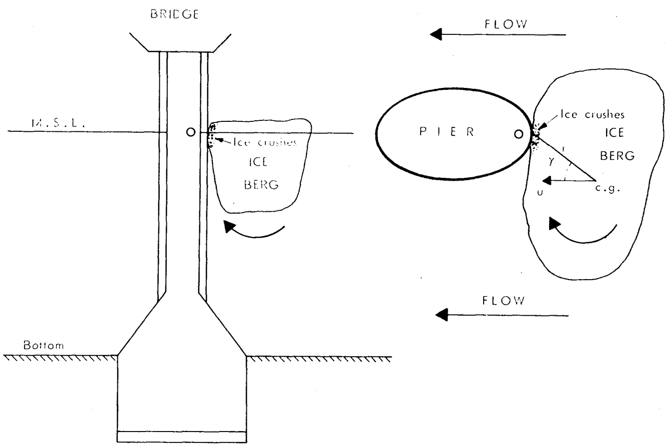

Fig. 19. Collision between bridge and ice berg

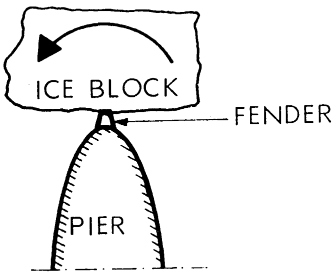

Fig. 20. Pier geometry with high - impact fender