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Effects of ice on structures and on navigation. Means of preventing ice formation and control of ice movement.

Action des glaces sur les ouvrages et la navigation. Moyens de prévenir leur formation et maîtrise de leur déplacement.

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XXIIIrd INTERNATIONAL NAVIGATION CONGRESS

S. II - 4

Section II - Ocean Navigation - Subject 4
(Common to Sections I and II)

Effects of ice on structures and on navigation.
Means of preventing ice formation and control of ice movement.

GENERAL REPORT

by

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INTRODUCTION

The XIXth Congress in 1957 provided a good general review of ice conditions in several countries, and the problems they create for shipping. Since that time there has been an appreciable increase in knowledge concerning these problems, and measures that can be taken to alleviate them. The papers submitted to the XXIIIrd Congress reflect this increase, and provide considerable detail concerning the effects of ice in navigable waterways and methods of ice control. Information they contain can be grouped into the following topics for discussion purposes : observations of ice conditions; effects of ice on structures and operations; methods of control of ice formation and movement; ice pressures on structures, and navigational aids.

SUMMARY OF PAPERS

Canada — Paper by T.F. Saunders and M. Timascheff.

This paper describes investigations undertaken for the design of a year-round wharf facility with two berths : one for a 100,000 DWT (English) crude oil tanker and one for a 20,000 DWT or smaller vessel. The facility was constructed on the St. Lawrence River near Quebec City, in an area subject to severe ice conditions.

Ice usually begins to appear at the site in early December, and starts to disappear about mid-April. Normal ice thickness is about 75 cm, but rafted and rigid ice, hummocks and hanging dams with a maximum estimated thickness of 15 m occur frequently. The main channel has never frozen over completely, but is usually covered with unconsolidated ice floes moving downstream under the influence of river and tidal currents. The site is subject to large tides of about 6 m, with a maximum of about 8 m.

Observations of ice conditions for one winter, undertaken to supplement climatological ice data, are described. Permanent shore ice at the site had a width of about 240 m. There was an additional belt, 90 to 120 m wide, of well compacted floes and ice fragments (board ice) having a thickness of about 1 m. From these observations it was concluded that the main berth would be located just outside the permanent shore ice and would be subject to severe impacts from large floes driven across the river by the winds during ebb tide. Probability of collisions during flood tide was considered to be minimal.

On the basis of climatic ice data, field observations and a hydraulic model study, it was decided to construct an open structure with ice deflectors to protect vessels and wharf head from floes moving upstream or downstream. Massive concrete gravity cells of circular cross-section proved to be most practicable and economical and to have a suitable shape. Various alternatives of alignment were studied to obtain a reasonable combination of berth protection and acceptable navigation characteristics.

Three of these cells, which are about 24 m in diameter, were placed in line with a rock-filled causeway connecting the wharf to the shore, providing protection to the berth for large ships, located on the river side of the facility. They were designed to withstand impacts from floes 4.5 m thick weighing 700,000 English tons, or an ice thrust of 9,000 kips applied 23 m above their base. The more sheltered berthing dolphins were designed for a maximum load of 6,500 kips. Floating, fibre-reinforced, pneumatic rubber fenders, 3.6 m in diameter were used to absorb shocks from large floes that might strike vessels.

The facility has been in operation since the summer of 1971, and was used without difficulty by 99 vessels during the winter of 1971-72.

The paper gives a good description of the design concept, the investigations made to establish design conditions, and of the structure and its performance to date.

Czechoslovakia — Paper by A. Sikora and I. Grund.

This paper reports a model study undertaken to establish the most effective way to move ice past the Gabčikovo power station on the Danube River, in order to minimize the time required to clear the upstream reservoir for boat traffic. The ice could be passed over auxiliary spillways located on each side of the power dam, or through a navigation channel adjacent to it.

A scale of 1 : 70 was chosen for the hydraulic model of the dam and navigation channel. Polygonal paraffin plates with a specific gravity about equal to that of ice, were used to model ice floes assumed to have a mean diameter of 5.0 m and thickness of 0.5 to 0.6 m. The study gave the total time to pass the ice beyond the dam, the area of ice passed per unit volume of water discharged, and the best way to control the flow to obtain the maximum discharge rate of ice without causing an ice jam.

It was found that when the auxiliary spillways were used alone, continual discharge of ice could not be maintained because it would pile up and jam in the approaches. Increasing the rate of flow in the approach channel by simultaneously discharging water through the power plant resulted in the occurrence of the same problem. Ice moved smoothly through the navigation locks for all rates of discharge when that method was used alone. When the rate of flow was increased by discharging at the same time either through the auxiliary spillways, the power plant or both, piling up of ice could occur upstream of the entrance to the navigation channel. The results of the model study are summarized in general form in a table. It is pointed out that temperature at the time of discharging ice, whether freezing or thawing is occurring, the total amount of ice to be passed, size of floes and rate at which ice is fed to the structure, influence the relationship between model and prototype behaviour.

The study indicated that a combination of ice discharge through the navigation channel and auxiliary spillways provide, potentially, the most favourable conditions. If this combination is to be used, however, methods will have to be developed that will prevent jamming of ice upstream of the auxiliary spillways. All of the methods tried consumed a large amount of water. Removal of ice using the least amount of water is achieved by discharging through the navigation channel only. The question is raised whether it might be better to use water for generating power than to advance the navigation season by removing ice.

Curves are presented showing the dependence of the rate of discharge of water on :

1. volume of water required to pass one square meter of ice;
2. time required to clear the ice from one square kilometer of water surface;
3. total volume of water required to clear the ice from all of the reservoir.

Two curves are also presented giving the time and volume of water required to clear all of the reservoir surface using the various methods and their combinations.

Denmark — Paper by P. Tryde.

This contribution presents formulæ for the calculation of ice pressures against an isolated cylindrical pile, vertical faces with width less than ten times the ice thickness, vertical and sloped piers with a triangular-shaped nose, and long straight walls with a vertical or sloped face. The forces acting on floes or continuous covers, and mobilized at the time of contact with a structure, are assumed to be shear stresses due to water currents and wind, inertial forces, and those associated with crushing or other modes of failure of the ice.

Equations are given for calculating the shear stresses exerted by wind and water on ice covers. The values for the force that would be obtained are smaller than would be calculated using equations given in the Russian Code and the same wind or current speed.

It is assumed for the pile, vertical-faced pier and long straight wall, that the ice fails in shear at an angle of 45° to the horizontal. The equation obtained takes into account geometry of failure (through a coefficient equal to $2 + 0.7\ e/d$, where e is the thickness of the ice and d the width of the structure), the shear strength and thickness of the ice, and the width of the structure. For a triangular-shaped pier with a vertical face, the force will increase to a maximum value after first contact as the structure gradually penetrates the floe. An equation is given for the dependence of the pressure on amount of penetration, and for the dependence of the penetration on the speed and mass of the floe.

Korzhavin's approach is used to calculate the maximum force on an inclined triangular pier. A reduction factor is presented that takes into account the wedge and slope angles of the pier, coefficient of friction at the contact face and the eccentricity of the normal force acting in the ice.

An argument is presented to show that for a long straight wall, the energy absorbed during crushing along its full length is sufficiently large to prevent any major pile-up of ice. Conditions for piling up of ice in front of a long straight inclined wall are discussed. An example is presented of forces on an inclined wall calculated from the derived equations using a computer. It is now planned to carry out model studies to test the derived equations.

Finland — Paper by T. Rekonen.

This paper is concerned primarily with the effects of ice on navigation and navigational aids. Ice forms first along the coast of Finland, producing a shore-fast cover that extends beyond the island zone. During the winter a zone of consolidated pack ice is frequently formed next to the shore-fast ice. Pack ice and the consolidated pack ice covers disappear first during spring thaw. The northern part of the Gulf of Bothnia is frozen over even in the mildest winters. In severe winters, the Danish and Baltic Sounds can be ice-covered. The maximum thickness of shore-fast ice varies from less than 50 cm in the coastal area near Helsinki, to 80 to 100 cm in the northern part of Bothnia Bay. Ridges of appreciable thickness can be formed in the pack ice and in the transition zone between shore-fast and consolidated pack ice.

The compressive strength of the ice, which has a low salinity, was found to be 28 kg/cm² perpendicular to the direction of growth. This strength increased 4.1 kg/cm² for each 1 °C decrease in temperature. The strength in bending was found to be between 3 and 6 kg/cm^2. Field observations have indicated that the temperature of the ice can be assumed to be between 0 and —2 °C during periods of maximum load.

Finland probably has a larger ratio of icebreakers to volume of traffic than any other country. The principal task of the breakers is to maintain shipping in southern harbours. In normal and severe winters, the northern part of the Gulf of Bothnia is closed for a few months. A description is given of normal winter ice-breaking operations.

It is very difficult to operate ships in the mobile pack ice, and it is found easier to break channels for them through the protected shore-fast ice. The location of these winter channels is based on several years of observations of ice conditions. A major problem is the development of suitable navigation aids for marking the channels. Large diameter winter buoys anchored to the bottom can be used at locations where the ice is not subject to much movement. Fixed bottom navigational aids are considered more suitable and consideration is being given to fitting such structures with unambiguous light systems and radar reflectors that will differentiate them clearly from other objects.

Conical-shaped, fixed, beacon structures have been used in the past. It is considered that there may be no advantage to having a sloped surface as the maximum ice thrust probably occurs when the ice cover frozen to the structure first starts to move. The tendency now is to use cylindrical structures. Tests have shown that the thrust due to ice decreases considerably with diameter, until the diameter is equal to the ice thickness. This is taken into consideration in the design of bottom-fixed buoys. Examples are given of channel edge beacons fixed in rock or in ground. A structure to be placed in the northern part of Bothnia Bay has been designed for a force of 450 metric tons and impulse loads of 550 tons. These new beacons are considerably less expensive than the Swedish lighthouse type, four of which were constructed in Bothnia Bay in 1964-65. Swedish-type structures were designed for a thrust of 1,110 tons (150 ton/m), and have performed satisfactorily.

Channel markers for inland waterways are subject to much smaller loads. Markers designed for a thrust of 7 tons have proved satisfactory. Beacon structures in lakes with ice thickness of 50 to 70 cm, designed for thrusts of 14 tons have also not failed. These low loads probably occur because the ice undergoes only small horizontal movements and tends to melt in place.

An equation is presented for calculating the maximum load on a cylindrical structure when the ice first starts to move.

France — Paper by M. Robert Vadot.

The writer reconfirms and brings up-to-date the experience presented at the 1957 Congress on the effects of ice on navigation on French waterways. Attention is given primarily to three points : action of ice on navigation works; means of preventing ice formation; and ice removal.

Ice is responsible for about one-third of the total time of stoppage of navigation, which is less time than that due to maintenance. Its occurrence, however, is unpredictable, and may last for up to three months. The formation of an ice cover, and especially of an ice dam, increases the water level and rate of flow, resulting in possible flooding, local bed erosion and damaging ice pressures on structures.

Every attempt is made to keep ice moving during its period of formation. Buoys are removed before they can be damaged by ice. Once a solid cover is formed navigation is usually stopped, particularly on the small inland waterways, until thaw begins. Ice removal starts as soon as possible once thawing starts. Good use is made of meteorological forecasts in determining the action to be taken with respect to ice.

The discharge of warm water from industrial operations and power generating plants into the navigation channels has been found to have an ameliorating effect. Icebreakers and air bubbling systems are effective for some locations and conditions. Continuous boat traffic, augmented if necessary by ice breaking vessels, can delay the establishment of a solid cover.

It is important to keep mobile the moving parts of all control and lock structures. Heating elements have been provided on some of them for this purpose. The greatest difficulties are experienced with old structures that were not designed for difficult ice conditions. In some cases these are left open during periods of ice formation if serious consequences can result from their being frozen shut.

Germany (F.R.) — Paper by R. Bock, F. Cordes, H.D. Dudziak, L. Franzius, H. Grothues-Spork, F. Günneberg, H. Wismer.

This paper discusses ice pressures, model tests for ice-breaking bulk carriers, behaviour of ferries in ice, effect of ice on shipping in the tidal zone of the Elbe River, and means of combating ice.

Observations of ice conditions and ice pressures in the Eider estuary were made during the construction of the Eider Dam. Ice blocks with a volume of 300 to 400 m^3 and thickness up to 4 m, and floes of area as great as 5,000 m^2 and 30 to 40 cm in thickness, are formed and moved back and forth with the tidal action at velocities of up to 1 m/s.

Measurements of ice pressures were made at piles supporting a bridge at the dam site. The piles were designed for an ice thrust of 100 Mp (*). Forces on one pile were measured with 56 pressure cells placed in 10 rows one above the other. At the second pile support, the pressure exerted on a 1.5 m diameter diaphragm mounted vertically in a square housing, was observed. Thickness of ice, velocity of floes, wind speed, water level and temperatures were also recorded.

(*) Mp = 10^6 kg force.

The greatest pressure on the piles did not occur on impact, but rather just before a floe was brought to a halt. Static pressures that were exerted after a floe had been stopped were always less than earlier dynamic pressures. The multicell installation indicated continually varying local loads. Pressures at both sites were found to depend on temperature, ice thickness, structure of the floes and form of the measuring device. The maximum thrust observed was about 30 Mp and peak pressures of 20 kp/cm² occurred. Destruction of the large diameter pressure measuring device indicated an ice thrust in excess of 60 Mp.

Observations of the deflection of isolated, tubular, steel, dolphins, 812.8 mm in diameter, indicated an ice thrust of 30 Mp.

The sluices on the dam were designed for static loads of 15 Mp/m and dynamic loads of 75 Mp/m. It was observed that a stone embankment was subject to erosion and that the tips of projecting granite blocks were rounded off by ice action.

An investigation of icebreaking hulls has been undertaken because of the need for large bulk carriers to navigate ice-covered waters. When a ship with a sloping prow moves through ice, bending stresses are produced that continuously break the ice. The pieces so formed are displaced downward and laterally. To progress, the ship must be able to produce sufficient power to break the ice, displace it and overcome the force of friction between the hull and the ice. Modeling of this behaviour is still questionable because of the incompatibility of the similitude laws for the different sources of resistance. Model studies can clarify, however, aspects of the icebreaking process, and a brief description is given of such a study of the forces produced on a hull at impact.

A description is presented of the operation of ferries on the Kiel Canal during periods when ice is present. The ferries must run essentially perpendicular to the channel used by ship traffic. They must maintain their service even when only large ships with icebreaker support are using the Canal. Ice produces conditions for which they were not designed, however, for less than 5% of their operating time.

The ice displaced by ships seriously intereferes with the operation of the ferries and the use of the berths. Air bubblers and flow developers have not been able to keep the ferry bays free of ice. Maximum use is made of the manœuvrability of the ferries which operate with equal ease forward or backward.

A description is given of ice conditions in the estuary of the Elbe River. Ice formation in the estuary region, as well as reduced flow from the non-tidal reaches of the river due to the formation of an ice cover, have a significant influence on tidal levels. This influence, as well as the effects of ice, must be taken into consideration for the operation of ships and the construction of hydraulic works. The ice in the river and estuary affects mainly small ships.

Traffic can be maintained by icebreakers on inland waterways only if the ice is less than 12 to 15 cm thick, and not growing. Interest is expressed in the use of warm industrial water to prevent ice formation.

Four examples are discussed : the possible effects of the waste warm water from the proposed Kümmel power station; the construction of power stations along canals; the effects of discharge of hot water into a canal near Hanover; and the use of cooling water from a nuclear power plant and heavy industry for keeping a lock installation on the Kiel Canal ice free. It is emphasized that if such sources of warm water are to be used, care must be taken in locating the power plants and industry from which it is to be obtained. Consideration must be given also to the problem of thermal pollution; it may be necessary to provide cooling for warm waste water in summer, or have some other method for its disposal.

The Netherlands — Paper by H.M. Oudshoorn and J.A. van Hiele.

There has been considerable construction of control structures in the Delta area of the Rhine River since the review of ice on Netherland waterways was presented to the XIX Navigation Congress in 1957. Information on the changes in the characteristics of ice formation that have occurred as a result of this construction, and experience concerning the control of ice and its effects on structures, is given in the contribution to the XXIII Congress.

The Rhine River discharges into the North Sea through several large sea arms subject to tidal action. Construction of a dam has divided the waters of this tidal delta into two basins. When the Delta project is completed, the most southerly of the two ba ins, through which a considerable amount of ice from the Rhine is usually discharged, will be completely cut off from the sea and will form an almost fresh water lake. The Rhine and the Meuse Rivers flow into the northern basin, which has direct communication with the sea by way of the Rotterdam Waterway. Flow through its major sea arm, which contains the Haringvliet and the Hollandsch Diep, is controlled by recently completed sluices across the mouth of the Haringvliet.

A large amount of ice is produced in the fresh water tidal estuaries. This ice drifts slowly out to sea, the rate depending on site, current and wind conditions. During the flood period of the tidal cycle in the transition zone between the tidal area and normal river flow, velocities are low and the ice tends to pack together. If conditions are favourable, this pack ice will freeze to form a solid sheet. The ice cover can then progress rapidly upstream due to consolidation of floes carried by the Rhine and Meuse Rivers.

Considerable information has been accumulated on the dependence of the rate of ice production and discharge on air temperature, current speed and location on the Rhine River and estuary systems. Some of this is summarized in Figure 2 of the paper. Particular attention has been given to hydraulic factors controlling ice jam formation in the tidal area. It has been found that the conditions associated with the formation of an ice jam are reasonably well defined by the Froude number. Critical values determined from field observations were found to be in the range 0.06 to 0.09 (see Fig. 9).

Navigation is hampered on the average only 8 to 10 days per year for small boats, and 4 to 7 for large ones. It is found to be very important to keep the ice moving. Buoys are removed at the last possible moment. In general, shipping on the wider waterways for which buoys are required, comes to a halt when ice floes cover almost all the water surface. For other waterways the density of traffic delays the formation of fast ice, and more powerful ships can continue to operate as long as the ice keeps moving.

Ice breaking is initiated as early as possible on the downstream edge of fast ice or ice jams. Breakers of up to about 375 h.p. are used for this work, and to prevent the formation of a solid cover. This prompt and continuing action, which can only be done effectively during ebb tide in the tidal area, has reduced river bed scouring associated with ice jams, and damage due to ice. Elimination of irregularities in the flow has improved the ice discharge characteristics of the river system.

A ground observation network has been established to provide a continuous picture of ice conditions. This is supplemented by reconnaissance from aircraft. An analogue computer, built to model conditions in the Delta area, has successfully modeled the effect on ice conditions of the construction and operation of hydraulic control structures. A general operational procedure to be followed during ice periods after completion of the Delta project has been established and is presented in the conclusions.

Poland — Paper by E. Jasinska and W. Robakiewicz.

This contribution presents a theoretical discussion of air bubbler systems, results of experiments carried out to confirm the theory, and observations of the use of such systems as ice barriers. It is assumed that the surface velocity, U, induced by the bubbler system is a function of two dimensionless numbers :

$$N_a = \frac{Q}{H^2 \sqrt{gH}} \frac{\rho'}{\rho}$$

where Q = the volume of air discharged.
H = the depth below the surface of the air outlets.
ρ' water density.
ρ air density.
g acceleration due to gravity

and

$$N_b = \frac{H}{D}$$

where D = the diameter of the air outlets.

Figures 2 and 3 of the paper give the observed dependence of $U/\sqrt{gH}$ on N_a for given values of N_b. Hole diameters were varied over the range 1.0 to 4.5 mm, depth of submergence between 0.30 m and 9.0 m, and air pressure from

0 to 5.0 $\times$ 10^5 N/m^2. A second set of experiments reported gives the dependence of Q on the diameter of the outlet holes, D, and the ratio p_o/p_r, where p_o is the absolute pressure on the outside of the perforated pipe, and p_r the absolute pressure inside.

Experience is reported on the use of air bubbling systems for prevention of the entrance of ice into a floating dock while it is being submerged or during the entrance of ships. For greatest effectiveness the spacing of holes should be such as to allow adjacent cones of rising air bubbles to merge at the surface. Holes must be of sufficient size that they will not be blocked by particles, and the rate of discharge of air must be great enough that the induced surface velocity will keep ice out of the dock during submergence. Details are given concerning air bubbling installations used successfully to keep ice out of ferry berths, and an experiment to investigate their use for keeping ice out of harbour areas.

United States of America — Paper by Dr. Charles C. Bates.

A description of the climate, ice conditions, effect of ice on navigation and measures taken to combat ice was given for the Great Lakes and the Mississippi waterway and its tributaries at the 1957 Congress. The present paper presents new initiatives to extend the navigation season on the Great Lakes, St. Lawrence Seaway, Upper Mississippi and its principal tributaries, and in the New England and Alaska coastal regions.

A major three-year program of observation of ice conditions and forces, environmental and ecological investigations, collection of technical data related to vessel design, investigation of ice control facilities and aids to navigation, model studies, and coordination and dissemination of information to shippers on weather and ice conditions, has been undertaken for the Great Lakes and St. Lawrence Seaway system. Techniques of surveillance include aerial photography of restricted channels, ground surveys of ice and snow characteristics and extent of coverage at 58 stations, aerial reconnaissance, and monitoring of water levels. This information is transmitted to an Ice Navigation Center twice weekly. The Center, which is also linked to the Canadian Ice Forecasting Centre, provides an ice summary and forecast five times per week. Information on ice formation and decay provided by these synoptic-type observations is being supplemented by more detailed studies. Improvements are being made to ice forecasting methods by utilizing information from satellites, lake thermal observations, ice climatological records and ice movement studies.

Investigations have been undertaken on reducing the friction between ice and a ship's hull with an air bubbling system, on breaking ice ahead of a ship by rapidly releasing the gases from the detonation of a propane-air mixture in a ram bow extending under the cover, and on the relative effectiveness of a vertical router and a « chain saw » for cutting ice 5 to 10 cm thick. It has yet to be determined if it is better to place broken ice in a channel on top of or beneath the adjacent shore-fast ice.

A summary is presented of efforts to solve the problem of the effect of ice on navigation systems, e.g., buoys. Structurally strengthened buoys with a modified lighting system have been tested, as well as six X-band radar transponder beacons and nine expendable structures placed on shore-fast ice. Two experimental navigational approaches using laser beams are being tried, and trials were initiated on a Precise Laser Navigation System. There are plans to experiment with a laser beam « wire in the sky effect » which would provide guidance during periods of suitable visibility. Experiments are also being carried out with LORAN guidance systems and underwater cables producing a magnetic field that can be detected from the ship.

Investigations have been undertaken on the optimum bow configuration for an ore ship, and various devices for reducing resistance offered by ice. Research is underway on the forces ice can exert on structures. Attention is being given to ice control and stabilizing structures; three basic conceptual design studies have been initiated on methods for improving winter navigation while avoiding interference with river flow.

Air bubbling systems are being investigated for maintaining ferry channels open and clearing ice from ferry berths. Experience obtained from these investigations is described. In one study, ice accumulated in a ferry slip was forced out by the release of a large blast of air. The release of the extra air was controlled by the ferry operator during the approach. The use of rigid polyethylene insulation for preventing ice build-up around hydraulic structures is being investigated.

On the Mississippi River, tows moving through ice are handled by towboats averaging about 400 to 500 h.p. per barge. Most of the new towboats are powered by « Kort Nozzles », and are not as efficient in ice as those with open propellers. These tows do not have difficulty in clear ice less than 10 cm thick; barge operations cease when the ice thickness exceeds 15 cm. Major problems have still to be overcome with respect to operating locks and dams, and navigation between locks. A summary of these and possible solutions is presented in Table II of the paper.

The principal problem in New England waters is the disruption of navigation buoys by drifting ice. Experience has shown that moving ice sheets 8 cm thick will disrupt 2.4 × 7.8 m lighted buoys with a 3,800 kg anchor, and ice 30 cm thick will submerge 2.7 × 11.5 m buoys, destroying lanterns and associated equipment. Freezing spray can build up on a buoy and eventually cause it to tilt or capsize. It can also block the ventilation systems causing the zinc air batteries to become inoperable. Experience concerning the performance of buoys during heavy ice conditions in Buzzard Bay are described. Improvement in ice buoy design has been undertaken.

Development of offshore oil and natural gas deposits, and the associated growth of Anchorage, Alaska, has created a requirement for year-round shipping in Cook Inlet. Most of the ships moving to Anchorage through the Inlet are of customary ocean-going construction. Eight vessels suffered cracks in the bow area near the waterline due to ice, during the winter of 1971-72.

During the ice season buoys are removed in Cook Inlet and no special aids to navigation are provided to replace them. A major problem is breaking of moorings and fittings caused by pressure of floes as much as 60 cm thick, being pushed by gale winds and tidal currents of 4 to 8 knots. Ground tackle of most commercial vessels is not strong enough for anchoring in the open roadstead. It is considered that an icebreaker of medium size (60 to 75 m), shallow draft about 6,000 shaft horsepower is required for the conditions in Cook Inlet.

Measurement of ice forces on offshore drilling structures in Cook Inlet indicated that the loading is less than 8.8 kg/cm². Forces imposed by ridges are two to three times those imposed by uniform floes; the maximum loading on a cylindrical leg is in the range of 27,000 to 31,500 kg for each 30 cm of diameter.

Discovery of oil on the North Slope of Alaska and the possibility of commercial deposits of coal, oil, natural gas and minerals in the Seward Peninsula area, has caused interest in year-round navigation as far north as the Arctic Ocean. Trial runs into the region with Wind-Class icebreakers, which indicate the extent to which such services are feasible, are described. A summary is given of the activities of petroleum companies with respect to shipping and offshore drilling in the Arctic. A brief description is given of the new Polar class icebreakers now under construction (60,000 shaft horsepower); this breaker should be able to go through ice 1.8 m thick.

Mention is made of recent studies of the characteristics of pressure ridges, development of a penetrometer for measuring ice thickness that can be dropped from an aircraft, and of experience in the use of side looking radar (SLAR) for observing ice cover characteristics. Results to date indicate SLAR is probably the most useful tool available for periodic, all weather, day or night observations of ice covers.

It is concluded that the results of the new initiatives to extend the navigation period in ice covered waters appear promising.

U.S.S.R. — Paper by A.F. Parfenov (prepared by V.V. Balanin, and L.V. Ivanov).

A comprehensive paper on the effects of ice on navigation in the U.S.S.R. and on methods used to combat it was presented to the 1957 Conference. This present contribution reviews developments during the past 15 years concerning principal problems encountered, trends in ice control methods, design of ice control facilities and experience gained in combating ice.

A good description is given of problems caused by ice formation on water and facilities at locks, wharves and docks. Vessels moving through canals and in and out of harbours continuously break ice and cause the cover to increase greatly in thickness due to rafting and hummocking. Damage can be caused by this ice if it is caught between a structure and a ship. Cost of docking in winter is 24 to 50% greater than in summer, and most of this increase is due to ice.

Sludge ice is a problem on some rivers. Its effects on shipping have been alleviated by the construction of hydraulic structures. Adhesion of this ice to vessels can be reduced by appropriate heating of the hull.

Extensive observations have been made of the ice regime on navigable waterways. This information has been used to specify icebreaking activities and the associated icebreaker fleet required to increase the shipping season at least 20 days in the autumn. On some short inland routes, year-round navigation can be maintained by high intensity ship traffic if the climate is suitable.

The importance of knowledge concerning the thermal and ice regime of navigation routes is emphasized. Conditions are described for the formation of bottom and surface ice in estuaries due to inflow of cold tidal sea water. The basis used for the design of air bubbling systems and flow developers for keeping areas free of ice is presented. Proper location of hot water sources, such as thermal power stations, is considered to be of great importance. Warm water can be used more effectively if it can be released from perforated pipes laid beneath the area where ice formation is to be prevented. Such an installation requires some means, such as an air bubbling system, for assisting the warm water to the surface. A system has been developed recently which ejects a steam-air mixture from perforated pipes placed under water. It operates most economically when controlled so that a 5 to 10 cm ice cover is retained on the water surface. Heating elements in flow generators are also used to keep small-size areas free of ice. Experiments have been conducted on the use of granular polystyrene for preventing ice formation in sheltered areas about structures. A device is described for preventing the freezing of the ice cover to piles.

The basis for the design of structures to withstand dynamic and static ice loads is summarized. Specifications that must be met for concrete that will be subject to freezing water are given. Protective, insulating coatings are applied to the surface of some structures.

Equations are given for calculating design loads on booms used to protect locks from ice. Such booms are either lowered into the water or drawn to one side to allow ships to enter. A barrier consisting of a system of floats has recently been developed for keeping ice out of ports, ferry berths or floating docks. When ice is driven against the floats they are pressed together. They are readily parted by a ship's hull, but remain in close contact with it as the vessel passes through.

A special net device has been developed for ferry berths. As the ferry enters, the net is forced ahead of it. When it leaves, the net returns, removing from the berth any ice that may have entered with the ferry. It also acts as a barrier to ice when the berth is not occupied.

Flow developers have been found to be effective for protecting water areas and structures, and removing broken ice from the bottom of ships prior to being put into dry or floating docks. Equations are presented for their design for the protection of floating docks during submersion and use.

Old aircraft jet engines have been found to be useful power sources for combating ice in harbour areas. The hot exhaust gases can be used to prevent icing of fenders, damping devices, pier walls, and moving elements of structures. They can also be used to heat work areas in dry docks and maintain areas of water in an ice-free condition. Power from the engine can be used to generate electricity and provide compressed air for bubbling systems.

A detailed description is given of the air bubbling, heating and boom systems used for locks that must operate in below-freezing conditions. The design of the systems depends on the climate, type of lock, length of period for which lock must operate under sub-zero air temperatures and other equipment features.

It is clear that good progress has been made in the solution of ice problems in harbour areas and at ferry berths, docks and locks through the judicious use of bubbling systems, flow developers, ice booms and heating devices. The main difficulties caused by ice at twelve dry and floating docks of ship repair facilities have been eliminated by using a combination of anti-ice devices.

Yugoslavia — Paper by Slobodan Petkovic.

This paper records a case of improvement of navigation conditions in winter through the construction of a hydro-electric power dam. Submerged rocks, narrow width of river, high flow velocities and ice have seriously interfered with the movement of boats on the Danube River in the border area between Yugoslavia and Rumania. The evolution of an ice cover on this section was characteristic of a relatively fast flowing river subject to a continental climate. The value of the Froude number was variable, often exceeding 0.109, and ice jams occurred frequently. Construction of the Djerdap dam greatly decreased the flow velocity and reduced the Froude number to well below the critical value for the formation of an ice jam. This region now has the characteristics of a lake and a solid ice cover forms on thermally stratified water.

Although ice begins to form on the reservoir at an earlier date than for the former river condition, the establishment of a solid continuous cover, rather than an unconsolidated cover and ice jams, has resulted in an improvement in navigation. It is now possible for ice breakers to assist and maintain shipping, whereas in the past this was prevented by difficult ice conditions.

DISCUSSION

Observations of Ice Conditions.

Detailed knowledge of ice conditions and the factors upon which they depend are absolutely necessary for the development of effective ice control methods and operational procedures for waterways and ports, and for the design of ice control structures and ship-handling facilities. This was demonstrated clearly by examples of their use for the development of the Delta Project in Holland, for applying measures to extend the shipping season in fall in the USSR, for determining shipping channels along the coast of Finland in winter, and for establishing design concepts for a major wharf in Canada.

Such observations are of principal interest for the waterway or facility involved. Perhaps their greatest use for other locations is to provide a basis for comparing ice problems and the efficiency of solutions that are applied. It is important that an internationally accepted classification of ice conditions and definition of terms be used for this purpose. Such a system has been established for sea ice (1) and is now under consideration for fresh water ice (2). PIANC should consider these classifications and recommend they be used by its members when reporting ice conditions.

Some information concerning ice conditions can be extrapolated to other sites, and particular attention should be given to its collection. An example is the critical flow condition associated with ice jams. Investigations have shown that the Froude number is a useful criterion for this condition, but additional evidence, such as that provided by the papers from the Netherlands and Yugoslavia, for a wide range of channel, flow and ice conditions, is required.

Quantitative correlations between rate of ice production at a given stage of development of an ice cover, and weather elements, such as air temperature and wind speed, can also be extrapolated to other sites. Information of this type, an example of which is given in the paper from the Netherlands, is relevant for the development of ice forecasting methods and vessel operating procedures. Its compilation should be encouraged.

Effects of Ice on Structures and Operations.

A harbour or waterway is a system composed of many parts. Their use in winter is dependent on the ability of ships to move through them, and the capability of each of the parts to perform acceptably under the ice conditions that prevail. Papers that have been presented to both the XIXth and XXIIIrd Congresses give a wealth of information concerning the effects of ice on facilities and the interaction between ice and ships. It is very difficult to generalize from or compare these experiences because ice conditions, type and density of traffic, characteristics of waterways and harbour facilities, and ice control capability vary so greatly from one location to another. It may be useful for purposes of discussion and comparison in the future to make a distinction between regions and facilities that are not affected seriously or for only brief periods each winter, those for which operations can be maintained by only continuous and sometimes considerable effort, and those for which some or all operations must cease for part of the period.

There appears to be appreciable informations concerning the ability of vessels of given size and horsepower to operate in ice covers of given thickness and state of consolidation, as indicated by the papers from France, USSR, USA, Finland, the Netherlands and Germany. For example, ships of a certain size can continue to use inland canals in some regions as long as the traffic keeps the ice broken and moving, and their progress is not stopped due to the accumulation of broken ice. Shipping is maintained with ice breaker support through the fast ice, about 0.5 m thick, along the south coast of Finland, but is not maintained in the northern part of Bothnia Bay where the ice is about 1 m thick. It would be useful if such information concerning the dependence of the use and performance of ships on power and ice conditions could be compiled and organized in an appropriate manner, as it would provide useful guidance for operational decisions.

It was clear from the papers that there exists a general need to reduce interruptions to navigation caused by ice. Many of these interruptions are due to effects of ice on facilities such as locks, wharfs, ferry berths, and submersible docks. These effects must be fully appreciated and thoroughly understood so that they can be taken into consideration at the design stage of new facilities. In this way, possible modifications can be made that will alleviate the problems caused by ice, as demonstrated by the USSR experience with locks and ship repair facilities, and the Canadian experience in the design and construction of a new wharf. The case records of the effects of ice can be very valuable, particularly if they are accompanied by a good description of associated weather and ice conditions.

Methods of Control of Ice Formation and Movement.

The severity of an ice problem is determined by the rate at which heat is being lost to the atmosphere from the surface of the ice cover or water, the length of time over which this loss has taken place, and the characteristics of the waterway or facility. Numerous methods have been developed to alleviate these problems which involve displacing the ice, preventing its formation by addition of heat, or reducing the rate of heat loss by using insulation. The method chosen depends upon the severity and economic importance of the problem, the characteristics of the site and the nature of the traffic. No matter what solution is chosen, it is important, as pointed out in the paper from the USSR, that it should be an integral part of the design of the waterway or facility, taking into account both traffic and operating conditions.

Flow developers and air bubbling systems have proved to be effective for some ice control problems. These systems may be used to prevent ice from entering into an area by generating a sufficiently strong surface current, or for preventing the formation of ice by bringing warm water to the surface. Considerable information is now available concerning their action and effectiveness. The contribution from Poland is a valuable addition to this store of knowledge. It would be useful to have this subject reviewed in order to determine if information concerning the design of such systems for ice control purposes is now adequate, and if not, to establish the research that is still required. It is probable that additional investigations are needed on their action in particular water and ice conditions, and for certain types of structures.

Much work has to be done on the development of heating and other ice control systems for special facilities such as locks and submersible docks that must operate under severe ice conditions. The USSR paper has a very useful contribution on this subject. Their experience indicates the close attention that must be given to ice, traffic conditions, and associated problems, when developing ice control systems or improving the design of ship facilities. Research and development of such systems should be encouraged.

There is currently great interest in the use of industrial waste warm water for preventing ice formation. Although this may be a very effective method of ice control in winter for some areas, it does introduce the possible problem of thermal pollution at other times of the year, as pointed out in the paper from Germany. Field observations are required to confirm methods of predicting the thermal effects caused by the addition of warm water. Investigations are also required that will provide the information required for locating and spacing sources such as power generating stations.

Practical methods have now been developed for modeling the movement of ice in rivers or about structures, as long as ice pressures are not involved. Such studies have been used effectively in the Netherlands in the development of the Delta Project and associated operational procedures, for investigating methods of moving ice past a dam in Czechoslovakia, and for the design of a wharf facility in Canada. Their application to other difficult ice control problems, such as keeping ferry berths ice free, or the improvement of ice conditions in a waterway through the use of booms, etc., should be actively encouraged.

There is a current interest in the design of ice breaking hulls, as shown by the papers from Germany and the USA. The interaction between ice and a ship is not yet fully understood, and deserves attention. Although such studies might be carried out primarily for the design of large ships, their results would also be of interest in the design of ferries and small vessels that operate on inland waterways. Consideration should be given also to other ways of breaking ice, such as the repetitive explosive device described in the paper from the USA.

The papers indicated that considerable imagination and ingenuity had been applied to the problems of ice control, and it was clear that good progress had been made on this subject since the XIXth Congress.

Ice Pressure.

Determining the maximum force that ice can exert on a structure is an engineering problem that is still not fully resolved. Good progress has been made in the USSR on the development of design codes for structures subject to forces due to ice. Theoretical and field investigations of ice pressures are being carried out in Europe and America. Understanding of the interaction between ice and structures and, therefore, of the modes of failure that ultimately determine the maximum load for given site and type of structure is still inadequate.

Because of the great variability in the properties of ice covers, the scale of the forces involved, and the complexity of the problem which prevents unambiguous predications based on laboratory measurements, there is a great need for field observations. These observations should include both the direct measurement of forces, as reported in the paper from Germany, and the performance of structures designed to withstand a given load, as reported in the paper from Finland. Such observations are necessary to confirm theoretical formulæ of the type presented in the paper from Denmark, and to confirm and further develop design codes such as those used by the USSR. It is of interest that although the pressure and shock from ice on the whole or part of a structure was one of the questions for Section II, Subject 5 of the 1969 Congress, no information was contributed on the subject.

Navigational Aids.

Several of the papers identified maintenance of navigational aids during the ice season as a major problem. For many routes, buoys and channel markers are removed when ice starts to form or reaches a given thickness or condition. Buoys that are left in position are sometimes damaged or displaced by ice. There is a great need to develop navigational aids that will function reliably under all ice and weather conditions.

The paper from Finland describes fixed bottom channel markers that have been designed to withstand forces in the landfast ice zone adjacent to the coast of Finland. In the USA development work has been undertaken on buoys to improve their ability to withstand the effects of ice, and investigations are underway on other systems for guiding ships. There is a great amount of technical knowledge that could be applied to this problem, and a major effort should be made to apply it to the development of reliable guidance systems for areas subject to ice.

CONCLUSIONS AND RECOMMENDATIONS

1. Reporting of ice conditions and associated effects on structures, facilities and navigation should be encouraged. It is essential that an internationally accepted ice classification and glossary be used for this purpose to provide a suitable basis for comparisons. It is recommended that the classification for sea ice prepared by the World Meteorological Organization, and that for fresh water ice proposed by the International Association of Hydraulic Research, be adopted.

2. There is now a good understanding concerning the factors controlling the formation of ice jams in rivers. More field observations of conditions associated with ice jams are required to confirm theoretical methods of prediction.

3. Information should be developed concerning the dependence. of rate of ice formation on weather, flow conditions and state of the ice cover, with particular reference to improving ice forecasting methods and operational procedures.

4. Considerable information is being published concerning effects of ice and performance of ice control methods. A basis should be developed for comparing the severity of ice problems and efficacy of control methods for given weather, water and traffic conditions.

5. Attention should be given to reporting details concerning ships and ice conditions that would allow at least general conclusions to be drawn concerning the ability of vessels of given size and power to move through ice.

6. Considerable information on air bubbling systems and flow developeis is now available, and it should be compiled and reviewed for adequacy for ice control purposes.

7. A major problem is the effects of ice on facilities such as locks, ferry berths, submersible docks and wharfs, and the development of effective ice control systems for such facilities should be encouraged.

8. The ability to predict maximum ice pressures is still not satisfactory for engineering purposes. Field measurements of ice pressures are required to confirm and further develop analytical methods and design codes.

9. There is a major requirement for reliable navigational aids for ice covered waters, and there is an urgent need to apply modern technology towards solving this problem.

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XXIII[e] CONGRES INTERNATIONAL DE NAVIGATION

S. II - 4

Section II - Navigation Maritime - Sujet 4

(Commun aux Sections I et II)

Action des glaces sur les ouvrages et la navigation.
Moyens de prévenir leur formation et maîtrise de leur développement.

RAPPORT GÉNÉRAL

par

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INTRODUCTION

Le XIX[e] Congrès, tenu en 1957, a donné un bon aperçu général des conditions de la glace dans plusieurs pays ainsi que des problèmes qu'elles posent pour la navigation. Depuis lors, on a acquis une connaissance plus approfondie de ces problèmes et des mesures que l'on peut prendre pour en atténuer la gravité. Les rapports soumis au XXIII[e] Congrès reflètent cet accroissement des connaissances et apportent des détails considérables au sujet des effets de la glace sur les voies d'eau navigables et des procédés de contrôle de celle-ci. En vue de la discussion, les informations contenues dans ces rapports peuvent être classées sous les rubriques suivantes : observations des conditions de la glace, effet de la glace sur les ouvrages et sur l'exploitation, procédés de contrôle de la formation et du mouvement de la glace, pression de la glace sur les ouvrages et aides apportées à la navigation.

RÉSUMÉ DES RAPPORTS

Allemagne (R.F.) — (MM. R. Bock, F. Cordes, H.D. Dudziak, L. Franzius, H. Grothues-Spork, F. Günneberg, H. Wismer).

Ce rapport discute les pressions exercées par la glace, les essais sur modèles pour les transporteurs de vrac-brise-glace, le comportement des ferry-boats dans la glace, l'effet de la glace sur la navigation dans la zone à marée de l'Elbe et les moyens de combattre la glace.

Pendant la construction du barrage sur l'Eider on a fait des observations sur les conditions créées par la glace et les pressions exercées par celle-ci dans l'estuaire de ce fleuve. Il se forme des blocs d'un volume de 300 à 400 m^3 et d'une épaisseur atteignant 4 m ainsi que des glaçons dont la surface atteint 5.000 m^2 avec une épaisseur de 30 à 40 cm qui, sous l'action de la marée, se déplacent d'un mouvement de va-et-vient à des vitesses atteignant 1 m/sec.

On a fait des mesures de la pression de la glace sur les pieux supportant un pont à l'endroit du barrage. Ces pieux étaient calculés pour une poussée de la glace de 100.000 tonnes force. Ces efforts furent mesurés à l'aide de 56 cellules de pression (jauges de contrainte) disposées en dix rangées l'une au-dessus de l'autre. Au second support formé par les pieux, on observa la pression exercée sur un diaphragme de 1,50 m de diamètre, monté verticalement dans un logement de forme carrée. On enregistra également l'épaisseur de la glace, la vitesse des glaçons, la vitesse du vent, le niveau et les températures de l'eau.

La plus grande pression sur les pieux ne se produisait pas à l'impact, mais plutôt juste avant l'arrêt d'un glaçon. Les pressions statiques qui s'exerçaient après l'arrêt étaient toujours inférieures aux pressions dynamiques précédentes. Les installations à cellules multiples indiquaient de manière continue les charges locales variables. On constata que les pressions aux deux endroits dépendaient de la température, de l'épaisseur de la glace, de la structure des glaçons et de la forme du dispositif de mesure. La poussée maximale observée fut de 30.000 tonnes et il se présenta des pressions de pointe de 20 kp/cm^2. La destruction du dispositif de grand diamètre pour la mesure de la pression indiqua une poussée de la glace dépassant 60.000 tonnes.

Les observations faites sur la flexion de ducs d'Albe isolés, en tubes d'acier, d'un diamètre de 812,8 mm, indiquèrent une poussée de la glace de 30.000 tonnes force.

Les vannes du barrage étaient calculées pour des charges statiques de 15.000 tonnes/mètre et des charges dynamiques de 75.000 tonnes/mètre. On observa qu'un enrochement était sujet à érosion et que les pointes en saillies des blocs de granit étaient arrondies sous l'action de la glace.

On entreprit une recherche concernant les coques destinées à briser la glace, en raison du fait que les grands transporteurs de vrac doivent nécessairement naviguer dans des eaux couvertes par celle-ci. Quand un navire avec une proue en pente se déplace à travers la glace, il se produit des efforts de flexion pour briser la glace de manière continue. Les morceaux de glace ainsi formés sont rejetés vers le bas et vers les côtés. Pour progresser, le navire doit être capable de développer une puissance suffisante pour briser la glace, la déplacer et vaincre l'effort de friction s'exerçant entre celle-ci et la coque. La reproduction de ce comportement dans un modèle est encore douteuse, en raison de l'incompatibilité des lois de similitude pour les différentes sources de résistance. Les études sur modèles peuvent toutefois élucider les aspects du processus de rupture de la glace et il est donné une brève description d'une étude de ce genre concernant les forces s'exerçant sur une coque au moment de l'impact.

Le rapport décrit l'exploitation des ferry-boats sur le canal de Kiel pendant les périodes de présence de la glace. Les ferry-boats doivent nécessairement naviguer perpendiculairement à la passe utilisée par le trafic des navires. Ils doivent assurer leur service, même quand seuls de grands navires assistés de brise-glace utilisent le canal. La glace crée des conditions pour lesquelles ils n'ont pas été prévus, mais pendant moins de 5 % de la durée du service.

La glace déplacée par les navires entrave sérieusement l'exploitation des ferry-boats et l'utilisation des accostages. Les barboteurs et les circulateurs n'ont pas pu tenir la glace éloignée des baies des ferry-boats. La manœuvrabilité de ces derniers, qui fonctionnent avec une égale facilité en marche avant ou en marche arrière, est utilisée au maximum.

Le document donne une description des conditions que crée la glace dans l'estuaire de l'Elbe. La formation de la glace dans cette région de même que la diminution du débit venant des sections du fleuve non influencées par la marée, qui résulte de la formation de la couverture de glace, ont une influence significative sur les niveaux de la marée. On doit tenir compte de cette influence aussi bien que des effets de la glace pour la circulation des navires et la construction des ouvrages hydrauliques. La présence de la glace dans le fleuve et son estuaire affecte principalement les petits navires.

Le trafic sur les voies d'eau intérieures ne peut être maintenu par les brise-glace que si l'épaisseur de la glace est inférieure à 12-15 cm et n'augmente pas. On manifeste de l'intérêt pour l'emploi de l'eau chaude industrielle en vue d'empêcher la formation de la glace. Quatre cas sont discutés : les effets éventuels de l'eau chaude résiduaire provenant de la centrale de Kümmel, la construction de centrales le long des canaux, les effets de la décharge d'eau chaude dans un canal près de Hanovre et l'emploi d'eau de refroidissement venant d'une centrale nucléaire et de l'industrie lourde pour éloigner la glace d'une installation d'écluse sur le canal de Kiel. Il est souligné que si l'on doit employer de telles sources d'eau chaude, la situation des centrales et de l'industrie qui doivent les constituer doit être choisie avec soin. On doit aussi tenir compte du problème de la pollution thermique; en été, il peut être nécessaire d'assurer le refroidissement de l'eau chaude résiduaire ou de prévoir quelque autre procédé pour son rejet.

Canada — (MM. T.F. Saunders et M. Timascheff).

Ce rapport décrit les recherches entreprises pour la construction d'un appontement pouvant fonctionner toute l'année, l'un pour un pétrolier de 100.000 tonnes port en lourd et l'autre pour un navire plus petit, de 20.000 tonnes port en lourd.

L'ouvrage fut construit sur le fleuve St-Laurent, près de la ville de Québec, dans une région où règnent des conditions que la glace rend sévères.

A cet endroit, la glace fait d'habitude son apparition au début de décembre et commence à disparaître vers la mi-avril. Son épaisseur normale est de 75 cm environ, mais on voit fréquemment des masses de glaces flottantes, des hummocks et des barrages suspendus d'une épaisseur maximale estimée à 15 m. La passe principale n'est jamais complètement gelée, mais elle est d'habitude recouverte de glaçons non consolidés, se déplaçant vers l'aval sous l'influence des courants du fleuve et des courants de marée. Le site est sujet à de grandes marées de 6 m environ avec un maximum de 8 m environ.

Le document décrit les observations faites sur les conditions de la glace pendant un hiver, entreprises pour compléter les données relatives au climat. La glace permanente adhérant au rivage avait à cet endroit une largeur approximative de 240 m. Il existait une ceinture supplémentaire, de 90 à 120 m de large et d'une épaisseur approximative de 1 m formée de glaçons et de fragments de glace bien compactés. On a conclu de ces observations que l'accostage principal se situerait juste à l'extérieur de la glace de rivage permanente et serait soumis à des chocs sévères par les gros glaçons dérivant en travers du fleuve, sous l'action du vent, pendant le reflux. On a considéré que la probabilité de collisions pendant la marée était minime.

Sur la base des données climatiques relatives à la glace, des observations faites sur le terrain et de l'étude d'un modèle hydraulique, il fut décidé de construire une structure ouverte avec des déflecteurs de glace pour protéger les navires et la tête de l'appontement contre les glaçons se déplaçant vers l'amont ou vers l'aval. Des cellules de béton massif, de section transversale circulaire, se sont révélées des plus pratiques et des plus économiques et comme ayant une forme appropriée. On a étudié diverses variantes d'alignement pour arriver à un compromis raisonnable entre la protection des accostages et des caractéristiques de navigation acceptables.

Trois de ces cellules, ayant environ 24 m de diamètre, furent alignées avec une digue en enrochement, reliant l'appontement au rivage située du côté du fleuve par rapport à l'installation et assurant une protection à l'accostage des grands navires. Ces cellules furent étudiées pour résister à l'impact de glaçons de 4,50 m d'épaisseur pesant 700.000 tonnes courtes ou à une poussée de la glace de plus de 4.000 tonnes appliquées à 23 m au-dessus de leur base. Les ducs d'Albe d'accostage, mieux abrités, furent calculés pour une charge maximale de 2.950 tonnes. Des défenses flottantes pneumatiques, en caoutchouc renforcé de fibres, de 3,60 m de diamètre, furent utilisées pour absorber les chocs de grands glaçons pouvant heurter les navires.

L'installation a été en service depuis l'été de 1971 et fut utilisée sans difficulté par 99 navires au cours de l'hiver 1971-1972.

Le document donne une bonne description du principe de la construction et des recherches faites pour en établir les conditions; il décrit la structure et indique son comportement à ce jour.

Danemark — (M. P. Tryde).

Ce rapport présente des formules pour le calcul de la pression des glaces contre un pieu cylindrique isolé, contre des faces verticales ayant une largeur inférieure à 10 fois l'épaisseur de la glace, des jetées verticales et inclinées avec un nez en forme de triangle et des longs murs rectilignes avec un parement vertical ou incliné. On admet que les forces agissant sur les glaçons ou les couvertures continues et se manifestant au moment du contact avec un ouvrage sont des tensions de cisaillement dues au courant et au vent, des forces d'inertie et des efforts associés à l'écrasement ou à d'autres modes de rupture de la glace.

Ce document donne les équations pour le calcul des tensions de cisaillement exercées par le vent et l'eau sur les couvertures glaciaires. Les valeurs que l'on obtiendrait pour la force sont inférieures à celle que l'on calculerait au moyen des équations données dans le code russe, avec la même vitesse du vent et du courant.

En ce qui concerne le pieu, la jetée à parement vertical et le long mur rectiligne, on suppose que la glace se brise par cisaillement, sous un angle de 45° par rapport à l'horizontale. L'équation obtenue tient compte de la géométrie de la rupture (par l'intermédiaire d'un coefficient égal à $2 + 0{,}7\ e/d$, où e est l'épaisseur de la glace et d la largeur de la structure), de la résistance au cisaillement et de l'épaisseur de la glace ainsi que de la largeur de l'ouvrage. Dans le cas d'une jetée de forme triangulaire avec une face verticale, après un premier contact, la force augmente jusqu'à une valeur maximale, à mesure que la structure s'engage graduellement dans le glaçon. Le rapport donne une équation montrant la relation entre la pression et l'importance de la pénétration, ainsi que la relation entre la pénétration, la vitesse et la masse du glaçon.

On utilise la méthode de Korghavin pour calculer la force maximale sur une jetée triangulaire inclinée. Un facteur de réduction tient compte des angles des coins et de la pente de la jetée, du coefficient de friction à la face de contact et de l'excentricité de la force normale agissant sur la glace.

L'auteur présente une thèse montrant que pour un long mur rectiligne, l'énergie absorbée pendant l'écrasement, sur toute sa longueur, est suffisamment importante pour empêcher toute accumulation majeure de la glace. Il discute les conditions d'accumulation de la glace devant un mur rectiligne incliné, de grande longueur. Il donne un exemple des forces s'exerçant sur un mur incliné, calculées d'après les équations dérivées, au moyen d'un ordinateur. On envisage maintenant des études sur modèle pour vérifier ces équations.

Finlande — (M. T. Rekonen).

Ce rapport concerne principalement les effets de la glace sur la navigation et les auxiliaires de celle-ci. La glace apparaît d'abord le long de la côte de Finlande où elle forme une couverture ferme, adhérant au rivage, qui s'étend au-delà de la zone insulaire. Au cours de l'hiver, une banquise consolidée se forme fréquemment à la suite de la glace collée au rivage. La banquise et les couvertures de glace consolidées disparaissent pour la première fois pendant le dégel de printemps. La partie nord du golfe de Bothnie est prise par les glaces, même au cours des hivers les plus cléments. Pendant les hivers rigoureux, les détroits danois et baltiques peuvent être couverts de glace. L'épaisseur maximale de la glace ferme adhérant au rivage varie de moins de 50 cm dans la zone côtière, près de Helsinki, à 80-100 cm dans la partie nord du golfe de Bothnie. Des crêtes d'une épaisseur appréciable peuvent se former dans la glace et dans la zone de transition entre la glace adhérant au rivage et la glace de banquise consolidée.

On a constaté que la résistance à la compression de la glace n'ayant qu'une faible salinité était de 28 kg/cm^2 perpendiculairement à la direction d'accroissement. Cette résistance augmente de 4,1 kg/cm^2 par degré centigrade de diminution de la température. La résistance à la flexion se situe entre 3 et 6 kg/cm^2. Des observations faites sur le terrain ont indiqué que l'on pouvait admettre une température de la glace se situant entre 0 et — 2°C pendant les périodes de charge maximale.

La Finlande possède probablement un nombre de brise-glace proportionnellement plus grand que n'importe quel autre pays par rapport au volume du trafic. La tâche principale des brise-glace est de maintenir la navigation dans les ports méridionaux. Pendant les hivers normaux et rigoureux, la partie nord du golfe de Bothnie est fermée pendant quelques mois. Le rapport donne une description des opérations normales de rupture de la glace au cours de l'hiver.

Il est très difficile de manœuvrer des navires dans la glace en mouvement et l'on trouve plus facile de leur ouvrir des passes dans la glace ferme adhérant au rivage. L'emplacement de ces passes hivernales se base sur plusieurs années d'observation des conditions de la glace. Le développement d'auxiliaires de navigation appropriés pour le repérage des passes constitue un problème majeur. Des bouées d'hiver, de grand diamètre, ancrées sur le fond, peuvent s'employer aux endroits où la glace n'est pas sujette à beaucoup de mouvements. On considère les auxiliaires de navigation fixés sur le fond comme mieux appropriés et on envisage de les équiper de systèmes lumineux non ambigus et de réflecteurs radar qui permettront de les distinguer nettement des autres objets.

On a utilisé dans le passé des structures de balises fixes, de forme conique. On considère qu'une surface en pente peut ne présenter aucun avantage, car la poussée maximale de la glace se produit vraisemblablement quand la couverture gelée adhérant à l'ouvrage commence à se déplacer pour la première fois. La tendance actuelle est à l'utilisation de structures cylindriques. Des essais ont montré que la poussée due à la glace diminue dans une mesure considérable avec le diamètre, jusqu'à ce que celui-ci soit égal à l'épaisseur de la glace. Il est tenu compte de ce fait dans l'étude des bouées fixées sur le fond. Le rapport donne des exemples de balises fixées dans la roche ou dans le sol, sur le bord des passes. Une structure à installer dans la partie nord du golfe de Bothnie a été calculée pour une force de 450 tonnes métriques et des charges d'impulsions de 550 tonnes. Ces nouvelles balises sont considérablement moins coûteuses que celles du type suédois dont quatre ont été construites dans le golfe de Bothnie en 1964-1965. Les structures du type suédois étaient calculées pour une poussée de 1.110 tonnes (150 tonnes/mètre) et se sont comportées de manière satisfaisante.

Les balises des passes des voies d'eau intérieures sont soumises à des charges beaucoup plus faibles. Des balises prévues pour une poussée de 7 tonnes se sont révélées satisfaisantes. On n'a pas non plus constaté de rupture de balises installées dans des lacs où l'épaisseur de la glace atteignait 50 à 70 cm et calculées pour des poussées de 14 tonnes. Ces charges sont probablement réduites par le fait que la glace n'est soumise qu'à de faibles mouvements horizontaux et a tendance à fondre sur place.

Le rapport donne une équation pour le calcul de la charge maximale s'exerçant sur une structure cylindrique quand la glace commence à se déplacer pour la première fois.

France — (M. Robert Vadot).

L'auteur confirme à nouveau et met à jour l'expérience rapportée au Congrès de 1957 au sujet des effets de la glace sur la navigation dans les voies d'eau françaises. L'attention se porte principalement sur trois points: action des glaces sur les ouvrages de navigation, moyens de prévenir leur formation et maîtrise de leur déplacement.

La glace est responsable d'un tiers environ du temps d'arrêt total de la navigation, c'est-à-dire un temps inférieur à celui qu'exige l'entretien. Son apparition est toutefois imprévisible et elle peut subsister jusqu'à 3 mois. La formation d'une couverture glaciaire et en particulier d'un barrage de glace relève le niveau de l'eau et augmente la vitesse du courant, en entraînant éventuellement une inondation, une érosion locale du lit et des pressions dangereuses sur les ouvrages.

Tous les moyens sont employés pour maintenir la glace en mouvement pendant sa formation. Les bouées sont enlevées avant que la glace puisse les endommager. Dès qu'il s'est formé une couverture solide, on arrête d'habitude la navigation, en particulier sur les voies d'eau intérieures de faible importance, jusqu'à ce que le dégel commence. L'enlèvement de la glace commence aussitôt que possible, une fois qu'il s'amorce. On fait bon usage des prévisions météorologiques pour déterminer les mesures à prendre en ce qui concerne la glace. On a constaté que le déversement d'eau chaude venant des exploitations industrielles et des centrales électriques dans les chenaux de navigation a un effet favorable. Les brise-glace et les systèmes de barbotage sont efficaces en certains endroits et dans certaines conditions. Le trafic continu des bateaux, accompagnés si nécessaire par des brise-glace, peut retarder l'établissement d'une couverture solide.

Il est important de maintenir en mouvement les organes mobiles de tous les ouvrages de contrôle et de toutes les écluses. A cet effet, des éléments chauffants ont été installés sur certains de ceux-ci. Les plus grandes difficultés se rencontrent dans les ouvrages anciens, qui n'étaient pas conçus pour les conditions difficiles dues à la glace. On les laisse ouverts pendant les périodes de formation de celle-ci, dans les cas où des conséquences sérieuses pourraient résulter de leur immobilisation par le gel.

Pays-Bas — (MM. H.M. Oudshoorn et J.A. van Hiele).

On a construit de nombreux ouvrages de contrôle dans le Delta du Rhin depuis la présentation au XIX^e Congrès de Navigation de 1957 de l'étude sur la glace dans les voies d'eau des Pays-Bas. Le rapport au XXIII^e Congrès apporte des informations sur les changements survenus dans les caractéristiques de la formation de la glace par suite de ces constructions et sur l'expérience acquise au sujet du contrôle de la glace et de ses effets sur les ouvrages.

Le Rhin débouche en mer du Nord par plusieurs grands bras de mer sujets à l'action de la marée. La construction d'une digue a divisé les eaux de ce fleuve à marée en deux bassins. Quand les travaux du Delta seront achevés, le bassin situé le plus au Sud, dans lequel se décharge d'habitude une quantité considérable de la glace charriée par le Rhin, sera complètement isolé de la mer et formera un lac d'eau peu salée. Le Rhin et la Meuse s'écoulent dans le bassin Nord qui est en communication directe avec la mer par le Rotterdam Waterway. L'écoulement par le bras de mer principal, qui comprend le Hollandsch Diep et le Haringvliet, est commandé par des écluses récemment achevées en travers de l'entrée de ce dernier.

Une grande quantité de glace se forme dans les estuaires à marée à eau fraîche. Cette glace dérive lentement vers la mer à une vitesse dépendant de l'endroit, du courant et du vent. Au moment du flux, dans la zone de transition entre la région soumise à la marée et le courant normal du fleuve les vitesses sont faibles et la glace a tendance à s'accumuler. Si les conditions sont favorables, cette banquise gèlera pour former une couche solide. La couverture de glace peut alors progresser rapidement vers l'amont, en raison de la consolidation des glaçons flottants charriés par le Rhin et par la Meuse.

On a rassemblé de nombreux renseignements au sujet de l'influence de la température de l'air, de la vitesse du courant et de la situation sur le Rhin ou les systèmes d'estuaires sur la vitesse de formation de la glace et de sa débâcle. Certains de ces renseignements sont résumés dans la figure 2 du rapport. Une attention particulière a été consacrée aux facteurs hydrauliques commandant la formation de l'embâcle dans la région soumise à la marée. On a constaté que les conditions dans lesquelles il se forme sont raisonnablement bien représentées par le nombre de Froude. Les valeurs critiques déterminées par des observations sur le terrain sont de l'ordre de 0,06 à 0,09 (voir fig. 9).

La navigation est entravée en moyenne 8 à 10 jours seulement par an pour les petits bateaux et pendant 4 à 7 jours pour les grands. On constate qu'il est très important de maintenir la glace en mouvement. Les bouées sont enlevées le plus tard possible. En général, la navigation sur les voies d'eau plus larges, où des bouées sont nécessaires, s'arrête quand les glaçons couvrent presque toute la surface de l'eau. Pour d'autres voies d'eau, la densité du trafic retarde la formation de glace ferme et les navires les plus puissants peuvent continuer à circuler aussi longtemps que la glace est en mouvement.

Le bris de la glace est commencé aussitôt que possible sur le bord aval de la glace ferme ou des embâcles. On utilise pour ce travail des brise-glace, dont la puissance peut atteindre approximativement 375 CV, qui empêchent la formation d'une couverture solide. Cette action prompte et continue qui, dans la zone à marée, ne peut être entreprise efficacement qu'au moment du reflux, a réduit le curage du lit du fleuve exigé par les embâcles et les dommages dus à la glace. L'élimination des irrégularités du courant a amélioré les caractéristiques du système fluvial en ce qui concerne la débâcle.

Un réseau d'observation terrestre a été établi en vue d'obtenir un relevé continu des conditions de la glace. Ce réseau est appuyé par la reconnaissance du bord d'un avion. Un calculateur analogique, construit pour reproduire les conditions dans la zone du Delta, a réussi à reproduire l'effet sur les conditions de la glace de la construction et du fonctionnement des ouvrages de contrôle hydrauliques. Une procédure opérationnelle générale, à adopter au cours des périodes où les fleuves sont gelés, après achèvement des ouvrages du Delta, a été établie et est présentée dans les conclusions.

Pologne — (MM. E. Jasinska et W. Robakiewicz).

Ce rapport présente une discussion théorique des systèmes de barbotage, des résultats d'expériences faites pour confirmer la théorie et des observations sur l'emploi de tels systèmes comme barrières contre la glace. On admet que la vitesse en surface, désignée par U, induite par le système de barboteur est une fonction de deux nombres sans dimension :

$$N_a = \frac{Q}{H^2 \sqrt{gH}} \frac{\rho'}{\rho}$$

où Q = volume d'air dégagé.
H = profondeur des orifices de sortie de l'air sous la surface.
ρ' = densité de l'eau.
ρ = densité de l'air.
g = accélération de la gravité

et $$N_b = \frac{H}{D}$$

où D = diamètre des orifices de sortie de l'air.

Les figures 2 et 3 du rapport indiquent la relation observée entre $U/\sqrt{gH}$ et N_a pour des valeurs données de N_b. On fit varier les diamètres des orifices entre 1 et 4,5 mm, la profondeur d'immersion entre 0,30 m et 9 m et la pression de l'air de 0 à 5 $\times$ 10^5 N/m². Une seconde série d'expériences donne la relation entre Q et le diamètre D des orifices de sorties ainsi que le rapport p_o/p_r, où p_o est la pression absolue à l'extérieur du tuyau perforé et p_r la pression absolue à l'intérieur de celui-ci.

Le document rapporte une expérience sur l'emploi des systèmes de barbotage pour empêcher l'entrée de la glace dans un dock flottant pendant son immersion ou pendant l'entrée des navires. En vue d'une efficacité maximale, l'espacement des orifices devrait permettre aux cônes adjacents formés par les bulles d'air ascendantes de se confondre en surface. Les orifices doivent être d'une dimension suffisante pour ne pas être obstrués par des particules et la vitesse de sortie de l'air doit être suffisamment grande pour que la vitesse induite en surface tienne la glace éloignée du bassin pendant son immersion. Le rapport donne également des détails au sujet des installations de barbotage utilisées avec succès pour maintenir la glace à l'écart des accostages des ferry-boats et au sujet d'une expérience destinée à étudier leur emploi pour éloigner la glace des zones portuaires.

Tchécoslovaquie — (MM. A. Sikora et I. Grund).

Ce rapport concerne une étude sur modèle entreprise pour établir le procédé le plus efficace pour déplacer la glace devant la centrale de Gabcikovo sur le Danube et réduire ainsi à un minimum le temps nécessaire pour dégager le réservoir amont et permettre le trafic des bateaux. On pouvait faire passer la glace par des déversoirs auxiliaires situés de chaque côté du barrage de la centrale ou par une passe navigable adjacente à celui-ci.

Une échelle de 1 : 70 fut choisie pour le modèle hydraulique du barrage et du chenal navigable. Des plaques de paraffine polygonales, ayant un poids spécifique à peu près égal à celui de la glace, furent utilisées pour représenter les glaçons supposés avoir un diamètre moyen de 5 m et une épaisseur de 50 à 60 cm. L'étude donne le temps total pour faire passer la glace au-delà du barrage, la surface de glace passée par unité de volume d'eau déversée et le meilleur moyen de contrôler le courant pour obtenir la vitesse maximale d'évacuation de la glace sans provoquer une embâcle.

On constata que quand on utilisait les seuls réservoirs auxiliaires, on ne pouvait maintenir une évacuation continue de la glace, parce qu'elle se serait accumulée et il se serait produit une embâcle aux approches du barrage. L'augmentation de la vitesse du courant dans le chenal d'approche, par un déversement simultané de l'eau de la centrale, faisait surgir le même problème. La glace passait normalement par les écluses de navigation à toutes les vitesses de déversement quand on utilisait ce seul procédé. Quand on augmentait la vitesse du courant en déversant en même temps, soit par les déversoirs auxiliaires, soit par la centrale, soit par les deux, l'accumulation de la glace pouvait se produire à l'amont de l'entrée du chenal de navigation. Les résultats de l'étude sur modèle sont résumés sous une forme générale dans le tableau. Il est signalé que la température au moment de l'évacuation de la glace, qu'elle se congèle ou qu'elle fonde, la quantité de glace à faire passer, la dimension des glaçons et la vitesse à laquelle la glace est amenée à l'ouvrage, influencent la relation entre le comportement du modèle et celui du prototype.

L'étude a montré qu'une combinaison de l'évacuation de la glace par le chenal de navigation et les déversoirs auxiliaires offre potentiellement les conditions les plus favorables. Toutefois, si l'on doit adopter cette combinaison, on devra mettre au point des procédés qui empêchent la formation d'embâcles à l'amont des déversoirs auxiliaires. Tous les procédés essayés consomment une forte quantité d'eau. L'élimination de la glace au moyen de la quantité minimale d'eau est réalisée en évacuant par le canal de navigation seulement. La question se pose de savoir si l'eau serait mieux utilisée en produisant de l'énergie qu'en avançant la saison de navigation par évacuation de la glace.

Le rapport montre les courbes montrant l'influence de la vitesse de déversement de l'eau sur :

1. le volume nécessaire pour faire passer un mètre carré de glace;
2. le temps requis pour évacuer la glace d'un kilomètre carré de surface d'eau, et
3. le volume total d'eau exigé pour débarrasser tout le réservoir de la glace.

Le document présente aussi deux courbes donnant le temps et le volume d'eau nécessaires pour dégager toute la surface du réservoir, en appliquant les divers procédés ou leur combinaison.

U.R.S.S. — [M. A.F. Parfenov (préparée par MM. V.V. Balanin et L.V. Ivanov)].

Un rapport circonstancié au sujet des effets de la glace sur la navigation en U.R.S.S. et sur les procédés utilisés pour s'y opposer a été présenté au Congrès de 1957. Le présent rapport passe en revue les progrès réalisés au cours des 15 dernières années, en ce qui concerne les principaux problèmes qui se sont posés, la tendance dans les procédés de contrôle de la glace, le calcul des installations de contrôle de celle-ci et l'expérience acquise en la combattant.

Le rapport expose clairement les problèmes posés par la formation de la glace sur l'eau et dans les installations, aux écluses, aux appontements et dans les bassins. Les bateaux circulant dans les canaux ainsi qu'à l'entrée et à la sortie des ports brisent continuellement la glace et déterminent une forte augmentation de l'épaisseur de la couverture par suite du flottage en train et de la formation de hummocks. Cette glace peut entraîner des dommages si elle est prise entre un ouvrage et un bateau. Le prix de revient de l'entrée en bassin, en hiver, dépasse de 24 à 50 % le coût de cette manœuvre en été et la plus grande partie de cette augmentation est due à la glace. La jeune glace pose un problème sur certains fleuves. Ses effets sur la navigation ont été atténués par la construction d'ouvrages hydrauliques. L'adhérence de cette glace aux bateaux peut être réduite en chauffant la coque de manière appropriée.

De nombreuses observations du régime des glaces ont été faites sur les voies d'eau navigables. On a utilisé les renseignements recueillis pour préciser l'activité des brise-glace et la flotte de brise-glace requise pour augmenter la saison de navigation de 20 jours au moins en automne. Sur certains itinéraires intérieurs de courte longueur, on peut maintenir la navigation toute l'année par un trafic de bateaux de forte intensité, si le climat le permet.

L'importance des connaissances relatives au régime thermique et au régime glaciaire des routes de navigation est mise en évidence. Le rapport décrit les conditions de formation de la glace de fond et de surface dans les estuaires, par suite de l'entrée de l'eau de mer froide au cours de la marée. Il décrit la base adoptée pour la construction des systèmes de barbotage et des accélérateurs de courant pour le maintien de zones libres de glace. On considère comme étant de grande importance un emplacement correct des sources d'eau chaude, telles que les centrales thermiques. On peut employer l'eau chaude plus efficacement en l'évacuant par des tuyaux perforés, posés en dessous de la zone où l'on doit empêcher la formation de la glace. Une telle installation requiert certains moyens, tels qu'un système de barbotage, pour faciliter la montée de l'eau chaude vers la surface. On a mis récemment au point un système qui éjecte un mélange d'air et de vapeur par des tuyaux perforés posés sous l'eau. Ce système fonctionne de la façon la plus économique lorsqu'il est contrôlé de manière à retenir une couche de glace de 5 à 10 cm à la surface de l'eau. Des éléments chauffants dans des générateurs flottants sont également employés pour maintenir des surfaces de faible étendue libres de glace. On a fait des expériences sur l'emploi de polystyrène granulaire pour empêcher la formation de glace dans les zones abritées, autour des ouvrages. Le rapport décrit un dispositif pour empêcher l'adhérence de la couverture de glace aux pieux.

Le rapport résume la base du calcul des structures pour résister aux charges statiques et dynamiques imposées par la glace. Il donne les spécifications à respecter pour le béton en contact avec l'eau en train de geler. Des revêtements protecteurs isolants sont appliqués à la surface de certains ouvrages.

Le document donne les équations pour le calcul des charges théoriques sur les barrages démontables utilisés pour protéger les écluses contre la glace. Ces barrages sont, soit immergés, soit traînés vers le côté pour permettre l'entrée des bateaux. On a mis récemment au point une barrière consistant en un système de flotteurs pour éloigner la glace des ports, des postes d'accostage des ferry-boats, ainsi que des bassins flottants. Quand la glace dérive contre les flotteurs, ceux-ci sont pressés l'un contre l'autre. Une coque de navire les écrate facilement l'un de l'autre, mais ils restent en étroit contact avec celle-ci pendant le passage du bateau.

On a mis au point un système de filet spécial pour les accostages des ferry-boats. Quand le bateau entre, il pousse le filet devant lui. Quand il s'en va, le filet revient en éloignant de l'accostage toute glace qui peut être entrée avec le bateau. Le filet agit aussi comme barrière contre la glace quand l'accostage n'est pas occupé.

On a constaté que les circulateurs étaient efficaces pour la protection des plans d'eau et des ouvrages ainsi que pour enlever la glace brisée du fond des navires avant leur entrée en cale sèche ou dans un dock flottant. Le rapport donne des équations pour leur construction, en vue de la protection des docks flottants pendant leur immersion et leur emploi.

On a constaté que des anciens moteurs d'avion à réaction constituaient des sources de puissance utiles pour combattre la glace dans les zones portuaires. Les gaz d'échappement chauds peuvent servir à empêcher le givrage des défenses, des dispositifs d'amortissement, des murs de protection des jetées et des éléments mobiles des ouvrages. On peut aussi les utiliser pour chauffer les ateliers dans les cales sèches et empêcher le gel de certaines étendues d'eau. La puissance du moteur peut s'employer pour produire de l'électricité ainsi que de l'air comprimé pour les systèmes de barbotage.

La communication donne une description détaillée des systèmes de barbotage, de chauffage et de barrages employés pour les écluses qui doivent fonctionner à des températures inférieures à la température de congélation. La construction de ces systèmes dépend du climat, du type d'écluse, de l'étendue de la période pendant laquelle une écluse doit fonctionner à des températures de l'air inférieures à zéro, ainsi que des autres caractéristiques de l'équipement.

Il est clair qu'on a réalisé de sérieux progrès dans la solution des problèmes que pose la glace dans les zones portuaires et les accostages de ferry-boats, les bassins et les écluses, grâce à un emploi judicieux des systèmes de barbotage, des circulateurs, des barrières à glace et des dispositifs de chauffage. On a éliminé, au moyen d'une combinaison de dispositifs anti-glace, les principales difficultés dues à la glace dans 12 cales sèches et docks flottants pour la réparation des navires.

U.S.A. — (Dr. Charles C. Bates).

Au Congrès de 1957, fut donnée une description du climat, des conditions résultant de la présence de la glace, de l'effet de la glace sur la navigation et des mesures prises pour combattre la glace, sur la voie d'eau des Grands Lacs et du Mississippi ainsi que de leurs affluents. Le présent rapport communique de nouvelles initiatives pour prolonger la saison de la navigation sur les Grands Lacs, la voie maritime du St-Laurent, le Mississippi supérieur et ses principaux affluents, ainsi que dans les régions côtières de la Nouvelle-Angleterre et de l'Alaska.

On a entrepris, pour le système des Grands Lacs et de la voie maritime du St-Laurent, l'exécution d'un programme, portant sur trois ans, d'observations des conditions et des forces de la glace, de recherches sur le milieu environnant et l'écologie, de rassemblement de données techniques relatives à la construction des navires de recherches, sur les installations de contrôle de la glace et des auxiliaires de la navigation, d'études sur modèles, de coordination et de diffusion des informations aux navigateurs au sujet des conditions météorologiques et résultant de la présence de la glace. Les techniques de surveillance comprennent la photographie aérienne des passes obstruées, les relevés terrestres des caractéristiques de la glace et de la neige à 58 stations, les reconnaissances aériennes et le contrôle des niveaux de l'eau. Cette information est transmise deux fois par semaine à un organisme dénommé « Ice Navigation Center ». Ce Centre, qui est aussi rattaché au « Canadian Ice Forecasting Centre », fournit un résumé de la situation créée par la présence de la glace, accompagné de prévisions, cinq fois par semaine. Les renseignements concernant la formation de la glace et la débâcle fournis par ces observations de type synoptique sont complétés par des études plus détaillées. Des améliorations sont apportées aux méthodes de prévision relatives à la glace, en utilisant l'information provenant des satellites, des observations techniques faites sur les lacs, des statistiques climatologiques relatives à la glace et des études du mouvement de celle-ci.

On a entrepris des recherches sur la réduction de la friction entre la glace et la coque d'un navire au moyen d'un système de barbotage, sur le bris de la glace devant un navire par un dégagement rapide des gaz provenant de la détonation d'un mélange air/propane dans une proue en forme d'éperon, s'étendant sous la couche de glace, ainsi que sur l'efficacité relative d'un couteau vertical et d'une scie à chaîne pour découper une glace de 5 à 10 cm d'épaisseur. Il reste à déterminer s'il vaut mieux placer la glace brisée dans une passe au-dessus ou en dessous de la glace adjacente adhérant au rivage.

Le rapport présente un résumé des efforts entrepris pour résoudre le problème de l'effet de la glace sur les systèmes de navigation, par exemple les bouées. On a soumis à des essais des bouées dont la structure est renforcée et qui sont équipées d'un système d'éclairage modifié ainsi que six balises transpondeuses radar à bande X et neuf structures destructibles placées sur la glace adhérant au rivage. Deux systèmes de navigation utilisant des faisceaux Laser sont en cours d'expérimentation et on a mis à l'essai un équipement dit « Precise Laser Navigation System ». Il existe des projets d'expériences avec un faisceau Laser à « effet de fil métallique dans le ciell» (« wire in the sky effect »), qui assurerait un guidage pendant les périodes de visibilité appropriée. On fait également des expériences avec des systèmes de guidage LORAN et des câbles sous-marins établissant un champ magnétique pouvant être détecté du navire.

Des recherches ont été entreprises sous la forme de proue optimale pour un minéralier et sur différents dispositifs réduisant la résistance opposée par la glace. Une étude est en cours sur les forces que la glace peut exercer sur les ouvrages. L'attention se porte sur les structures de contrôle et de stabilisation de la glace; on a commencé trois études fondamentales des principes à appliquer pour améliorer la navigation hivernale, tout en évitant une interférence avec le courant du fleuve.

Des essais de barbotage sont en cours pour maintenir ouverts les chenaux des transbordeurs et débarrasser leurs accostages de la glace. Le rapport décrit les résultats de ces investigations. Au cours d'une étude, la glace accumulée dans un slip de transbordeur fut chassée par un violent jet d'air. L'échappement de l'air supplémentaire fut contrôlé par l'opérateur du transbordeur pendant l'essai.

On étudie l'emploi d'une isolation en polyéthylène rigide pour empêcher l'accumulation de la glace autour des ouvrages hydrauliques.

Sur le fleuve Mississippi, les convois se déplaçant à travers la glace sont desservis par des remorqueurs dont la puissance moyenne par barge est approximativement de 4 à 500 CV. La plupart des nouveaux remorqueurs sont équipés de tuyères Kort et ne sont pas aussi efficaces en face de la glace que ceux équipés d'hélices « ouvertes ». Ces convois ne rencontrent aucune difficulté dans la glace claire de moins de 10 cm d'épaisseur mais la circulation des barges cesse quand l'épaisseur de la glace dépasse 15 cm. Des problèmes importants doivent encore être résolus en ce qui concerne la manœuvre des écluses et des barrages ainsi que la navigation entre les écluses. Le tableau II du rapport résume ces problèmes et les solutions possibles.

Le principal problème dans les eaux de la Nouvelle-Angleterre est la destruction des bouées de navigation par la glace dérivante. L'expérience a montré que des plaques de glace mouvante de 8 cm d'épaisseur détruiront des bouées éclairées de 2,4 × 7,8 m avec une ancre de 3.800 kg, et qu'une glace de 30 cm d'épaisseur submergera des bouées de 2,7 × 11,5 m, en détruisant les lanternes et l'équipement qui les accompagne. Le givre peut s'accumuler sur une bouée et éventuellement la faire basculer ou la faire chavirer. Il peut également bloquer les systèmes de ventilation et mettre hors d'usage les batteries d'accumulateur air-zinc. Le document décrit l'expérience relative au comportement des bouées au cours des conditions sévères créées par la glace dans la Buzzard Bay. On a entrepris de perfectionner la construction de bouées résistant à la glace.

La mise en exploitation des gisements de pétrole et de gaz naturel au large des côtes ainsi que le développement de la ville d'Anchorage en Alaska a fait surgir la nécessité de la navigation durant toute l'année dans le Cook Inlet. La plupart des navires faisant route vers Anchorage par cette voie sont de la construction habituelle des navires de haute mer. Au cours de l'hiver 1971-72, huit navires ont présenté des fissures dues à la glace, dans la partie avant, près de la ligne de flottaison.

Pendant la saison des glaces, les bouées sont enlevées du Cook Inlet et il n'est prévu aucune aide spéciale à la navigation pour les remplacer. Un problème majeur est celui de la rupture des amarres et des accessoires sous la pression de glaçons atteignant 60 cm d'épaisseur, poussés par des vents de tempête et des courants de marée de 4 à 8 nœuds. La chaîne de toueur de la plupart des navires de commerce n'est pas suffisamment résistante pour l'ancrage dans la rade foraine. On considère qu'un brise-glace d'une dimension moyenne (60 à 75 m), de faible tirant d'eau et d'une puissance sur l'arbre de 6.000 CV environ est nécessaire pour les conditions qui prévalent dans le Cook Inlet.

Des mesures des forces exercées par la glace sur les structures de forage au large dans le Cook Inlet ont indiqué que la charge est inférieure à 8,8 kg/cm^2. Les efforts imposés par les arêtes représentent de 2 à 3 fois ceux dus à des glaçons uniformes; la charge maximale sur un montant cylindrique est de l'ordre de 27.000 à 31.500 kg par 30 cm de diamètre.

La découverte de pétrole sur le Versant Nord de l'Alaska et la possibilité de découvrir des gisements de valeur commerciale de charbon, de pétrole, de gaz naturel et de minerais dans la région de la péninsule Seward a suscité de l'intérêt pour une navigation de toute l'année vers le Nord jusqu'à l'océan Arctique. Des voyages d'essais dans cette région avec des brise-glace de la classe « Wind » ont indiqué la mesure dans laquelle de tels services sont possibles. Le document donne un résumé des activités des compagnies pétrolières en ce qui concerne la navigation et le forage au large dans la région arctique. Le rapport donne une brève description des brise-glace de la nouvelle classe « Polar » maintenant en cours de construction (puissance sur l'arbre 60.000 CV); ce brise-glace devrait être capable de traverser une glace de 1,80 m d'épaisseur.

Une mention est faite des récentes études des caractéristiques des crêtes de pression, de la mise au point d'un pénétromètre pour mesurer l'épaisseur de la glace, que l'on peut lancer d'un avion, et de l'expérience acquise dans l'emploi du radar latéral (SLAR) pour relever les caractéristiques de la couverture glaciaire. Les résultats obtenus à ce jour indiquent que le « SLAR » est probablement l'outil le plus utile dont on dispose pour l'observation périodique de jour et de nuit, par tous les temps, des couvertures de glace.

On en conclut que les résultats des nouvelles initiatives pour prolonger la période de navigation dans les eaux couvertes de glace semblent prometteurs.

Yougoslavie — (M. Slobodan Petkovic).

Ce rapport décrit un cas d'amélioration des conditions de la navigation en hiver par la construction d'un barrage de centrale hydroélectrique. Des roches submergées, une faible largeur du fleuve, des courants de grande vitesse et la glace ont sérieusement entravé le mouvement des bateaux sur le Danube dans la région frontière entre la Yougoslavie et la Roumanie. L'évolution d'une couche de glace dans cette section était caractéristique d'un fleuve à courant relativement rapide soumis à un climat continental. La valeur du nombre de Froude est variable et dépasse souvent 0,109 et des embâcles se produisent fréquemment. La construction du barrage de Djerdap a fortement diminué la vitesse du courant et réduit le nombre de Froude bien en dessous de la valeur critique pour la formation d'une embâcle. Cette région présente maintenant les caractéristiques d'un lac et une couche de glace solide se forme sur l'eau thermiquement stratifiée.

Quoique la glace commence à se former sur le réservoir plus tôt que dans les anciennes conditions du fleuve, l'établissement d'une couche continue solide au lieu d'une couche non consolidée et des embâcles a eu pour résultat une amélioration de la navigation. Les brise-glace peuvent maintenant assister la navigation et la maintenir, tandis qu'anciennement, elle était empêchée par les conditions que la glace rendait difficiles.

DISCUSSION

Observations des conditions que crée la présence de la glace.

Une connaissance détaillée des conditions qu'entraîne la formation de la glace et les facteurs dont ces conditions dépendent est absolument nécessaire pour la mise au point de procédés efficaces de contrôle de la glace et de procédures d'exploitation des voies d'eau et des ports ainsi que pour la construction des ouvrages de contrôle de la glace et des installations de desserte des navires. Ceci a été clairement démontré par des exemples d'application au développement du projet Delta en Hollande, à la mise en vigueur de mesures destinées à prolonger la saison de navigation automnale en U.R.S.S., à la détermination de la position des passes de navigation le long de la côte de Finlande en hiver et à l'établissement des principes de construction d'une importante jetée au Canada.

Ces observations sont d'un intérêt primordial pour la voie d'eau ou l'installation qu'elles concernent. Peut-être leur plus grande utilité pour d'autres implantations est-elle de fournir une base de comparaison des problèmes que pose la glace et de l'efficacité des solutions adoptées. Il est important d'adopter dans ce but une classification, acceptée internationalement, des conditions que crée la présence de la glace et une définition des termes. Un tel système a été instauré pour la glace de mer et est maintenant envisagé pour la glace d'eau douce. L'A.I.P.C.N. devrait examiner ces classifications et recommander leur adoption par ses membres lorsqu'ils traitent des conditions qu'entraîne la présence de la glace.

On peut extrapoler, pour d'autres emplacements, une certaine partie des informations concernant ces conditions et on devrait attacher une attention particulière à les recueillir. On peut citer comme exemple la situation critique d'écoulement en cas d'embâcle.

Des recherches ont montré que le nombre de Froude est un critère utile pour cette situation, mais il est nécessaire de disposer de renseignements supplémentaires, tels que ceux apportés par les rapports des Pays-Bas et de la Yougoslavie, pour un grand nombre de canaux, de conditions de débit et de situations créées par la présence de la glace. On peut aussi extrapoler, pour d'autres situations, les corrélations quantitatives entre la vitesse de formation de la glace à un stade déterminé de développement d'une couverture glaciaire ainsi que les renseignements météorologiques tels que la température de l'air et la vitesse du vent. Des informations de ce type, dont le rapport des Pays-Bas donne un exemple, sont intéressantes pour le développement des méthodes de prévision relatives à la glace et les procédures de desserte des navires. On devrait encourager l'étude de ces données.

Effets de la glace sur les ouvrages hydrauliques et leur manœuvre.

Un port ou une voie d'eau constitue un système formé de nombreux éléments. Leur utilisation en hiver est fonction de l'aptitude des navires à s'y déplacer et de la possibilité pour chacun de ces éléments de maintenir une activité acceptable dans les conditions que crée la présence de la glace. Les rapports présentés aux XIXe et XXIIIe Congrès sont une source précieuse d'informations concernant les effets de la glace sur les installations et l'interaction entre la glace et le navire. Il est toutefois très difficile de généraliser à partir de ces expériences ou de les comparer entre elles, parce que les conditions créées par la présence de la glace, le type de trafic et la densité de celui-ci, les caractéristiques des voies d'eau et des installations portuaires ainsi que la possibilité de contrôle de la glace varient dans une large mesure d'un endroit à l'autre. Il peut être utile, en vue de futures discussions et comparaisons, d'établir une distinction entre les régions et les installations qui, en hiver, ne sont pas sérieusement affectées, ou ne le sont que pendant de brèves périodes, et celles dont on ne peut maintenir l'exploitation qu'au prix d'un effort continu et parfois considérable ou pour lesquelles l'exploitation doit cesser partiellement ou complètement pendant une partie de la période.

Il semble qu'il existe une information appréciable au sujet de la possibilité pour des navires d'une puissance et d'un tonnage donnés de circuler dans des couvertures de glace d'une épaisseur et d'un état de consolidation déterminés, comme l'indiquent les rapports émanant de la France, de l'U.R.S.S., des Etats-Unis, de la Finlande, des Pays-Bas et de l'Allemagne. Par exemple, des navires d'un certain tonnage peuvent continuer à utiliser les canaux intérieurs de certaines régions aussi longtemps que le trafic peut maintenir la glace brisée en mouvement et que sa progression ne soit pas arrêtée par l'accumulation de glace brisée. L'assistance de brise-glace permet de maintenir la navigation dans la glace ferme d'une épaisseur approximative de 0,50 m le long de la côte méridionale de Finlande mais non dans la partie septentrionale du golfe de Botnie où la glace a une épaisseur de 1 m environ. Il serait utile de pouvoir utiliser et diffuser de manière appropriée l'information concernant la relation entre l'utilisation des navires, leur puissance et les conditions dues à la présence de la glace, car elle constituerait un guide utile pour les décisions à prendre en pratique.

Il résulte clairement des rapports qu'il existe un désir général de réduire les interruptions de la navigation dues à la présence de glace. Beaucoup de ces interruptions sont dues aux effets de la glace sur les installations telles que les écluses, les appontements, les accostages de ferry-boats et les docks submersibles.

Ces effets doivent être pleinement appréciés et bien compris de manière à pouvoir en tenir compte lorsqu'on arrive au stade de l'étude de nouvelles installations. On peut de cette façon apporter éventuellement des modifications qui atténueront les problèmes que pose la glace, comme le démontre l'expérience russe à propos des écluses et des installations de réparation des navires ainsi que l'expérience canadienne dans l'étude et la construction d'une nouvelle jetée. L'enregistrement cas par cas des effets de la glace peut être précieux, en particulier s'il est accompagné d'une description adéquate des conditions résultant des intempéries et de la présence de glace.

Procédés de contrôle de la formation et du mouvement de la glace.

L'importance d'un problème posé par la glace est déterminée par la vitesse à laquelle la chaleur se dissipe dans l'atmosphère à partir de la surface de la couche de glace ou de l'eau, par la période de temps sur laquelle s'est étendue cette perte et les caractéristiques de la voie d'eau ou de l'installation. On a mis au point, pour atténuer ces problèmes de nombreuses méthodes qui impliquent le déplacement de la glace, la prévention de sa formation par l'apport de chaleur ou la réduction de la vitesse de dissipation de la chaleur au moyen d'une isolation. Le procédé retenu dépend de la gravité et de l'importance économique du problème, des caractéristiques du site et de la nature du trafic. Quelle que soit la solution choisie, il est important, comme le fait ressortir le rapport de l'U.R.S.S., qu'elle fasse partie intégrante de la construction de la voie d'eau ou de l'installation, compte tenu à la fois des conditions du trafic et des conditions de l'exploitation.

Les circulateurs et les systèmes de barbotage se sont révélés efficaces pour certains problèmes de contrôle de la glace. Ces systèmes peuvent s'appliquer pour empêcher l'entrée de la glace dans une zone déterminée en engendrant un courant de surface suffisamment fort ou en empêchant la formation de la glace par une amenée d'eau chaude à la surface. On dispose maintenant d'une information considérable au sujet de leur action et de leur efficacité. Le rapport de la Pologne est une contribution précieuse à cet ensemble de connaissances. Il serait utile de revoir ce sujet afin de s'assurer que l'information relative à la conception de ces systèmes en vue du contrôle de la glace est maintenant adéquate et, dans la négative, de déterminer la recherche qui est encore indispensable. Il est probable que des enquêtes supplémentaires seront encore nécessaires au sujet de leur action dans des conditions particulières quant à l'eau et à la glace et dans le cas de certaines structures.

Beaucoup de travail a déjà été accompli au sujet du développement du chauffage et d'autres systèmes de contrôle de la glace pour des installations spéciales telles que les écluses et les docks submersibles qui doivent fonctionner dans des conditions sévères en présence de la glace. Le rapport de l'U.R.S.S. apporte une contribution très utile sur ce point. L'expérience de ce pays indique toute l'attention que l'on doit consacrer à la glace, aux conditions du trafic et aux problèmes connexes lors de la mise au point de systèmes de contrôle ou de l'amélioration de la conception des installations pour navires. On devrait encourager l'étude et le développement de tels systèmes.

L'emploi d'eau chaude industrielle résiduaire pour empêcher la formation de la glace suscite actuellement un grand intérêt. Quoique ce procédé puisse se révéler efficace pour le contrôle de la glace en hiver dans certaines régions, il pose le problème éventuel d'une pollution thermique à d'autres époques de l'année, comme le fait ressortir le rapport allemand. Des observations sur le terrain sont nécessaires pour confirmer les méthodes de prévision des effets thermiques dus au déversement d'eau chaude. On devra aussi procéder à des enquêtes qui fourniront les informations requises pour l'implantation et l'espacement des sources de chaleur telles que les centrales électriques.

On a maintenant mis au point des méthodes pratiques pour reproduire au moyen d'un modèle le mouvement de la glace dans les fleuves ou autour des ouvrages, pour autant que ce mouvement n'implique pas de pressions. Ces méthodes ont été utilisées efficacement aux Pays-Bas pour le développement du projet Delta et la mise au point des procédures opérationnelles, pour des recherches relatives à la glace en mouvement au franchissement d'un barrage en Tchécoslovaquie et pour la construction d'une jetée au Canada. Leur application à d'autres problèmes difficiles posés par la présence de la glace, tel que le dégagement des accostages de ferry-boats ou l'amélioration des conditions de navigation sur une voie d'eau par l'emploi de barrières, etc., devrait être encouragée activement.

Comme le montrent les rapports de l'Allemagne et des Etats-Unis, on manifeste actuellement de l'intérêt pour la construction de coques brise-glace. L'interaction entre la glace et un navire n'est pas encore complètement comprise et mérite l'attention. Quoique ces études puissent être entreprises principalement pour la construction des grands navires, leurs résultats seraient aussi intéressants pour la construction de ferry-boats et de petits bateaux qui circulent sur les voies d'eau intérieures. On devrait aussi porter son attention sur d'autres moyens de briser la glace, tels que le dispositif détonant à répétition décrit dans la communication des Etats-Unis.

Les rapports ont indiqué qu'on a appliqué au problème du contrôle de la glace beaucoup d'imagination et d'ingéniosité et il est évident qu'on a réalisé à ce sujet un progrès intéressant depuis le XIX[e] Congrès.

Pression de la glace.

La détermination de la force maximale que la glace peut exercer sur une structure est un problème technique non encore complètement résolu. On a réalisé en U.R.S.S. de bons progrès dans la mise au point de codes de construction pour les ouvrages soumis aux efforts de la glace. Des recherches théoriques et sur le terrain au sujet des pressions exercées par les glaces sont en cours en Europe et aux Etats-Unis. La compréhension de l'interaction entre la glace et les structures et par conséquent des modes de rupture qui déterminent finalement la charge maximale pour une implantation et un type de structure donné est encore inadéquate.

En raison des grandes variations des caractéristiques des couches de glace, de l'importance des forces en jeu et de la complexité du problème qui empêchent des prévisions sans ambiguïtés basées sur des mesures de laboratoire, il existe un grand besoin d'observations sur le terrain. Ces observations devraient porter à la fois sur la mesure directe des forces, comme indiqué dans le rapport allemand, et sur le comportement des structures calculées pour résister à une charge donnée, comme indiqué dans la communication de la Finlande. Ces observations sont nécessaires pour confirmer les formules théoriques du type présenté dans la communication danoise et pour confirmer et développer davantage les codes de construction, tels que ceux en usage en U.R.S.S. Quoique la pression et le choc de la glace sur l'ensemble ou sur une partie d'une structure eussent fait l'objet de l'une des questions de la Section II, Sujet 5 du Congrès de 1969, aucune information ne fut apportée sur ce point.

Aides à la navigation.

Plusieurs des rapports considèrent comme un problème majeur l'entretien des aides à la navigation pendant la saison où la glace est présente. Sur de nombreux itinéraires, on enlève les bouées et les balises des passes quand la glace commence à se former ou atteint une épaisseur ou un état déterminé. La glace endommage parfois ou même déplace les bouées laissées en position. Il existe un grand besoin d'aides à la navigation, fonctionnant en toute sécurité dans tous les états de la glace et toutes les circonstances de temps.

Le rapport de la Finlande décrit des balises fixées sur le fond des passes, qui ont été calculées pour résister aux efforts se manifestant dans la zone adjacente à la côte où la glace ferme adhère au rivage. Les Etats-Unis ont entrepris la mise au point de bouées pour améliorer leur aptitude à résister aux effets de la glace et des investigations au sujet d'autres systèmes de guidage des navires sont en cours. Il existe une importante expérience technique que l'on pourrait appliquer à la solution de ce problème et l'on devrait faire un sérieux effort pour l'utiliser à la mise au point de systèmes de guidage sûrs destinés aux régions exposées aux effets de la glace.

CONCLUSIONS ET RECOMMANDATIONS

1. On devrait encourager les rapports au sujet des états de la glace et des effets qui en résultent pour les ouvrages, les installations et la navigation. Il est nécessaire que l'on adopte dans ce but une classification des glaces et une terminologie acceptées internationalement, afin de s'assurer une base de comparaison appropriée. Il y a lieu de recommander l'adoption de la classification pour la glace de mer préparée par l'Organisation Météorologique Mondiale et celle pour la glace d'eau fraîche proposée par l'Association Internationale de Recherche Hydraulique.

2. On comprend bien maintenant les facteurs régissant la formation des embâcles dans les fleuves. D'autres observations des conditions qui les caractérisent sont nécessaires pour confirmer les méthodes de prévision théoriques.

3. On devrait multiplier les informations au sujet de la relation qui existe entre la vitesse de formation de la glace et des facteurs tels que le temps, les conditions d'écoulement et l'état de la couche de glace, en insistant particulièrement sur le perfectionnement des méthodes de prévision et des procédures opérationnelles.

4. Une information considérable est publiée au sujet des effets de la glace et l'efficacité des méthodes de contrôle de celle-ci. On devrait mettre au point une base permettant de comparer la gravité des problèmes que pose la glace et l'efficacité des méthodes de contrôle dans des conditions de temps, d'eau et de trafic données.

5. On devrait porter l'attention sur la publication des détails concernant les conditions relatives aux navires et à la glace, qui permettraient au moins de tirer des conclusions générales concernant l'aptitude des navires d'une dimension et d'une puissance déterminées à circuler à travers la glace.

6. On dispose maintenant d'une information considérable au sujet des systèmes de barbotage et des circulateurs et on devrait l'étudier et la revoir afin de s'assurer de l'efficacité de ces équipements pour le contrôle de la glace.

7. Les effets de la présence de la glace sur les installations telles que les écluses, les accostages des ferry-boats, les docks submersibles et les jetées posent un grave problème et l'on devrait encourager la mise au point de systèmes de contrôle efficaces de la glace pour ces installations.

8. La possibilité de prédire les pressions maximales exercées par la glace ne suffit pas encore pour les nécessités techniques. Des mesures sur place des pressions de la glace sont nécessaires pour confirmer et améliorer davantage les méthodes analytiques et les codes de bonne pratique.

9. Il existe un très grand besoin d'aides à la navigation, de fonctionnement sûr, pour les eaux couvertes de glace et une urgente nécessité d'appliquer la technologie moderne à la solution de ce problème.

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Section II

OCEAN NAVIGATION — NAVIGATION MARITIME

Subject 4 — Sujet 4

(Common to Sections I and II) — (Commun aux Sections I et II)

Effects of ice on structures and on navigation. Means of preventing ice formation and control of ice movement.

Action des glaces sur les ouvrages et la navigation. Moyens de prévenir leur formation et maîtrise de leur déplacement.

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S. II - 4

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S. II - 4

PAPER

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ICE EFFECTS ON PLANNING, DESIGN AND OPERATION OF A MAJOR OIL TERMINAL

To meet its growing market position in the Provinces of Quebec and Ontario, Golden Eagle Canada Limited decided in 1968 to construct a new refinery at St. Romuald, which is situated on the south shore of the St. Lawrence River and opposite Quebec City (Fig. 1). The 100,000 barrel a day refinery, which includes a storage capacity of 6,000,000 barrels for crude oil and residual fuels, is the first in the region and of the largest single unit construction anywhere in Canada. Its location is at the head of deep water navigation on the St. Lawrence River and, in addition to the normal overland transportation systems, it provides access to the heartland of industrial North America by shipping through the St. Lawrence Seaway.

A vital part of the refinery is its private marine terminal, some 2 1/2 miles away. The wharf has been designed to receive crude oil from tankers in the 100,000 DWT class and to provide for shipping of refined products in vessels ranging in size from 2,500 DWT to 20,000 DWT on a year round basis. Turn around time of vessels is kept to a minimum with a crude oil unloading rate of 30,000 barrels per hour.

Prior to the Golden Eagle development, no significant wharf facilities existed along this portion of the south shore. Abandoned stone-filled timber cribs and breakwaters, insignificant by present day standards, extended a few feet beyond the edge of the 600 to 1,000 feet wide tidal flats, and pointed to former marine activity around the turn of the century when timber was shipped from the south shore during the ice-free season. The absence of previous modern day instal-

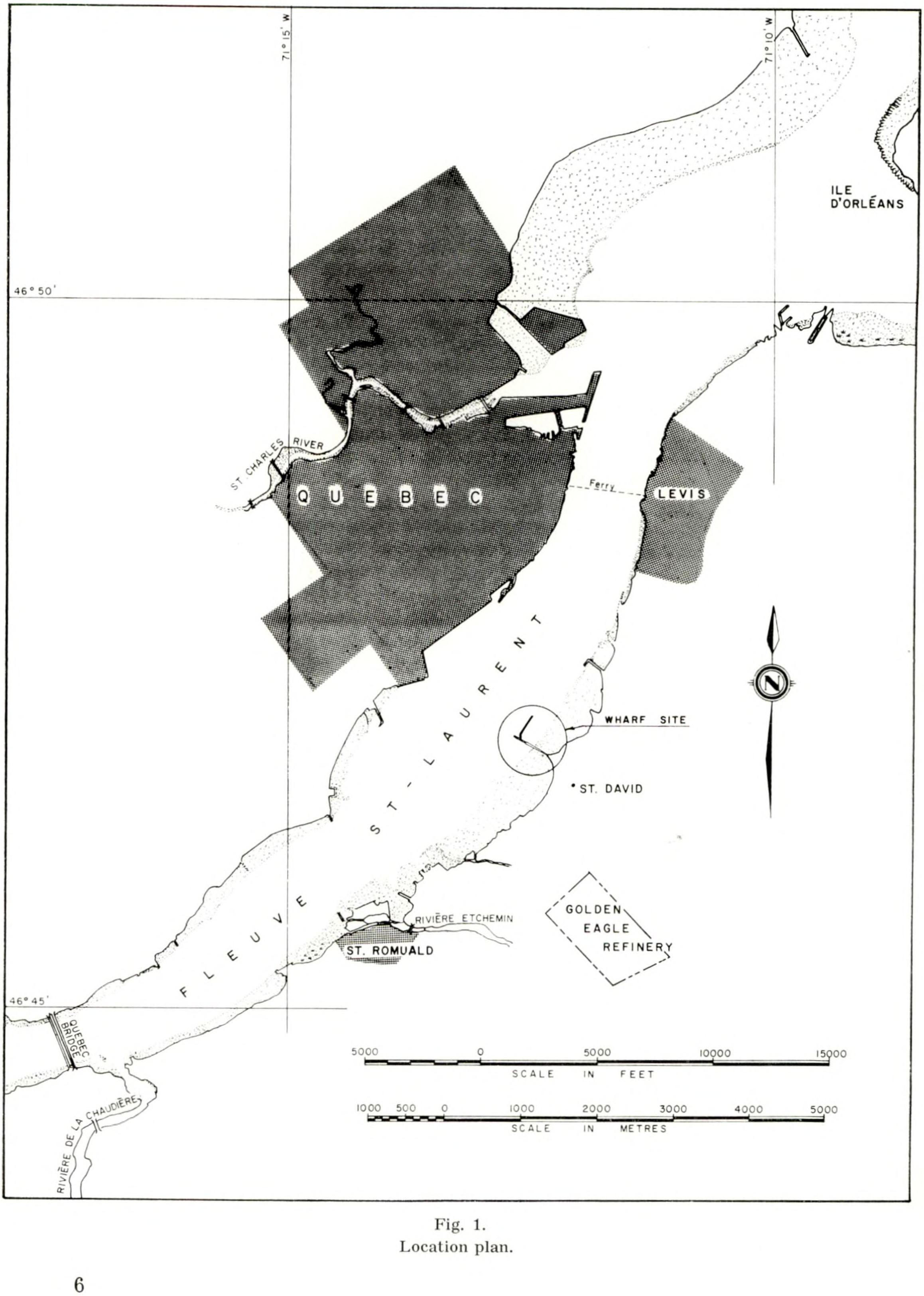

Fig. 1.
Location plan.

lations in this section of the south shore, could only partially be attributed to a lack in demand by the industry. The major deterring factor had been the history of severe ice conditions, which in the opinion of many effectively precluded any major marine terminal development.

It is this latter site feature which sets the Golden Eagle wharf site apart from most other wharf sites, and which required the engineers to develop new concepts in wharf design to meet the mandatory objective of a year round operation.

THE SITE

Above the Quebec Bridge, the St. Lawrence flows relatively straight in an east-northeasterly direction for a number of miles. Between the bridge and Levis the river experiences a very gradual change to a north-northeasterly sense. This curving is quite pronounced on the south shore, whereas the north shore remains fairly straight. The site is situated near the extreme point of this gentle sweep, where the normal, low water shore-to-shore distance measures approximately 6,000 feet. Corresponding channel widths at the Quebec Bridge and opposite Levis are some 1,900 and 3,200 feet respectively.

The river bed is deepest near the south shore, reaching 85 to 115 feet at normal low tide at a distance of roughly 1,200 feet from the low water line; however, the St. Lawrence Ship Channel runs very close to the north shore, and has a depth there of only 53 feet.

Downstream from Levis, the southern channel around Ile d'Orleans which is used by shipping, turns very abruptly in an easterly sense. Along this arm, beginning some 20 miles below the site and extending from there about 12 miles downriver, is the only section of the entire run to the Gulf which requires dredging. At the time of the preliminary investigations, the guaranteed depth of water in this dredged channel was 30 feet at low water. The Federal Government had, however, carried out studies on the feasibility of deepening this channel, with the result that the implementation of the work was only a matter of time. It is on the strength of this information that plans to construct a wharf for vessels in excess of 100,000 DWT were entertained.

A preliminary site evaluation revealed that average maximum air temperatures at Quebec were below freezing through the months of December, January, February and March, ice correspondingly forming in early December and break-up occuring by mid-April. Documented, yearly observations by the Department of Transport of Canada (DOT) indicated that the size of ice floes that could be expected below the Quebec Bridge was limited by the space between its piers only. The data showed frequent sightings of thick winter ice, medium size floes, rafted and ridged ice, hummocks and hanging dams with a maximum estimated thickness of 60 feet. Normally, ice reportedly built up to about a 30 inch thickness; the main channel never froze over completely but was usually

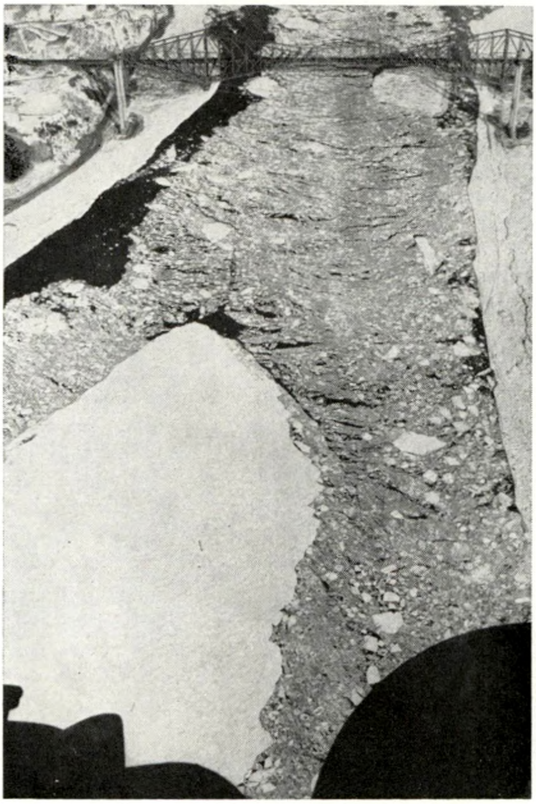

Fig. 2.

Part of a floe of 42-inch thick board ice, about 1,500 × 3,500 feet in size, upstream from and travelling toward the Quebec Bridge at the top of the photo.

covered with various thicknesses of mostly unconsolidated ice formations travelling downstream with ebbs and returning part of the way on reversal of the tidal currents.

In the spring, the latter reach a velocity of 7 feet per second at the south shore with only a minor reduction in the other seasons. Large tides at Quebec are about 20 feet in height, but extreme differences in elevation between high and low tides had been reported at 27.8 feet.

Recorded climatological observations showed that winds from the southwestern direction are predominant in this area. For the period of December through April, winds from the significant southwest, west, northwest and northeast directions have an average frequency of some 30%, 25%, 9% and 25% respectively. The maximum wind velocity of one hour duration was established at 50 miles per hour.

A maximum possible wind generated wave height of 8.5 feet was computed on the basis of a 6 mile long body of water and a sustained 50 mile per hour average wind velocity.

The entire St. Lawrence valley was designated by design codes as a zone of major seismic disturbances, the immediate vicinity of the site being criss-crossed by a number of faults.

Soil information available at the early stage of the project indicated substantial depths of stratified dense clayey silts and some layers of sand and gravel capable of supporting at least 5 tons per square foot.

PLANNING

The major objectives in developing the wharf concept were :

1. To provide an installation with two berths for year round operations, one

for vessels of the 100,000 DWT class, the other for vessels up to 20,000 DWT, with minimum water depths of 55 and 32 feet respectively.

2. To design a structure capable of resisting the most severe ice conditions considered possible with due consideration of the other criteria.

3. To plan the layout of the structure for maximum protection of vessels at berth from ice damage, and to prevent the breaking of moorings under the impact of ice floes on the vessels.

4. To ensure that the layout would permit adequate navigation in the swift ice-laden waters around the wharf.

The basic concept envisaged ice deflector structures to protect vessels and wharf head against ice floes from both the upstream and downstream directions. It was postulated that, as closely as practical, natural flow patterns should be maintained at the wharf to avoid eddies which would be objectionable to manœuvres at the dock. On the premise of compatible soil conditions, an open structure of massive concrete gravity structures offered the most feasible and economical approach. Cells of circular cross-section developed to be the most advantageous in the realm of suitable shapes, and therefore they were accepted as the basic unit of the substructure :

— Hydraulically, a round cylinder presented relatively little resistance to flow, the local flow pattern being symmetrical and the same for any direction of flow.
— The omnidirectionally uniform structural properties were ideally suited for the local conditions, where earthquake and ice forces could be expected from any or at least from many directions.
— The possibility of ice damage to the cells was minimized, because of the absence of weak, exposed corners or smaller structural members.
— A curved interface at impact with ice was considered favourable, particularly because of its tendency to split the floes.
— Standardization of the basic cross-section was practical and the shape economical, both of paramount importance to construction.

Preliminary layouts showed that it was economically unfeasible to pursue a solution of total protection against ice, coupled with optimum conditions for navigation. Therefore alternatives of compromise wharf head alignments were studied to give a combination of reasonable berth protection against ice, acceptable navigation characteristics for approaching and departing vessels and an economically plausible location with respect to natural contours. The verification of the concept and the final choice of alternative depended on detailed studies of site conditions.

In the winter of 1968/69, weekly observations of ice with the assistance from DOT's helicopters and icebreakers were undertaken, each of 1 to 3 days duration, to establish in detail the types, thickness, and movement of ice formations, and the effect of tidal and climatic conditions relative to the proposed site. This was followed by measurements of currents, to establish vertical and horizontal profile patterns for use in hydraulic model testing of the proposed layouts and by a program of soil investigation.

Field observations.

When winter temperatures set in, the formation of ice on the river is very quick, especially in the tidal flats because of the shallow depth and slower currents there. Most of the ice is prevented from moving into the main stream by attaching itself to irregularities along the shore and on the flats. The growth is further augmented by the piling up of current and wind driven ice which first freezes together loosely, but which consolidates to thicknesses of eight feet or more through repeated wetting at high tides and alternate exposure to cold air at low tides; trapped precipitation freezes to add to the thickness. This shore ice remains in place throughout the winter, and protects the previously mentioned timber cribs from being destroyed by impacts of floes.

The formation of ice in the deep channel is characteristic to that in fast flowing rivers. Throughout the winter the St. Lawrence is covered with an assortment of frazil, slush, shale ice, and slabs of ice broken loose from the shore ice. Often this ice travels in packs, during which time some limited cohesion occurs to give these formations the appearance of mosaic type floes; however, strong wind action on them very quickly results in a mass of highly fragmented ice.

The most dangerous floes are a direct result of wind action on the ever present masses of drift ice. Strong winds drive this ice into the permanent shore ice, to which it adheres; successive impingement of ice upon ice causes these accumulations to be well compacted and to form additional land-fast ice sometimes up to 4 feet thick and often exceeding a width of 1,000 feet, depending on the local river configuration. With the right combination of climatic conditions, this first accumulation beyond the permanent shore ice consolidates into board ice and usually remains in place to form the normal ice shore until spring break-up. In the spring, when tidal action is more pronounced, when currents are swifter and temperatures milder, this board ice breaks loose and descends the river in huge floes. Occasionally this occurs following a warm spell in mid-winter, providing a number of other favourable conditions for such an occurrence also take place at the same time (Fig. 2).

A very frequent type of floe observed intermittently throughout the winter season is similarly formed at the shore, and develops from ice accumulations extending several hundred feet beyond the normal shore ice. These masses are often well compacted, and since equilibrium conditions limit lateral growth beyond a certain point, persistent strong winds sometimes produce rafting and pile-ups several feet high above the stationary ice and several tens of feet deep below the ice sheet. Since such extensive accumulations effectively constrict the channel and provide strong resistance to the river flow, they are set adrift under much less favourable conditions than are required to dislodge the more permanent board ice; floes several hundred feet in width and over 2,000 feet in length are a common occurrence. Although only minor refreezing may take place in these floes, their dynamic qualities in terms of water and ice carried make them most dangerous.

At times, and in some sections of the river, notably just above the Quebec Bridge and downstream from Levis, riverwide ice jams form, either because of local constrictions or because of strong opposing action of winds and currents. The ice jams consist of all the types of drift ice present on the river at the time of formation, and invariably lead to substantial hanging ice dams, unless broken up quickly. Such jams completely immobilize river traffic and when such compacted ice slowly moves along the river it tends to shear off anything which extends beyond the normal shore-fast ice.

The configuration of the St. Lawrence River in this section and the momentum imparted to the ice by currents, cause it to hug the south shore during the ebb part of a tide cycle. For the same reasons flood currents keep ice close to the north shore, especially larger floes. Floes returning upstream to this river section are smaller than those moving past the site with ebb currents.

Permanent shore ice at the site forms over a width of about 800 feet to the low water line; an additional belt of board ice 300-400 feet wide completes the normal shore ice near the -20 ft. contour. The predominant west-south-westerly winds coincide with ebb currents at this location, and moving ice follows the pattern set by currents; ebb currents, combining with frequent westerly wind or winds from the northwest in excess of about 10 miles per hour, cause intermittent ice accumulations of up to 600 feet beyond the normal ice shore for periods of 2 to 3 weeks. East-northeasterly winds on the other hand promote the natural clearing of the wharf site, and generally keep drift-ice at the north shore. In the 1968/69 winter season the maximum observed board ice thickness was 42 inches.

At Quebec the ebb tide is about one hour longer than the flood tide, and flood and ebb currents appear approximately one hour after low and high water levels respectively. Furthermore because of the river configuration, ebb currents persist at the south shore for a period of about 15 minutes while the currents have already reversed along the north shore; the reverse is also true when the change of current is in the other direction. The path and magnitude of both ebb and flood currents are basically the same at the site. Reversals are complete and the rate of change of velocity through the reversal is rapid and follows a straight line; moreover, vertical and horizontal profiles of measured currents are uniform throughout the tide cycle.

Development of the concept in detail.

From these field observations, the following conclusions were drawn :

— The wharf head, by virtue of the required depth at the main berth, would be located just outside of the normal ice shore.

— The exposed structure would be subject to severe impacts by large current and wind-driven floes across the river.

— The probability of collisions with large floes moving with flood tides was minimal.

— Chances of an ice field forming across the river were very remote because of the large width of the river at the site.

— Structures located within the normal land-fast ice would be protected by the same.

— Temporary accumulations of wind-driven ice should be expected to occur intermittently through the ice season.

The final layout shown in Figure 3 was developed on the basis of these conclusions, extensive studies of alternatives on a hydraulic model, and consultations with the river pilots, who would be responsible for the docking of vessels.

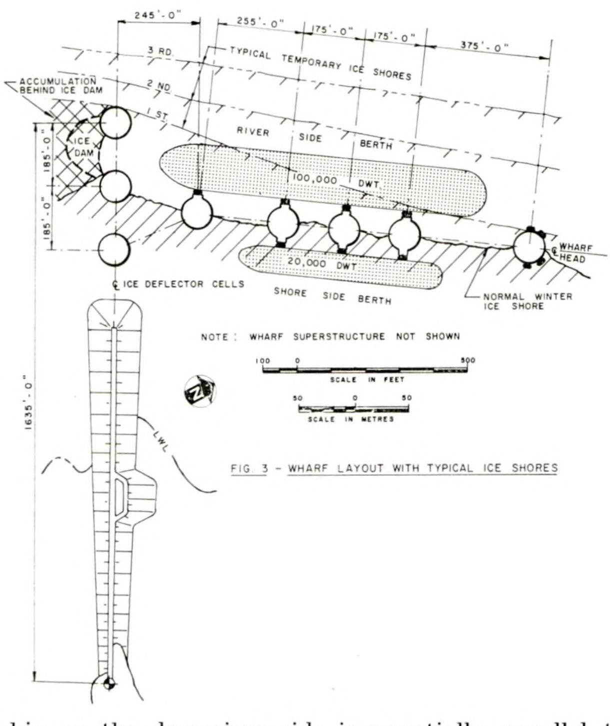

FIG. 3 - WHARF LAYOUT WITH TYPICAL ICE SHORES

A rock filled causeway was planned to run straight out from shore through the protection of land-fast ice to the vicinity of the normal ice shore. Three ice deflector cells were placed beyond the causeway and in line with it, the furthest one near the -65 foot contour. The wharf head was located on the downriver side of the causeway at an angle of 10 degrees to the currents, and its furthest cell downstream was set at the -55 foot contour. The line joining the outer end of the ice deflector with the last wharf head dolphin on the downriver side is essentially parallel to the currents and encloses a dredged, triangular pocket which provides adequate protection against current-driven ice.

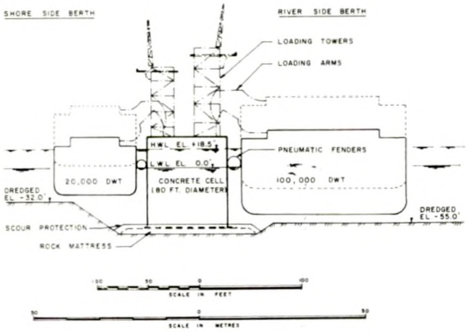

Fig. 4.

Cross-sections at loading towers.

The ice deflector was designed to take the full impact of large floes from upriver, to prevent direct collisions with the end of a vessel at berth. It was believed, however, that the more frequent situation would involve the formation of ice dams above the cells and the artificial creation of ice accumulations along the shore, which would deflect drifting ice away from the berthing area. In such case, only the most exposed cell would be subject to frequent impacts from floes, the latter incurring substantial losses of energy in rotation and subsequent deflection into the deeper channel (Fig. 5 et 6).

The number of cells in the ice deflector, and the open spaces between them were chosen by studying a series of options to provide the desired hydraulic characteristics on the one hand, and to limit the size of floe which could pass through the openings on the other hand; their location relative to the wharf head was mainly governed by an attempt to direct the movement of ice away from critical areas. This latter consideration applied in particular to ice penetrating through the deflector structure, where danger of the formation of a wedge between dock and vessel existed.

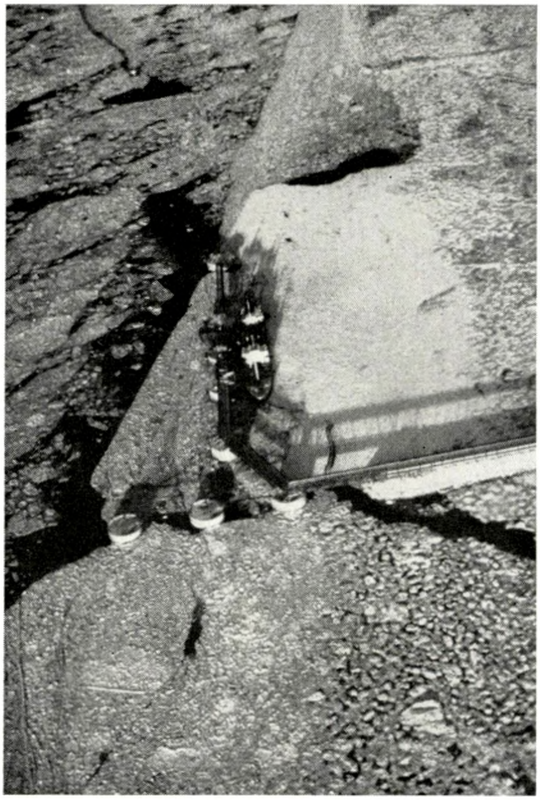

Fig. 5.

Ice accumulations in the foreground are held by the ice protective structure, deflecting drift ice away from berthing areas.

Provision was made for multiple moorings to the two external deflector cells, to give added security to vessels in the outer berth.

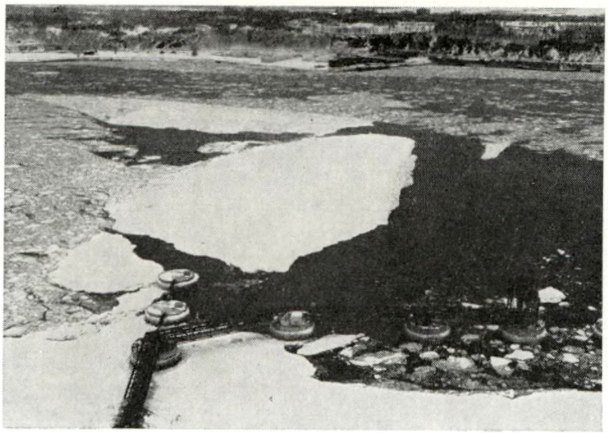

Fig. 6.

On impact with the rounded face of the cell, the floe is split on one side of the cell, and sheared and rotated away from the dock on the other side.

For overall safety and efficienty of operations quick release mooring hooks were used throughout the installation.

Basic protection against a potential, heavy upstream flow of ice was provided by the selected orientation of the wharf head itself; its extreme downriver cell was also planned for the remote possibility of full collision with a large floe from that direction. The very low probability of such an event did not, however, warrant the expense of a complete shielding of the downstream end of vessels in the outer berth when they are in their normal unloading position. This type of protection would render manœuvering exceedingly difficult and if the need for extra protection ever arose the vessel could temporarily move deeper into the pocket.

A novel method was developed to cope with glancing blows from large floes which are propelled by wind across the normal current pattern. The system adopted involved the use of floating, fiber reinforced, 12 foot diameter pneumatic rubber fenders manufactured in Japan. Beyond their normal functional capacity, an overload safety valve will release air to approximately maintain a preset working pressure, thereby allowing a substantial additional absorption of energy in deflection at acceptable unit loads on the hull of a vessel.

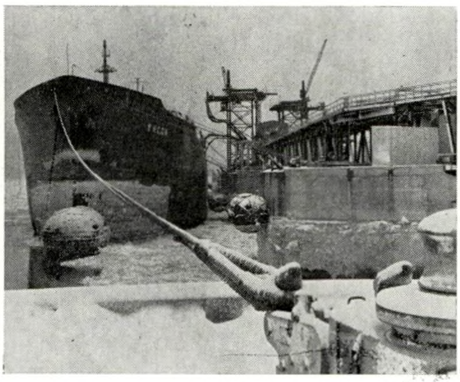

Fig. 7.

Pneumatic rubber fenders in the outer berth protect the vessels against glancing blows by large winddriven floes. Lifting mechanisms permit the retraction of fenders as required.

Floating fenders were well suited for this high tidal range application, where gravity structures provided the necessary vertical face. To forestall the freezing of fenders into an ice sheet with the inherent danger of being carried away during a natural clearing of ice, lifting mechanisms were provided to raise them above the high water level when no vessels were at the dock. Both berths were equipped with the same type of fender system but different in size (Fig. 7).

The seemingly high inclination of berthing faces relative to the directions of currents was fully justified in view of the advantages that were to be gained, and the anticipated features of navigation particular to this installation.

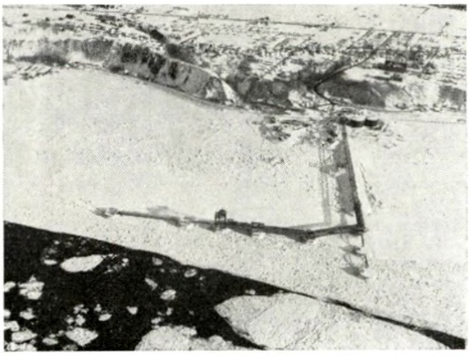

Fig. 8.

View showing position of the structure relative to shore ice formations, including temporary accumulations outside the wharf head.

The chosen orientation permitted a wharf head with one berth on each side — a compact, well utilized and economic layout. It allowed a direct and safe approach from the shipping channel opposite Quebec City into the riverside berth and a reasonable angle of entry into a shoreside berth. The alignment of the wharf head provided the necessary protection to the outer berth from upstream movement of ice. The inside location of the berth for smaller vessels completely eliminated the need for special expenditures on its protection against ice floes.

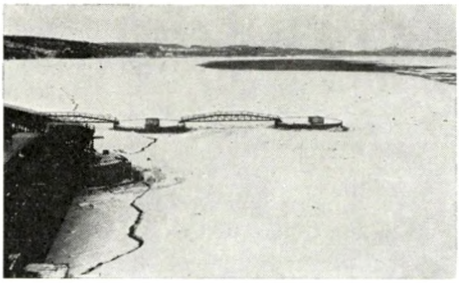

Fig. 9.

Outside berth with ice accumulations, a few weeks old. The Quebec Bridge is in the background.

Indications received were that all vessels would be handled by tugs at all times. In addition, since the passage of large tankers through the dredged portion of the shipping channel had to be timed around high tides, manœuvring at the dock would be in relatively slow currents.

Fig. 10.

Outside berth the next day, following a natural clearing overnight.

Intermittent, wind accumulated ice masses in the berthing areas were not belived serious with the anticipated traffic to prevent consolidation, and the option of having government icebreakers stationed at Quebec City aid in keeping the berths navigable at all times (Fig. 8, 9 and 10).

DESIGN

Based on established thiknesses of solid ice, sizes of floes and estimated volumes of unconsolidated ice masses occurring in hanging dams, floes of an average, equivalent consolidated ice thickness of 15 feet and weighing some 700,000 tons were assumed for the structural analysis. Basic research data indicates that ultimate, sustained dynamic stresses in ice at high collision velocities are in the order of 200 psi; however, once a floe is stopped static stresses can rise to 400 psi for short durations.

According to the degree and type of exposure, and relative to their basic diameter of 79 feet, the three ice deflector cells and the downstream cell of the wharf head were designed for an ice thrust of 9,000 kips, whereas the more sheltered berthing dolphins were designed for a load of 6,500 kips. These forces were applied 77 feet above the base of the 90 foot high sub-structures. Currents, waves, wind, earthquake and berthing forces proved to have little influence on the structural design. Stability computations were based on safety factors of 2.0 against both sliding and overturning.

All cells were of the same basic construction, a peripheral concrete wall, and internal vertical concrete wall diaphragms in two directions to carry lateral loads to the base, and to stiffen the latter against high overturning pressures. Flat faces were cast for fenders as required. Where high point loads were expected from ice impacts, the outside walls were thickened on the inside. The base slabs of cells varied in diameter reflecting the magnitude of actual applied loads. Under high ice loads of short duration, base pressures of 10 tons per square foot were allowed. Graded mattresses of appropriate thickness were placed on a prepared bottom, to spread the load over a wider area of the underlying soil strata (Fig. 4).

The main bridges were laid out as through-trusses, carrying a roadway at the lower chord, and a pipeway at the upper; each bridge was completely preassembled on land, then floated on barges and set using tidal action. The working deck elevations were established taking into consideration wave and tidal effects as well as observed heights of ice pile-ups.

Tides were also used to advantage in the construction of concrete cells. A tidal drydock with a sill elevation of + 2.0 feet was built on the adjacent tidal flats as part of the project. Construction commenced in the drydock with the concrete pouring of bases and walls, using slip forms for the latter. At a total average height of some 15 feet, the cells were floated and towed to their final location in the river. There they were attached to and held in position against the reversing currents by an arrangement of 3 strategically placed anchor systems. Pouring then resumed in a continuous operation, at a rate of 6 to 8 inches per hour, and under a programmed sequence of water ballasting to ensure adequate floating stability at all times. When full height was reached, the cells were set during low tide and filled with sufficient water to prevent re-floating. Final ballasting involved filling of the entire height with graded granular material, and water to the mean waterlevel of the river.

The development of adequate and safe floating characteristics for the construction phase, compatible with the design for functional and structural requirements, formed a major and integral part of the overall planning and proportioning of the cell structures.

Contrary to usual practice, fenders for the outer berth were chosen by their capacity to protect the vessels at berth against ice. Taking the possible case of a large floe striking the vessel with a perpendicular velocity component of 1 foot per second, it was found that with part of the energy spent just prior to and during the initial contact, another 8,000 foot-kips remained to be absorbed at the wharf face. The four selected fender units, on which a 100,000 DWT tanker would rest, could by the automatic activation of its overload feature absorb an aggregate 9,450 foot-kips at a deflection of 72.5% and with a terminal load of 785 kips on each of the four cells.

Individually, and within their normal service range of 55% deflection and 998 foot-kip energy absorption capacity, each fender could more than adequately handle the energy imparted by a 100,000 DWT vessel docking with an approach speed of 0.5 feet per second perpendicular to the berthing face.

OPERATIONS

On completion of construction just prior to the winter of 1970/71, another season-long series of observations was conducted to monitor ice behavior at the finished structure; the results fully confirmed anticipated behavior as may be seen from some of the illustrations. Experimental clearing operations undertaken by icebreakers on a number of occasions proved very satisfactory, even in undisturbed normal shore ice.

Since the arrival of the first crude oil tanker on July 7, 1971, in 12 months of operations, a total of 143 vessels have used the outer berth and 105 the inner; for the winter months of 1971/72 the numbers are 51 and 48 respectively. But even though the occupancy of the berths has not been at full capacity during the first winter operations, no icebreaker service was required. With the safety of vessels at berth proven, navigators came to regard winter conditions as advantageous in a number of aspects.

Firstly, the heavy shore ice and to some extent the frequent accumulations above the ice deflector tend to reduce the inclination of currents with respect to the wharf head. Secondly, the normal winter ice shore clearly outlines the dredged limits of the inner berth and its approach, and protects vessels from running aground on the shallow flats if control were lost. Thirdly, the usual presence of stationary ice between adjacent cells and the cushioning effect of loose ice in the berths lend an extra degree of safety to berthing and in absorbing glancing blows from floes. Unlike normal docking procedure during the ice-free season, Figure 11 shows that the tanker Germik can hold a position parallel to

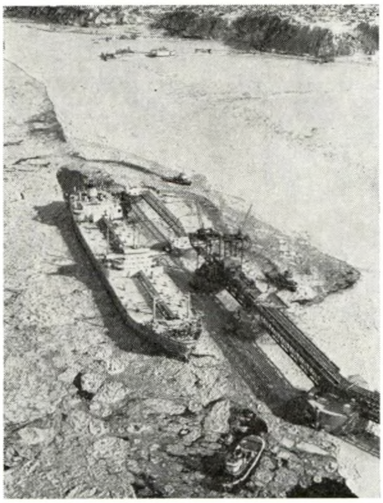

Fig. 11.

Approach of the « Germik » in to the outer berth in mid-winter conditions In preparation for docking all fenders in the outside berth are floating; fenders in the other berth are raised (courtesy of Golden Eagle Canada Limited).

the berthing face under its own power, while the usual three tugs clear paths for loose ice to drift out of the berthing areas.

Small vessels usually dock without tug assistance and their schedule is not dictated by the tide cycle. The arrival and departure of large tankers is scheduled at approximately 2 hours after and 1 hour before high tide respectively, because of draft restrictions in the dredged section of the ship channel. Thus the larger ships always arrive with head currents, giving them the necessary control against being carried into the ice deflector structure.

The particular docking or casting-off manœuvre used on any one occasion is decided by the pilot, and depends largely on the prevailing ice conditions and the exact time relative to slack water. When conditions are favourable, vessels will stop opposite the wharf in mid-river and make à 180° swing, stern first, into the berth; this places the ship in the proper attitude for direct departure downstream. When conditions are less favourable, the vessel makes a direct approach from the ship channel at Quebec City into the berth. On departing, either one of two alternates is employed to point the bow downriver : One involves a 180° swing, stern first, into mid-river, the other consists of pulling away from and backing up parallel to the wharf, and terminating in a 180° swing, bow first, past the extreme ice deflector cell.

The largest ships to visit to date have been in the order of 70,000 DWT. When fully loaded, their passage through the dredged channel section is still a tidal operation. The ever-increasing size and frequency of these vessels has caused growing concern for the environment. Due to the added potential hazard of ice jams trapping a deep draft vessel in shallow waters, tankers, during last winter's operations, were lightered to a 30 foot draft prior to entering the channel of restricted depth.

However, with supertankers virtually and figuratively speaking on the doorstep of Quebec Harbour, the continuing improvements of conditions for navigations on the St. Lawrence are picking up in pace. Programs are well under way for, close monitoring of ice in the shallow channel below Quebec City, increased icebreaker activity to prevent ice jams, the installation of radar bouys and the deepening of the dredged channel to a guaranteed 41 feet by 1973.

Thus the arrival of the first fully loaded 100,000 DWT tanker at the Golden Eagle wharf early in 1974 is now almost assured. If at some point in the future it came practical to bring vessels of the 200,000 DWT class as far as Quebec City, the oil terminal at St. Romuald would have to undergo only some relatively minor modifications in order to accommodate tankers of this size.

The implications of the constriction of Golden Eagle's wharf at St. Romuald go beyong the successful accomplishment of the prime objective of securing the new refinery's life line. Experience with wharf installations in severe ice climates is still very limited; this wharf adds an important piece of knowlegde to the subject which may well find future application in developments in the far northern and Arctic waters. Locally, the impact of the new facility is equally significant and timely in view of Quebec Harbour's 1972 study of its overall growth potential and vocation in the future; this project marks the beginning of the supertanker era for the Harbour, and the feasibility of major installations on the south shore is no longer a question, it is a certainty with the potential of its possible development now a reality.

RÉSUMÉ

Les effets des glaces sur la planification, la conception et l'exploitation d'un terminal pétrolier d'envergure

La construction du nouveau quai de la raffinerie Golden Eagle sur la rive sud du fleuve Saint-Laurent, à la hauteur de la ville de Québec, constitue un évènement marquant. (Voir fig. 1). Un régime sévère de glaces pendant quatre mois de l'année avait empêché toute tentative antérieure de construire des installations maritimes dans cette section de la rive sud et nécessitait le développement de nouveaux concepts.

L'objectif du projet était de construire un quai à deux postes d'amarrage susceptible de recevoir des navires à longueur d'année; un des postes était prévu pour des pétroliers jaugeant 100.000 tonnes et l'autre 20.000 tonnes. La structure devait être en mesure de résister à l'impact sérieux des glaces tout en assurant une protection adéquate des navires accostés contre les dégâts éventuels des glaces et, par la même occasion, maintenir des conditions favorables à la navigation.

L'action combinée d'un certain nombre d'autres conditions difficiles présentées par l'emplacement compliquait le développement du concept, soit des marées de 20 pieds, des courants réversibles de 7 pieds par seconde, la direction défavorable des vents et la haute probabilité de secousses telluriques dans cette région.

Des observations approfondies sur le chantier ont permis d'évaluer le genre et les dimensions des formations glaciaires ainsi que l'action des courants et des vents sur ces glaces. A la suite de ces observations les ingénieurs ont pu déterminer le degré de protection requise contre les glaces et l'ampleur probable de la force exercée par ces glaces sur la structure projetée. Ainsi, il a été possible de constater qu'il fallait prévoir l'impact sur la structure des glaces poussées par le courant et le vent d'amont (fig. 2), ainsi que les chocs causés par les bancs de glace poussés par le vent à travers le fleuve. Par contre, le risque de collision avec les bancs de glace venant de l'aval était minime. De plus, vu la largeur du fleuve à cet endroit il était peu probable qu'un champ de glace puisse se former d'une rive à l'autre.

L'illustration n° 3 montre l'agencement final du quai. Le trait saillant de cette installation est constitué par une structure qui protège le quai contre la glace descendant avec le reflux des eaux soit en retenant ou en faisant dévier les glaces. (voir fig. 5 et 6). La direction de la tête du quai, inclinée de 10° par rapport aux courants, empêche l'impact entre les navires accostés et les glaces poussées en amont. Un nouveau concept employé pour les défenses a permis d'assurer la protection contre les glaces poussées par le vent à travers le fleuve. Les défenses pneumatiques

en caoutchouc utilisées ici se caractérisent par leur résistance aux surcharges rendant ainsi possible l'absorption de l'énorme quantité d'énergie résultant d'un grand banc de glace qui frapperait le navire en perpendiculaire à une vitesse d'un pied par seconde; l'absorption d'énergie requise pour l'accostage n'en constitue qu'une fraction, (voir fig. 7).

L'infrastructure de base est formée par une imposante structure cellulaire en béton — à gravité — de 90 pieds de haut et de 79 pieds de diamètre. Cette structure a été choisie à cause des avantages offerts par sa forme et aussi parce qu'il était indispensable d'employer une structure de forme ouverte afin de fournir des caractéristiques hydrauliques favorables (voir fig. 4).

Des essais très poussés ont été effectués sur maquette hydraulique afin de déterminer l'alignement le plus avantageux et l'espacement des cellules.

La conception a été réalisée en prenant comme base un bac de glace ayant une épaisseur consolidée équivalente à environ 15 pieds et pesant approximativement 700.000 tonnes. Compte tenu du genre et du degré d'exposition aux glaces ainsi que du diamètre de base de 79 pieds, les trois cellules destinées à faire dévier les glaces et la cellule d'aval de la tête du quai ont été conçues pour résister à une poussée de 9.000.000 livres, alors que les autres cellules, plus à l'abri, ont été conçues pour résister à une poussée de 6.500.000 livres.

Depuis l'arrivée du premier pétrolier en juillet 1971 toutes les prévisions ont été confirmées, c'est-à-dire le quai se comporte tel que prévu sous l'action des glaces. L'inclinaison de 10° par rapport aux courants était justifiée en termes de protection obtenue contre les glaces et les caractéristiques particulières de navigation à l'emplacement. Une zone draguée, environ 20 milles en aval, permet le passage des navires chargés à pleine capacité à travers le chenal dragué à marée haute seulement. Par conséquent, l'arrivée et le départ des pétroliers dans le quai même se fait avec des courants relativement peu impétueux. Au cours de l'hiver, la présence des glaces flottantes dans les postes d'amarrage n'a pas constituer d'obstacle, mais par contre s'est avérée avantageuse (voir fig. 11).

La portée de la construction du quai de la raffinerie Golden Eagle va plus loin que l'objectif initial visé, c'est-à-dire la viabilité de la nouvelle raffinerie.

Pour le moment, l'expérience dans le domaine des quais construits dans les climats glaciers est plutôt limitée. Par conséquent, la réalisation de ce quai vient ajouter des connaissances appréciables à ce domaine particulier, lesquelles pourraient être appliquées aux aménagements futurs dans les eaux du Nord et de l'Arctique. A l'échelle locale, l'impact de ces installations a une égale signification et vient très à propos en ce qui concerne l'étude effectuée en 1972 sur le potentiel de croissance du port de Québec et de son objectif futur. La réalisation de ce projet marque le début de l'ère des super-pétroliers pour le port de Québec et la rentabilité de la construction des installations majeures sur la rive sud ne peut plus être mise en question, c'est un fait prouvé et le potentiel de son aménagement est devenu une réalité.

S. II - 4

PAPER

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SKIMMING OF ICE THROUGH HYDRAULIC STRUCTURES OF THE RIVER POWER PROJECT GABCIKOVO

The undesirable prolongation of the winter interruption of navigation on inland waterways due to the slower ice cover melting in the backwater reaches leads to the search for possibilities of maintaining artificially the passage of those critical sections by means of ice-breakers. The released section is to be cleared off from the broken ice which could again obstruct the waterway, or eventually close it completely. The most reliable solution is to drift the broken ice towards the outlet structures and discharge it through those structures into the tail water.

Skimming of ice through the structures of the river power project is demanding with respect to the water consumption. The construction solution and dimensioning of outlet structures has to be adapted so as to provide continual and smooth feed of ice floes to those outlet structures. It is often necessary to adapt also the lay-out solution and the connection of those structures to the upstream reservoir according to this requirement.

With respect to the endeavour not to extend the forced winter navigation break in the Czechoslovak reach of the Danube the problem of ice skimming became one of the tasks to be dealt with in connection with the river power project of the Danube river utilization within the section of fords downstream of Bratislava.

The transfer of the navigation into the lateral canal is connected with further problems due to the clearing of the navigation channel from ice and it is necessary to consider also the section of the approach channel and therefore we had to study also the discharge of ice through the canal stage structures.

As far as the river power project structures is concerned, following of them can be used for discharging of ice from the approach channel :

a) auxiliary outlets of the power station with the spillway crest of a total length $B_j = 4 \times 14 = 56$ m and maximum thickness of the overfall beam of 3.0 m, to which corresponds a discharge $Q_{max.} = 470$ m^3/s.

b) navigation locks, by opening of which a spillway crest is formed having a length $B_K = 2 \times 34 = 68$ m with a possibility of passing a discharge $Q_{max} = 1{,}900$ m^3/s, the thickness of the overfall beam being up to 6.5 m.

According to the requirement, either the first or the second structure can be used for ice skimming, or eventually both of them simultaneously and in the case of need, when by increasing of velocities higher transportation capacity is to be attained in the proper channel — it is possible to combine also the discharge released through the spillways of the auxiliary outlets and navigation locks with the discharge of a certain volume of water through the adjacent hydraulic power plant.

Considering the adequacy of respective structures or means of ice discharging it is necessary to bear in mind also the character of the flow in the channel and the upstream reach of the power project structures, and above all the water, required for ice skimming.

For the flow conditions estimation during the washing away of ice in the upstream reach of the auxiliary outlets and downstream of navigation locks the aerodynamic model in the scale M = 1 : 1 000/500 was used. The water consumption Q_p at different variants of skimming was studied on a large, geometrically similar hydraulic model in the scale M = 1 : 70.

For ice floes simulation on the hydraulic model parafine polygonal blocks were applied having the specific gravity similar to that of ice. The parafine blocks dimensions were chosen so as to correspond to the dimensions of ice floes having in reality the medium diameter of 5.0 m, thickness 0.5 to 0.6 m.

The skimmed area of ice floes was established indirectly. A sample of piled up ice floes, having a known unit area, was taken from the ice cover, formed before the test in the approach channel had been carried out. This sample was weighed. After having finished the test with ice skimming the whole washed away mass of ice was weighed and divided by the weight of the sample. Thus we have obtained the ice area P discharged during the test. Further the water discharge Q, released through the respective structure, was measured, as well as the total time of skimming T. Water consumption, required for washing away of the unit area of ice, was than expressed by means of the formula

$$Q_p = \frac{QT}{P} \qquad (1)$$

1. SKIMMING OF ICE THROUGH THE AUXILIARY OUTLET SPILLWAYS

a) Hydroelectric power plant out of operation.

The character of the flow upstream of the structures of the project, the auxiliary outlets being in operation, can be seen in Fig. 1. According to the

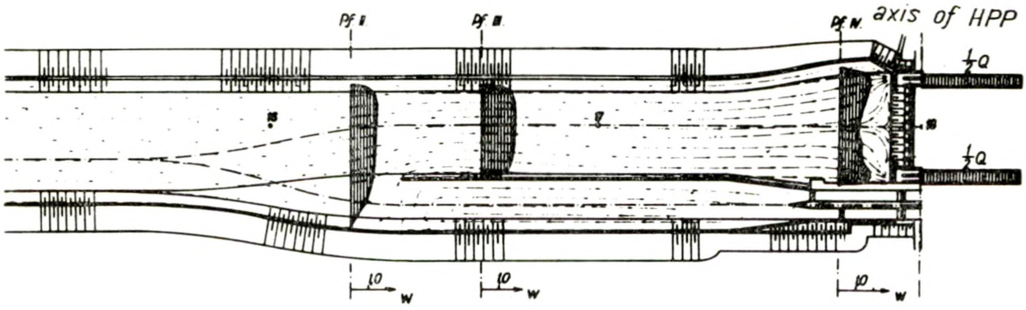

Fig. 1.

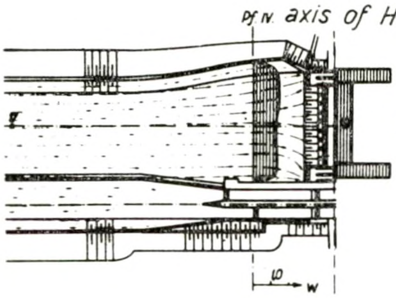

Fig. 2.

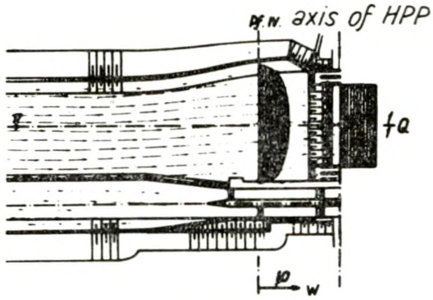

Fig. 3.

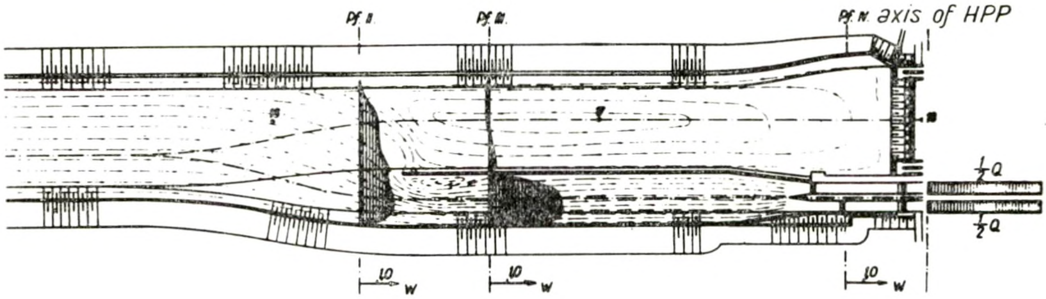

Fig. 4.

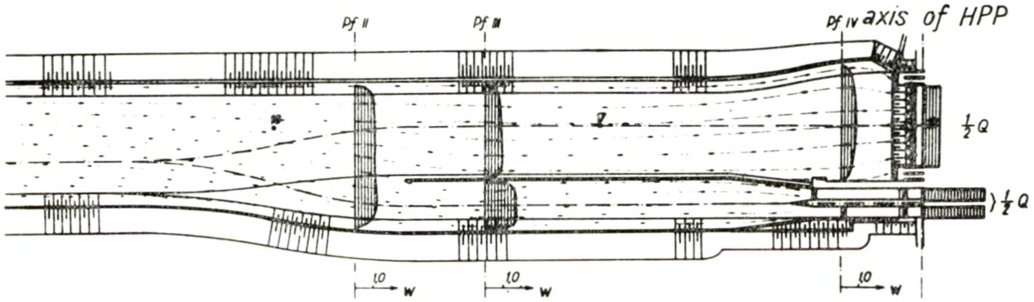

Fig. 5.

Fig. 1, 2, 3, 4, 5.

Flow conditions at different variants of the discharge distribution. Aerodynamical model.

Remark : The W ordinates in the pictures of velocity distribution express the relative value of surface velocities with regard to the average profile velocity V_p in the prismatic section of the canal

$$V_p = \frac{Q}{F_p}; \ V_{skut} = W.\ V_p$$

course of the surface streamlines and velocity distribution in the transitional section of the channel — upstream reach of the power plant it is evident that the passage of ice floes through this section will be continual. Close to the auxiliary outlet spillways, where the expressive disproportion between the relatively large upstream reach width and actual spillways width becomes evident, the ice floes would pile up against the auxiliary outlets from the side. The negative effect of the transversal feed of floes to the spillways would be manifested by a noticeable slowdown of the transport.

The tests on the hydraulic model have shown that without an artificial ice releasing a continual ice skimming could not be achieved. The masses of ice floes often piled up upstream of the approaches to auxiliary spillways, forming vaults and bridges leaning against the dividing piers of respective overfall blocks and the ice skimming was interrupted (Fig. 6). It was evident that the width of blocks, having the dimensions of 14.0 m, is not adequate.

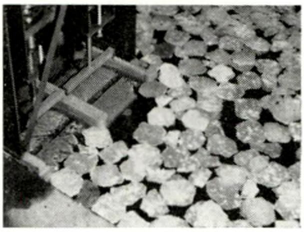

Fig. 6.
Discharge of ice floes using auxiliary outlets. Development of ice bridges.

So as to be able to evaluate, on the basis of experiments, the water consumption required for washing away of the unit area of ice floes from the reservoir, an artificial release of vaults, developed in the upstream reaches of the auxiliary spillways, was carried out. Under those conditions the water consumption, required for skimming of 1 m^2 of ice cover area, ranged from 40.0 to 48.0 m^3/m^2 (Fig. 10). The time, required for skimming of 1 km^2 of broken ice area, ranged from 23 to 29 hours (Fig. 11), and the whole channel area $P = 5.5$ km^2 would be cleared from ice in about 6 days on the average.

Then the water consumption needed for washing away of ice floes from the whole area of the approach channel would amount to about 242 mil. m^3.

b) **Hydropower plant in operation.**

Simultaneous discharging through hydropower plant will cause the general increase of velocities in the approach channel. Coincidentally the transporting capacity of the water stream and the ice floes progressing towards the auxiliary outlet spillways is intensified. In spite of the straightening of streamlines upstream of the spillway blocks (Fig. 2, 3) the increased ice floes feed from the upper sections of the channel will block also the side spillway approaches and the skimming of ice will be interrupted. From this point of view the discharging of larger flows through the power plant could be less advantageous than of smaller ones.

The experiments with ice skimming through the auxiliary outlet spillways at a simultaneous discharge through the hydropower plant $Q_E = 3{,}225$ m^3/s have shown that the ice skimming was not improved, as compared with the previous case. The vaults were formed again in the upstream reaches of auxiliary spillways and it was again necessary to release artificially the ice bridge upstream of the spillway blocks. The effect of a higher discharge velocity in the approach channel appeared in the decreased water consumption for skimming of 1 m^2 of ice — to a value $Q_p = 25\ m^3/m^2$ and also the time necessary for the clearing of channel from ice decreased to 3.45 days, the volume of water passing through the scheme without power generation being 140 mil. m^3.

2. SKIMMING OF ICE THROUGH THE NAVIGATION LOCKS

a) Hydropower plant out of operation.

The lay-out and the conditions during the skimming of ice through the navigation locks can be deduced from Fig. 4. The areas of the entrance into the navigation lock approaches and upstream of the power plant will be the critical points for piling up of ice floes in the navigation channel in the case given. It is, therefore, purposeful to shift the navigation locks towards the left bank and arrange their lay-out so that a direct continuation of the approach channel will be formed. However, in spite of these conditions, it is necessary to consider the skimming of ice through navigation locks as more advantageous than skimming through auxiliary outlets.

In the course of the tests with ice skimming through navigation locks also the effect of different thickness of the overfall beams was studied, i.e. the effect of the change of specific discharges q. The diagram in Fig. 8 has shown that the water consumption Q_p = increases with increasing of the specific discharge and at $q = 28.0\ m^3/s/m$ amounts to $Q_p = 55.0\ m^3/m^2$. At all discharges the ice floes were skimmed smoothly through the navigation locks taintor gates (Fig. 7). On the basis of measured values a relationship has been developed, determining at different values of the specific discharge the time, required for the skimming of 1 km^2 of the ice area from the channel. The diagrams on Fig. 10 show how the total water consumption balance varies.

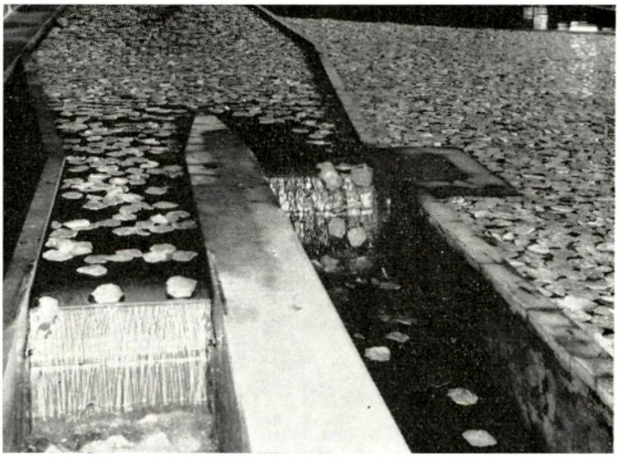

Fig. 7.

Discharge of the ice floes through the navigation locks.

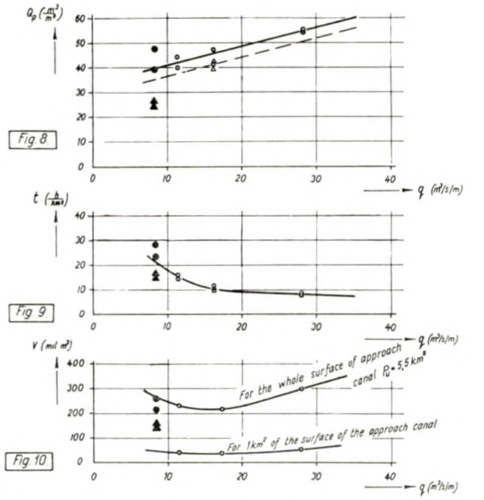

Fig. 8, 9, 10.
The research of ice skimming
Hydraulic model 1:70

LEGEND

○ Skimming through navigation locks $Q_E = \varnothing$, $Q_j = \varnothing$

△ Skimming through navigation locks $Q_E = 3{,}695\ m^3/s$, $Q_j = \varnothing$

● Skimming through the spillways of the auxiliary outlets $Q_E = \varnothing$, $Q_K = \varnothing$

▲ Skimming through the spillways of the auxiliary outlets $Q_E = 3{,}225\ m^3/s$, $Q_K = \varnothing$

b) **Hydropower plant in operation.**

Experiments with ice skimming through navigation locks with simultaneous operation of the hydropower plant have shown, the higher approach velocity has only a negligible effect on the water consumption Q_p (Fig. 8). This is quite logical, since at a full dividing wall the flow in the upstream reach of the power plant is completely separated from that in the roadstead (Fig. 5) and its favourable effect upon the floes skimming velocity cannot appear. On the contrary, the increased feed of ice floes from the upper channel section may cause the collection of ice upstream of the roadstead entrance and also a slowdown of the skimming due to the high intensity of the ice run in the channel and due to surpassing of the critical value of the discharge through the power plant.

3. SIMULTANEOUS ICE SKIMMING THROUGH THE NAVIGATION LOCKS AND AUXILIARY OUTLET SPILLWAYS

As a last variant of the ice skimming the simultaneous use of navigation locks and auxiliary outlet spillways was studied, either conbined with releasing of a part of discharges through the power plant or without this combination.

At known partial parameters of the water consumption and skimming time for respective structures the total values for the case of their combination can be determined analytically. If the time, required for ice skimming from the unit surface of the approach channel through auxiliary outlets will be t_j and through navigation locks t_K, and for that part of the channel area, from which the ice will be skimmed by means of auxiliary outlets the notation P_j will be used; or at skimming through navigation locks P_K, following balance relationships are valid at combined application of both structures :

for the whole skimmed surface :

$$P = P_j + P_K \tag{2}$$

for the whole time of skimming

$$T = P_j t_j = P_K t_K \tag{3}$$

and for the total volume of water consumed for skimming

$$V = T(Q_j + Q_K) \tag{4}$$

where Q_j is the discharge released through the auxiliary outlets and Q_K — the discharge released through the navigation locks.

The value P, occurring in these relationships, is given, Q_j and Q_K have to be chosen and the values t_j and t_K, pertaining to the considered specific discharges q_j and q_K can be read from the diagram in Fig. 9.

The unknown parameters T, P_j and P_K can be then obtained from the formulas

$$T = P \frac{t_j \ t_K}{t_j + t_K} \tag{5}$$

$$P_j = P \frac{t_K}{t_j + t_K} \tag{6}$$

$$P_K = P \frac{t_j}{t_j + t_K} \tag{7}$$

The relationships determined in this way, showing the time required for ice skimming and the total consumed water volume at different skimming variants for different values of the total channel surface covered by broken ice are shown in diagrams in Figs. 11 and 12.

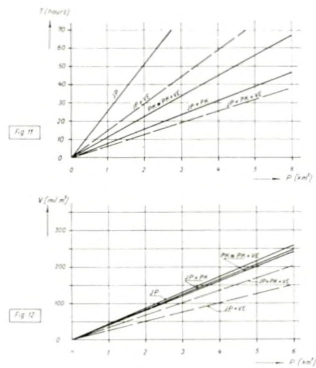

Fig. 11, 12.

The time T and the volume of water V necessary for the skimming of the ice floes from the surface P through single structure and through their combination.

4. RESULTS AND CONCLUSIONS

The results obtained have been tabulated in order to gain a general idea about the conditions affecting the ice skimming from the approach channel in respective variants (see table on page 8).

Variant of skimming	Discharge /m³/s/			Time of skimming (days)	Water consump. (mil. m³)	Comment
	Q_j	Q_K	Q_E			
Auxiliary outlet	470	—		5.26 ÷ 6.64	214 ÷ 270	Assumed spillway blocking
Power plant and auxilary outlet	470	—	3,225	3.45	140	Accumulation of ice upstream of power plant
Navigation lock (*)	—	1,900	—	1.82	300	Smooth ice run
Navigation lock (**)	—	1,020	—	2.54	224	Smooth ice run
Navigation lock and power plant	—	1,020	3,780	2.3	203	Assumed ice accumulation upstr. of navig. locks
Auxiliary outlet and navigation lock	470	1,020	—	1.78	229	Assumed blocking of spillway
Auxiliary outlet and navigation lock, and power plant	470	1,020	3,310	1.46	188	Piling up of ice upstr. of navig. locks and upstr. of the power plant

(*) Variant of skimming, using the full navigation locks capacity

(**) Variant of ice skimming through navigation locks with the minimum water consumption.

Considering the values of the time of skimming and water consumption it is to be stressed that they have a rather informative character. In comparison with model test conditions, the effect of floe ice freezing during the frosty periods in nature, or effect of ice melting, when the total mass of ice in the approach channel decreases, have to be considered, further the effect of different sizes of broken ice floes, intensity of the ice feed towards the structures etc., all those phenomena can affect the above mentioned values negatively, as well as positively.

It is evident from the table that if skimming of ice is to be attained at minimum water consumption, the most favourable method seems to be the skimming of ice through the auxiliary outlets at simultaneous operation of the hydropower plant. A grave deficiency of this variant is the circumstance that at the lay-out solution of the river power project piling up of floe ice and blocking of auxiliary outlet spillways occurs in the upstream reach of the power plant, causing permanent interruption of the ice skimming.

If this method of ice skimming should be applied, it would be advisable to diminish the jeopardizing possibility of ice jam upstream of the spillways by following measures :

a) to increase the spillway blocks clearance at least to the double value of their designed width,

b) to concentrate the blocks of auxiliary outlets into one unit and locate them on the side of the power plant adjacent to the navigation locks,

c) to regulate the supply to the spillway by means of inlet wings so as to provide a continual increase of velocities upstream of spillways.

The most speedy ice skimming from the approach channel can be achieved by simultaneous releasing of the discharge through all structures, of course at the cost of the corresponding increase of the total water volume, required for the skimming. So as to provide at the same time the assumed operation of spillways, it would be necessary to take into consideration all the comments to their solution, mentioned above.

With regard to the reliability of skimming, the variant at which the ice skimming is provided from the approach to the tailrace canal only by navigation locks is to be evaluated as the best one. From the point of view of the minimum water consumption the discharge $Q_K = 1{,}020\ m^3/s$ represents the optimum. In case of a higher emphasis placed on the reduced skimming period it is possible to fulfil this requirement by the full opening of the navigation locks.

In any case all the variants of ice skimming from the approach channel show unjustifiably high water consumption, the water being discharged without any utilization, as well as a long term interruption, or in a better case limitation of the water power generation. In the light of the above mentioned data it is evident that it is a question of economy, whether the clearing of channels from ice, with the aim to accelerate the beginning of the navigation period, is worth while and whether the construction of particular structures for ice skimming — as for instance the auxiliary outlet spillway — is indispensable.

RÉSUMÉ

Les expériences et les résultats de la recherche d'évacuation de glace sur le modèle réduit du barrage de dérivation de Gabcikovo comme partie du projet d'utilisation navigo-énergétique de la section du Danube en aval de Bratislava sont décrits dans ce rapport. La dépendence du succès du charriage de glace de l'alimentation continue des glaçons vers les ouvrages d'évacuation est soulignée et le besoin en eau indispensable pour l'évacuation est analysé.

La convenance d'utilisation des écluses, des déversoirs auxiliaires sans et avec l'usine hydroélectrique en action est évaluée. Pour les conditions données le procédé optimal d'évacuation de glace du point de vue du besoin d'eau minimal, du temps nécessaire pour le charriage et la sécurité d'évacuation des glaçons par l'ouvrage de dérivation de Gabcikovo est déterminé.

S. II - 4

PAPER

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FORCES EXERTED ON STRUCTURES BY ICE FLOES

CONTENTS

NOMENCLATURE

Structure :	Width of structure	d	(m)
	Inclination of face or wedge to horizontal . .	β	(degrees)
	Included angle at point of wedge in horizontal plane	2α	(degrees)
Ice floe :	Length of floe	l	(m)
	Width of floe	b	(m)
	Thickness of floe	e	(m)
	Mass of floe.	M	(tons)
	Velocity of floe	u_c	(m/sec)
	Movement of floe	x	(m)
	Distance, travel of floe during crushing . . .	x_c	(m)
	Distance, travel of floe after break-off of ice .	x_i	(m)
	Distance of line of rupture from face of contact	y	(m)

Wind :	Velocity of wind	u_a (m/sec)
	Shear stress, wind	s_a (kN/m²)
	Total force, wind	S_a (kN)
Water	Velocity of water	u_w (m/sec)
	Shear stress, water	s_w (kN/m²)
	Total force, water	S_w (kN)
	Factor : 2.45 10^{-3}1b (used in water shear) . .	Q (tons m)
Ice properties :	Density of ice	ρ (tons/m³)
	Crushing strength	σ_c (kN/m²)
	Shear strength	c (kN/m²)
	Bending strength	σ_b (kN/m²)
Forces :	Horizontal force in crushing (at edge)	F_a (kN)
	Rupture force	H (kN)
Time :	Time	t (sec)

1. INTRODUCTION

The present paper deals with the problem of ice floes in open sea, which are either moving towards a structure, or initially are at rest in contact with an obstruction and acted upon by external forces, which may produce a rupture, resulting in movement of the ice. The external forces originate from the wind acting on the surface or from the water acting at the underside of the floe. No other forces such as current forces along the edges of the floe have been considered. These forces will be insignificant for larger floes in comparison with the surface shear forces.

The obstructions may have different shapes, which can be shown to influence the magnitude and the nature of the forces. The ruptured or crushed ice will normally be able to escape from structures such as bridge piers or lighthouses, while the debris along an extended length of structure as for instance a breakwater, may be piled up as an ice-piling, producing two problems : one of destructive forces in motion and another of an accumulation of huge quantities of ice debris. Some of the aspects of these problems are dealt with in the following.

Basic formulae of the forces and the characteristics of the rupture will be given, with references to the existing literature for detailed information.

Finally a numerical solution employing a Fortran IV programme computed on an IBM 370/165 is obtained for the differential equations involved.

2. THE TYPES OF STRUCTURES INVESTIGATED

The different types of structures and the mode of rupture are illustrated in Figures 1 and 2.

For the structure of type *a*) and *b*) a simple formula may be given for the shearing (or crushing) force as will be stated in article 5.1. The force in these two cases will reach almost instantly the maximum value as the floe approaches with sufficient inertia to produce rupture. In case *c*) the force will gradually increase as the penetration increases until the full width is mobilised. This means that the maximum force may not be reached if the inertia is not sufficient to produce complete penetration. This is evaluated in article 5.2.

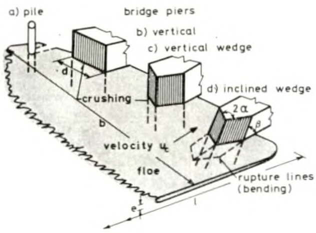

Fig. 1.

Different types of structures : bridge piers, cylindrical caissons, etc.

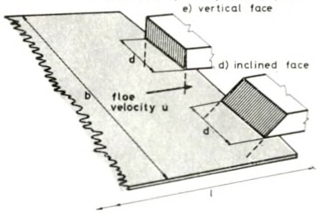

Fig. 2.

Different types of structures : breakwaters, shore protection works, etc.

Finally in case *d*), the inclined wedge, quite a different type of rupture occurs. The ice is broken up in smaller pieces by bending failure in zones parallel to the faces. This will result in a smaller and intermittent force, which is only active at the time of rupture. This is described in article 5.3.

For case *e*) the formulae of case *b*) are applicable. Since crushing rupture takes place with corresponding large forces, the floe is arrested before any relevant volume of debris is created.

A much more complex situation will, however, develop at an extended inclined face due to the occurrence of bending rupture. Under given conditions large ice-piling will result, as shown in article 5.4.2.

3. THE DYNAMIC SYSTEM

Considering the floe drifting with a velocity u_c towards the structure, acted upon by the wind and/or water shear forces and, at the time of impact, also by the rupture force, the following differential equation is valid :

$$M \frac{d^2x}{dt^2} = S_a + Q\left(u_w - \frac{dx}{dt}\right)^2 + F_a\left(\sigma, x_c, d, \ldots\right) \quad (1)$$

where : M is the mass of the floe (tons).

- x is the movement of the floe (m).
- t is the time.
- Sa is the total wind shear force acting on the floe.
- $Q(\frac{dx}{dt})^2$ is the total water shear acting on the underside of the floe (kN).

$Q =$ 2.45 10^{-3} 1 b (tons m).
u_w is the velocity of the water (m/sec).
F_a is the force of crushing at the edge of floe as a function of penetration during impact (kN).

Forces and velocities are measured positive when acting towards the structure.

Formula (1) is a simplified form of the equation of motion. The relevant factors, such as mass, length, etc. decrease as the encounter progresses. Although the influence of this is of minor importance to the evaluation, it has been allowed for in the computer programme.

For computation, the differential equation (1) is replaced by the corresponding difference equation

$$\Delta u_c = \frac{\Delta t}{M}\left(S_a + Q\left(u_w - u_c\right)^2 + F_a\right) \qquad (2)$$

which is evaluated step by step, the consecutive results illustrating the action and establishing the forces and other relevant data, progressing in time.

4. EXTERNAL FORCES FROM WIND AND WATER

Two external forces act on the floe :

1) Wind shear.

When the wind blows over the surface, wind shear stresses are transmitted to the ice :

$$s_a = 2.7\ 10^{-6}\ u_a^2\ (kN/m^2) \qquad (3)$$

where u_a is the wind velocity 10 meter above the ice sheet in m/sec. For a high wind of 30 m/sec, this will give a stress of 2.43 10^{-3} kN/m^2.

The total force acting is :

$$S_a = s_a\ 1\ b\ (kN) \qquad (4)$$

Since the wind velocity is large relative to the floe velocity, the wind force on the floe is considered constant for the given conditions in the computation.

2) Water shear.

The expression « current shear » frequently used has been avoided, as it may as well be the floe which is moving. The water shear stress will be :

$$s_w = 2.45\ 10^{-3}\ (u_w - u_c)^2\ (kN/m^2) \qquad (5)$$

where u_c is the velocity of the floe and u_w the velocity of the water in m/sec.

A relative velocity of 1.0 m/sec gives a stress of 2.45 10^{-3} (kN/m^2) i.e. almost equal to that originating from a wind of 30 m/sec, indicating a physical possibility of interplay of forces.

The total force acting is :

$$S_w = s_w \, l \, b \ (kN) \tag{6}$$

A correction for the variation in water shear corresponding to the change in floe/water velocity is allowed for in the computation.

5. THE RUPTURE FORCE

5.1. **Piles and bridge piers (vertical face).**

For the piles and bridge piers with vertical faces the force may be written

$$H = N_c \, c \, e \, d \ (kN) \tag{7}$$

where : N_c is a non-dimensional factor, called the coefficient of rupture. (Analogy with soil mechanics).

c is the shearing strength (kN/m^2).

e is the thickness of ice (m).

d is the horizontal dimension of the structure (m).

N_c can be derived by considering the shear planes in rupture assumed to be 45° with horizontal and the stresses in the end-triangles in shear.

Considering the forces acting in the shear plane the following formula is derived :

$$N_c = 2 + 0.7 \, e/d \qquad 0 \leqslant e/d = 2.0 \tag{8}$$

for piles $N_c \sim 2.7$ as $e/d \sim 1.0$ and for caissons $N_c \sim 2.0$ as e/d is equal to or smaller than 0.1. For a structure wider than 10 times the ice thickness the side effect is thus negligible.

5.2. **Bridge pier with vertical wedge.**

If the structure is shaped as shown in Figure 1*c*, the force will gradually increase as a greater width of wedge is engaged.

The force at penetration a (see Fig. 4) is :

$$H = N_c \, c \, e \, d \, \frac{a}{a_o} \ (kN) \tag{9}$$

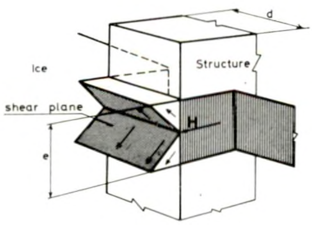

Fig. 3.

Rupture planes.

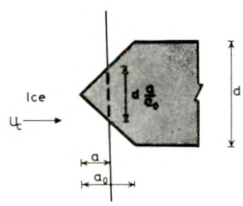

Fig. 4.
Wedge penetrating into floe.

This formula can be used in equation (1), but in this case it is also possible to use an energy equation in order to determine the penetration :

$$\left(\frac{a}{a_o}\right)^2 = \left[\frac{u_c^2\ \rho}{N_c\ c}\right]\left[\frac{A}{d\ a_o}\right] \tag{10}$$

which is suitable for graphical presentation using the parentheses as non-dimensional parameters.

5.3. **Bridge pier with inclined wedge.**

This type of structure has been investigated by K.N. Korzhavin (ref. 1) and it has been proved that a considerable reduction of the forces acting may be obtained. When the ice strikes the wedge the floe is lifted up and breaks along lines parallel with the longitudinal axis, one in the center and one at each side, after which the ice breaks along lines parallel with the sloping faces and located approx. 2 to 3 times the ice thickness from the faces. The vertical forces produce a bending rupture as the force reaches the maximum value, where after it drops suddenly to zero until a new contact has been established. An intermittent force in thus introduced.

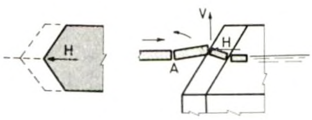

Fig. 5.

Wedge with inclined faces.

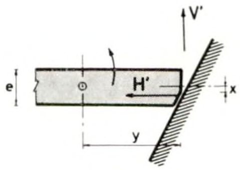

Fig. 6.

Section at rupture face.

The resulting force H can be expressed :

$$H = \sigma_b\ e\ d\ f_a \tag{11}$$

where : σ_b is the bending strength (kN/m²).
f_a is a reduction factor.

Korzhavin considered the bending moments acting along the rupture lines and reference to the relevant literature is made (see ref. 1 and ref. 2).

In the present paper the investigation is widened to include also the normal forces in the rupture section as well as a possible friction in the contact faces.

The reduction factor is found from the expression : (ref. 2)

$$f_a = \frac{\sin\alpha \left\{\dfrac{\tan\beta}{\sin\alpha} + \mu\right\}}{\sin\alpha\left(\dfrac{\tan\beta}{\sin\alpha} + \mu\right) + \dfrac{6\sin\alpha}{e}\left\{y\left(1 - \mu\dfrac{\tan\beta}{\sin\alpha}\right) - x\left(\dfrac{\tan\beta}{\sin\alpha} + \mu\right)\right\}} \tag{12}$$

where μ is the coefficient of friction at the contact face, y is the arm of the bending moment and x is the eccentricity of the normal force. The value of y is taken as two times the ice thickness and x as 0.25 times e.

A table is made showing the variation of the reduction factor with various combinations of the wedge angle 2α and the angle with the horizontal β.

TABLE I

Reduction factor f_a

$\mu = 0.1$

$2\alpha/\beta$	45°	50°	55°	60°	65°
120°	0.16	0.18	0.22	0.30	0.40
110°	0.16	0.18	0.22	0.30	0.40
100°	0.16	0.18	0.24	0.30	0.42
90°	0.16	0.18	0.24	0.32	0.44
80°	0.16	0.18	0.24	0.32	0.46
70°	0.16	0.20	0.24	0.34	0.48
60°	0.18	0.20	0.26	0.36	0.54

Table I is in good agreement with the recommendations of Korzhavin.

The vertical component of the force from actual computations has been found to vary slightly and can be taken as :

$$V = \sigma \; e \; d \; 0.16 \; (kN) \tag{13}$$

for any combination of angles α and β within the values given in table I.

The formula for the horizontal force to be used in equation (1) can be written :

$$F_a = \sigma_c \; d \; x_c \; \tan\beta \tag{14}$$

where σ_c is the crushing strength (kN/m^2), d is the total width of the wedge (m) and x_c is the crushing length (m).

The calculation is executed as follows :

The first stage is a crushing of the edge of the floe. The maximum force H is known, and the force F_a is assumed to increase linearly until the value H is reached after which the floe is broken and the force falls to the value nil until the succeeding contact.

5.4. **Structures of great length as breakwaters, shore protection works, etc.**

For the type of structures as shown in Figure 2 the action is a matter both of forces and of the possibility of ice-piling up in front of the structure.

For simplicity a 1 meter wide strip is considered as the influence from the edge conditions may be neglected for the wide structures.

5.4.1. *Vertical wall.*

In the type of structure with a vertical wall the force to crush the ice will be :

$$H = N_c \ c \ e \ 1.0 \ (kN) \qquad (15)$$

The magnitude of such a force can be illustrated by an example, assuming $N_c = 2.0$, $c = 500$ (kN/m^2) and $e = 0.3$ (m) :

$H = 2.0 \ 500 \ 0.3 = 300$ (kN/m).

If the floe is assumed to be 1,000.0 (m) long and striking the wall with the velocity $u_c = 1.0$ (m/sec), the kinetic energy will be :

$E = 1/2 \ 1{,}000 \ 0.3 \ 0.94 \ 1.0^2 = 140$ (kN/m).

The crushing length is therefore only :

$x = 0.5$ (m).

It is apparent from this result that generally the force will be large and the risk of ice-piling small.

For extreme cases of floe size, high floe velocity, limited width of structure, and limited water depth, the possibility of an artificial, inclined face being formed by ice debris would be separately considered, applying the treatment of the inclined face given in the following article.

However, if formula (1) is used to compute the incident, a constant force H as given by formula (15) should be applied.

5.4.2. *Inclined face.*

At the inclined face the floe is broken into smaller pieces but not crushed, as observed and described for the inclined wedge (see article 5.3). At the inclined wedge it was assumed that the moment arm y was a constant equal to two times the ice thickness. For the inclined face now investigated, it can be shown that the distance y is a complex function of the parameters involved as demonstrated in the following. For a detailed description of the theory, see ref. 3.

If the floe is at rest against the inclined face and is acted upon by for example the wind shear force, the following formula is valid :

$$\frac{y}{e} = \frac{\tan\beta}{6}\left(\frac{\sigma_b e}{S_a} - 1.4\right) \qquad (16)$$

assuming an eccentricity of 0.4 times e for the normal force (S_a may be replaced by S_w or $S_a + S_w$).

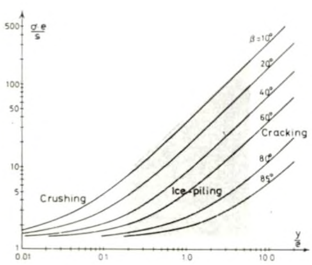

Fig. 7.

Graph showing relationship $\frac{\sigma_b e}{S}, \frac{y}{e}$.

From this formula it is possible for any given condition to calculate whether ice-piling may take place. If the value y/e is in the interval from approx. 0.2 to say 6.0, ice-piling may occur. This criterion is obtained from ref. 3, « A Method of Predicting Ice Piling », from which the following graph is taken. Gravity forces acting on the floes situated on the inclined face have not been included.

With the data inserted in formula (16) we obtain the debris size of the broken up ice floe and the rupture force is in this case equal to either S_a or S_w or a combination S, provided the value of y/e is within the interval of 0.2 to 6.0.

The force as a function of the crushing travel at the edge of the floe in contact with the sloping face can be written :

$$F_a = \sigma_c \, x_c \, \tan\beta \tag{17}$$

with the maximum at value S. For an illustration of this, see article 6.

This is valid only at the initial stage before any appreciable velocity is gained.

In the case of a floe striking the inclined face without any wind or water forces acting, a similar formula is valid : (for further details, see ref. 3)

$$\frac{y}{e} = 0.47 \left(\frac{\sigma_b}{\sigma_c}\right)^{1/3} \left(\frac{\sqrt{\frac{E}{\rho}}}{u_c}\right)^{1/3} = \frac{5.6}{\sqrt[3]{u_c}} \tag{18}$$

assuming $\sigma_b = 0.5\ \sigma_c$; $E = 10^7\ kN/m^2$ and $\rho = 0.94\ t/m^3$ where E is Young's modulus.

The corresponding maximum force to be used is :

$$H = 1/6 \tan\beta \, \sigma_b \, e \frac{\sqrt[3]{u_c}}{5.6} \tag{19}$$

with :

$F_a = \sigma_b \, x_c \, \tan\beta$

during the calculation of the impact force.

During the run of the floe, until the next contact is established, the force is assumed to be zero.

The static and dynamic case may be combined into one (slightly simplified) formula as follows :

$$\frac{y}{e} = \frac{\tan\beta}{6.0\left(\frac{S}{\sigma_b \, e} + \frac{\tan\beta}{6.0}\frac{\sqrt[3]{u_c}}{5.6}\right)} \tag{20}$$

where S stands for S_a or S_w or $S_a + S_w$. The corresponding maximum force is :

$$H = S + 1/6 \tan\beta \, \sigma_b \, e \frac{\sqrt[3]{u_c}}{5.6} \tag{21}$$

In formula (20) the normal force has not been included, and, as before, the force during the numerical integration is assumed to follow the equation :

$$F_a = \sigma_c \, x_c \, \tan\beta$$

during the impact.

Based on these formulae it is now possible to calculate the breaking up of the ice into smaller debris-floes as demonstrated in the examples to follow.

6. COMPUTED SOLUTION FOR THE EQUATION OF MOTION

The difference equation stated in formula (2) has been used in the executions of the Fortran IV programme which follows. The relevant data are read into the computer : L, B, E, Ro, BE, SIGB and UA, UC, UW, G. G is a factor 1.0,

Programme in Fortran IV executed on IBM 370/165 NEUCC

```
      REAL M,H,L
      READ(5,10) L,B,D,E,RO,BE,SIGB
   10 FORMAT(7F10.2)
      ICE FLOE AGAINST STRUCTURE
      READ(5,11) UA,UC,UW,G
   11 FORMAT(4F10.2)
      WRITE(6,12) L,B,D,E,RO,BE,SIGB
   12 FORMAT(1H1,'LENGTH OF FLOE L=',F10.2,' METER',/,
     *1X,'WIDTH OF FLOE B=',F10.2,' METER',/,
     *1X,'WIDTH OF STRUCTURE D=',F10.2,' METER',/,
     *1X,'THICKNESS E=',F10.2,' METER',/,
     *1X,'DENSITY RO=',F10.2,' TONS/CU.METER',/,
     *1X,'ANGLE WITH HORIZONTAL BE=',F10.2,' DEGREES',/,
     *1X,'BENDING STRENGTH SIGB=',F10.2,' KN/SQ.METER',/)
      WRITE(6,13)UA,UC,UW
   13 FORMAT(1H0,'VELOCITY OF WIND UA=',F10.2,' M/SEC',/,
     *' VELOCITY OF FLOE UC=',F10.2,' METER/SEC',/,
     *1X,'VELOCITY OF WATER UW=',F10.2,' M/SEC',/)
      Q=G*2.45/1000*L*B
      BEA=3.1416*BE/180
      AB=TAN(BEA)
      SA=0.0027/1000*L*B*UA**2
      M=L*B*E*RO
      WRITE(6,14) M,SA
   14 FORMAT(1H0,'MASS OF FLOE M=',F10.2,' TONS',/,
     *' WIND SHEAR FORCE SA=',F10.2,' KN'/)
      WRITE(6,20)
   20 FORMAT(///2X,' TIME   VEL.FLOE  DIF.VEL.  DISTANCE  MOVEMENT',
     *'    FORCE       Y/E',/2X,' SEC       M/SEC      M/SEC      METER',
     *'      METER      KNEWTON')
      WRITE(6,21)
   21 FORMAT(/3X,'T',8X,'UC',8X,'UD',9X,'X',7X,'XI XC',6X,'FA',8X,'YOE')
      T=0
      X=0
      XC=0
      XI=0
    1 AT=0.001
      AM=E*UC*AT*RO
      AUC=AT/(M-AM)*(SA+Q*(UW-UC)**2-SIGB*AB*XC)
      UC=UC+AUC
      UD=UW-UC
      X=X+UC*AT
      XC=XC+UC*AT
      FA=SIGB*AB*XC
      H=SA+Q*(UW-UC)**2+1.0/6*AB*SIGB*E*UC**0.333/5.6
      YOE=SIGB*AB*E/(6.0*H)
      Y=YOE*E
      T=T+AT
      IF(FA.LE.H) GO TO 1
      WRITE(6,15)
   15 FORMAT(1H ,'BREAKING')
      WRITE(6,16) T,UC,UD,X,XC,FA,YOE,Y
   16 FORMAT(1H ,F6.2,7F10.4)
      L=L-XC
      XC=0
      XI=0
    3 AT=0.01
      AUC=AT/(M-AM)*(SA+Q*(UW-UC)**2)
      UC=UC+AUC
      UD=UW-UC
      X=X+UC*AT
      XI=XI+UC*AT
      FA=0
      AM=E*UC*AT*RO
      T=T+AT
      IF(XI.LT.Y) GO TO 3
      WRITE(6,17)
   17 FORMAT(1H ,'MOVEMENT')
      WRITE(6,18) T,UC,UD,X,XI,FA,YOE,Y,H,L
   18 FORMAT(1H ,F6.2,9F10.4)
      L=L-XI
      SA=0.0027/1000*L*B*UA**2
      Q=G*2.45/1000*L*B
      IF(T.GE.70) GO TO 6
    4 IF(X.GT.20) GO TO 6
    5 IF(YOE.LT.10) GO TO 1
      WRITE(6,22)
   22 FORMAT(1H0,' SYSTEM NOT APPLICABLE')
```

which is either positive or negative corresponding to the direction of the resulting water shear, (negative away from the structure).

In the examples given a strip 1.0 m wide has been chosen for both structure and floe.

Example I: Floe at rest against inclined face acted upon by wind shear

```
LENGTH OF FLOE L=     1000.00 METER
WIDTH OF FLOE B=         1.00 METER
WIDTH OF STRUCTURE D=       1.00 METER
THICKNESS E=          0.30 METER
DENSITY RO=           0.94 TONS/CU.METER
ANGLE WITH HORIZONTAL BE=        45.00 DEGREES
BENDING STRENGTH SIGB=     500.00 KN/SQ.METER

VELOCITY OF WIND UA=       30.00 M/SEC
VELOCITY OF FLOE UC=        0.00 METER/SEC
VELOCITY OF WATER UW=       0.00 M/SEC

MASS OF FLOE M=       282.00 TONS
WIND SHEAR FORCE SA=       2.43 KN
```

TIME SEC	VEL.FLOE M/SEC	DIF.VEL. M/SEC	DISTANCE METER	MOVEMENT METER	FORCE KNEWTON	Y/E
T	UC	UD	X	XI XC	FA	YOE
BREAKING 1.44	0.0061	-0.0061	0.0065	0.0065	3.2471	7.7001
MOVEMENT 23.97	0.1976	-0.1976	2.3174	2.3109	0.0000	7.7001
BREAKING 24.02	0.1976	-0.1976	2.3273	0.0099	4.9420	5.0704
MOVEMENT 30.78	0.2527	-0.2527	3.8501	1.5230	0.0000	5.0704
BREAKING 30.82	0.2527	-0.2527	3.8605	0.0104	5.1814	4.9131
MOVEMENT 36.19	0.2953	-0.2953	5.3350	1.4747	0.0000	4.9131
BREAKING 36.23	0.2953	-0.2953	5.3456	0.0106	5.3165	4.8276
MOVEMENT 40.86	0.3310	-0.3310	6.7958	1.4503	0.0000	4.8276
BREAKING 40.89	0.3310	-0.3310	6.8064	0.0106	5.2967	4.7746
MOVEMENT 45.03	0.3621	-0.3621	8.2413	1.4350	0.0000	4.7746
BREAKING 45.06	0.3620	-0.3620	8.2521	0.0109	5.4318	4.7399
MOVEMENT 48.85	0.3898	-0.3898	9.6771	1.4250	0.0000	4.7399
BREAKING 48.87	0.3897	-0.3897	9.6880	0.0109	5.4574	4.7171
MOVEMENT 52.39	0.4149	-0.4149	11.1042	1.4164	0.0000	4.7171
BREAKING 52.42	0.4148	-0.4148	11.1150	0.0108	5.3934	4.7023
MOVEMENT 55.73	0.4378	-0.4378	12.5262	1.4113	0.0000	4.7023
BREAKING 55.75	0.4378	-0.4378	12.5372	0.0109	5.4731	4.6934
MOVEMENT 58.89	0.4591	-0.4591	13.9453	1.4082	0.0000	4.6934
BREAKING 58.91	0.4590	-0.4590	13.9563	0.0110	5.5088	4.6889
MOVEMENT 61.91	0.4788	-0.4788	15.3631	1.4069	0.0000	4.6889
BREAKING 61.93	0.4788	-0.4788	15.3741	0.0110	5.5066	4.6878
MOVEMENT 64.82	0.4974	-0.4974	16.7836	1.4107	0.0000	4.6878
BREAKING 64.84	0.4973	-0.4973	16.7943	0.0109	5.4713	4.6894
MOVEMENT 67.62	0.5148	-0.5148	18.1993	1.4070	0.0000	4.6894
BREAKING 67.64	0.5147	-0.5147	18.2098	0.0108	5.4053	4.6931
MOVEMENT 70.34	0.5313	-0.5313	19.6200	1.4122	0.0000	4.6931

The programme computes two conditions alternately. In the first phase the floe is being crushed and broken by the acting forces. In the second phase the arresting force is zero, while the floe is drifting along until contact is reestablished.

<u>Example II</u>: Ice drifting with velocity 1.0 in a current of 1.0 m/sec without wind. Programme terminated after movement of 20 m.

```
LENGTH OF FLOE L=        1000.00 METER
WIDTH OF FLOE B=            1.00 METER
WIDTH OF STRUCTURE D=          1.00 METER
THICKNESS E=         0.30 METER
DENSITY RO=         0.94 TONS/CU.METER
ANGLE WITH HORIZONTAL BE=      45.00 DEGREES
BENDING STRENGTH SIGB=     500.00 KN/SQ.METER

VELOCITY OF WIND UA=       0.00 M/SEC
VELOCITY OF FLOE UC=       1.00 METER/SEC
VELOCITY OF WATER UW=        1.00 M/SEC

MASS OF FLOE M=     282.00 TONS
WIND SHEAR FORCE SA=       0.00 KN
```

TIME SEC	VEL.FLOE M/SEC	DIF.VEL. M/SEC	DISTANCE METER	MOVEMENT METER	FORCE KNEWTON	Y/E
T	UC	UD	X	XI XC	FA	YOE
BREAKING 0.01	0.9999	0.0001	0.0090	0.0090	4.4999	5.6001
MOVEMENT 1.70	0.9999	0.0001	1.6989	1.6899	0.0000	5.6001
BREAKING 1.71	0.9999	0.0001	1.7079	0.0090	4.4996	5.6002
MOVEMENT 3.40	0.9999	0.0001	3.3976	1.6898	0.0000	5.6002
BREAKING 3.41	0.9998	0.0002	3.4066	0.0090	4.4993	5.6004
MOVEMENT 5.10	0.9998	0.0002	5.0961	1.6896	0.0000	5.6004
BREAKING 5.11	0.9997	0.0003	5.1051	0.0090	4.4990	5.6005
MOVEMENT 6.80	0.9997	0.0003	6.7947	1.6896	0.0000	5.6005
BREAKING 6.80	0.9997	0.0003	6.8037	0.0090	4.4987	5.6006
MOVEMENT 8.49	0.9997	0.0003	8.4931	1.6894	0.0000	5.6006
BREAKING 8.50	0.9996	0.0004	8.5021	0.0090	4.4985	5.6007
MOVEMENT 10.19	0.9996	0.0004	10.1913	1.6893	0.0000	5.6007
BREAKING 10.20	0.9996	0.0004	10.2003	0.0090	4.4982	5.6008
MOVEMENT 11.89	0.9996	0.0004	11.8895	1.6892	0.0000	5.6008
BREAKING 11.90	0.9995	0.0005	11.8985	0.0090	4.4979	5.6010
MOVEMENT 13.59	0.9995	0.0005	13.5876	1.6891	0.0000	5.6010
BREAKING 13.60	0.9994	0.0006	13.5966	0.0090	4.4976	5.6011
MOVEMENT 15.29	0.9994	0.0006	15.2855	1.6890	0.0000	5.6011
BREAKING 15.30	0.9994	0.0006	15.2945	0.0090	4.4973	5.6012
MOVEMENT 16.99	0.9994	0.0006	16.9820	1.6889	0.0000	5.6012
BREAKING 17.00	0.9993	0.0007	16.9909	0.0090	4.4970	5.6013
MOVEMENT 18.69	0.9993	0.0007	18.6774	1.6888	0.0000	5.6013
BREAKING 18.70	0.9992	0.0008	18.6863	0.0090	4.4967	5.6014
MOVEMENT 20.38	0.9992	0.0008	20.3728	1.6887	0.0000	5.6014

The programme includes the effect of the decreasing length of the floe. If the factor y/e becomes greater than 10, the system is not applicable and the calculation is terminated.

<u>Example III</u>: **An ice floe drifting in water at rest (may occur if the floe is drifting into area without current)**
Rejected for calculation as y/e greater than 10.

```
LENGTH OF FLOE L=      1000.00 METER
WIDTH OF FLOE B=          1.00 METER
WIDTH OF STRUCTURE D=         1.00 METER
THICKNESS E=           0.30 METER
DENSITY RO=            0.94 TONS/CU.METER
ANGLE WITH HORIZONTAL BE=       45.00 DEGREES
BENDING STRENGTH SIGB=      500.00 KN/SQ.METER

VELOCITY OF WIND UA=        0.00 M/SEC
VELOCITY OF FLOE UC=        1.00 METER/SEC
VELOCITY OF WATER UW=       0.00 M/SEC

MASS OF FLOE M=        282.00 TONS
WIND SHEAR FORCE SA=        0.00 KN
```

TIME SEC	VEL.FLOE M/SEC	DIF.VEL. M/SEC	DISTANCE METER	MOVEMENT METER	FORCE KNEWTON	Y/E
T	UC	UD	X	XI XC	FA	YDE
BREAKING						
0.00	0.9999	-0.9999	0.0050	0.0050	2.4999	12.4100
MOVEMENT						
3.79	0.9681	-0.9681	3.7334	3.7284	0.0000	12.4100

SYSTEM NOT APPLICABLE

In Figure 8 is shown the intermittent force as a function of time : example 1 has been used.

7. FINAL REMARKS

In order to verify some of the results presented in this paper it is planned to run tests with artificial ice which is being developed at the Institute. These tests will comprise investigations with dynamic models of floes drifting against different shapes of obstacles. Until these tests have been performed the formulae should be used with caution. This is particularly applicable to problems concerning ice-pilings.

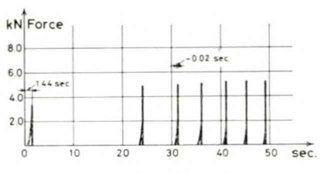

Fig. 8.

Intermittent force at impact on inclined face.

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Ref. 2, 3, 4, 5, and 6 are all published at the Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark.

ACKNOWLEDGEMENTS

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RÉSUMÉ

Ce rapport traite le problème de banquises flottantes (ice-floes) en pleine mer, soit en mouvement vers une structure massive soit en repos originel en contact avec un obstacle actionné par des forces extérieures susceptibles de produire une rupture ayant comme résultat un mouvement des glaces.

Des obstacles de formes différentes ont été étudiés, et des formules de forces agissant sur les glaces sont présentées.

Les équations du mouvement de la banquise sont indiquées, et une description est donnée des différents stades de chocs produisant des forces intermittentes. Le rapport traite aussi le problème d'entassement des glaces devant une large construction massive et il prouve qu'il sera possible, à l'aide de données adéquates du système, de pronostiquer un amoncellement des glaces.

Une programmation basée sur les résultats présentés et faite par l'application de l'équation de différence de mouvement, a été traduite en Fortran IV en vue d'une solution numérique. Des cas variés ont été traités.

S. II - 4

PAPER

by

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EFFECTS OF ICE ON NAVIGATION AND ON NAVIGATIONAL AIDS

1. INTRODUCTION

In Finland where ice is a phenomenon recurring every winter, it has a very strong and manifold influence in navigation and water structures. Considering shipping and activities serving it, the effects of ice are unfortunately purely negative. It makes navigation dependent on ice-breakers, slows down vessels, makes it necessary to build vessels so that they can navigate in ice, which means risen construction and operation cost, brings about accidents and ice damages and increases the maintenance of structures. As an intermediate effect, ice hampers signing of channels.

Until the last few years Finnish caisson lighthouses have been the only navigational aids founded in water. All the other aids to navigation placed in water have had to be removed for winter since they have not been able to resist the movement of ice. As a consequence, navigation has had to be based mainly on leading marks and lights. The edges of channels have been signed mainly by temporary summer beacons.

The effect of ice on navigation and structures in Finnish conditions is a tangible matter and a manifold problem as to its economic consequence. This paper deals only with the effect of ice on navigation in general and in larger detail and its effect on the navigational aids. It is naturally necessary to describe local conditions as far as understanding the plans is concerned.

2. ICE CHARACTERISTICS IN FINNISH ENVIRONMENTS

2.1. Freezing.

The sea around Finland freezes in the following manner :

The formation of ice starts from the coasts proceeding to islands at the edges of the coast, then to the front of the islands and finally, when the temperature of water has gone sufficiently low, to the open sea.

Freezing of the island zone preceding that of the open sea means the formation of a zone of solid ice important to navigation. This phenomenon extends later outside the island zone. During the winter, a zone of pack ice is frequently formed at the edge of solid ice. The zone of pack ice is very important from the point of view of the ice loadings of structures, because the largest ice loads within the zone of pack ice are evidently created from the thermal expansion of ice while in the open sea, the structure must be able to break moving, solid ice. From the point of view of navigation, the zone of pack ice is the most difficult obstacle in winter traffic.

Melting or in many cases the disappearence of ice takes place in the reserve order. Particularly, ice in the open sea starts to move easily and disappears towards the spring along with the winds before actual melting takes place.

As for vessel traffic, solid ice and loose ice in the open seas must be separated. A channel made in solid ice by an ice-breaker stays open even in the wind. As a consequence, ship channels protected by islands are most safe in winter and they can be kept satisfactorily open by ice-breakers. On the other hand, difficulties in the open sea are manifold. The channel made by an ice-breaker is rapidly closed by moving ice, enormous forces are created when large ice masses are pushed by the wind and loose ice is packed, for example, against solid ice into pack ice is often difficult to break by ice-breakers. A vessel caught in the pressure of ice is generally fully disabled and exposed to the risk of sinking. As it is moved off the marked route by ice it also faces the risk of running aground.

2.2. **Wideness of Ice.**

The Baltic Sea is situated in a zone where ice appears in winter. There are large variations in the times of ice formation as well as in the severity of winters. An impression of these variations can be obtained by comparing the largest extensions of ice occurring in different winter seasons (Fig. 1). In the mildest

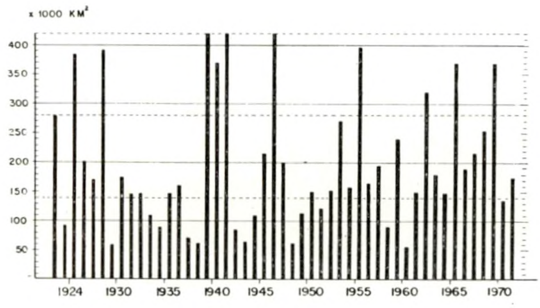

Fig. 1.

The maximum extent of the ice cover on the Finnish coast during period 1924-1972. Broken lines are limits between mild, average and hard winters.

winters such as 1960-61, the northernmost part of the Gulf of Bothnia was frozen for a short time while the Gulf of Bothnia and the northern part of the Baltic stayed open (Fig. 2). The overall area of ice was about 60,000 km². In the most severe winter of this century in 1941-1942 the Baltic and the Danish Sounds were covered by ice in February and the overall area of ice was around 420,000 km² (1). The extent of ice during an average winter is shown in Figure 3. Figure 4 shows the process of freezing from December to its maximum during a severe winter.

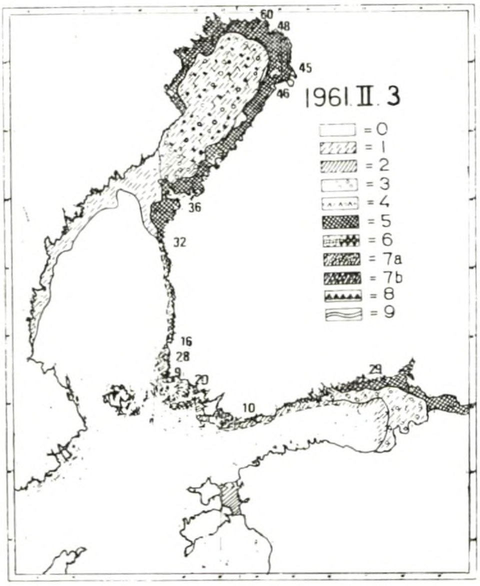

Fig. 2.

The ice situation on February 3, 1961.

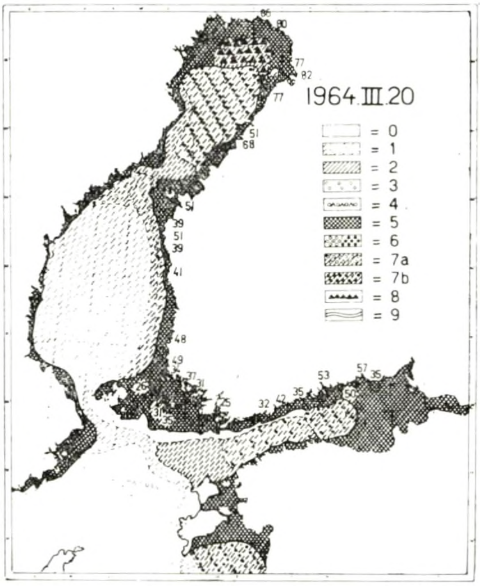

Fig. 3.

The ice situation on March 20, 1964.

EXPLANATIONS :

0 = Open water.
1 = New-ice.
2 = Young fast-ice.
3 = Open drift-ice.
4 = A compressed accumulation of sludge.
5 = Winter fast-ice.
6 = Close pack-ice.
7a = Very close pack-ice.
7b = Pack-ice frozen together.
8 = Pressure-ice.
9 = Shorelead.

The formation and spreading of ice from the coast outwards does not take place at an even rate. The edge of ice stays for long at the edge of large open sea areas. As the sea has cooled completely in course of continuing cold days the open sea may be frozen almost simultaneously. It means that the distribution of ice winters by the largest extent of ice is not uniform when freezing stops frequently at the edge of the open sea.

2.3. **Formations of Pack Ice.**

Pack ice is formed when the wind pushes the ice field of the open sea against the solid ice field of the coast. The thinner ice field of the open sea is broken and ice slabs get packed both below the edge of solid ice and partly above it

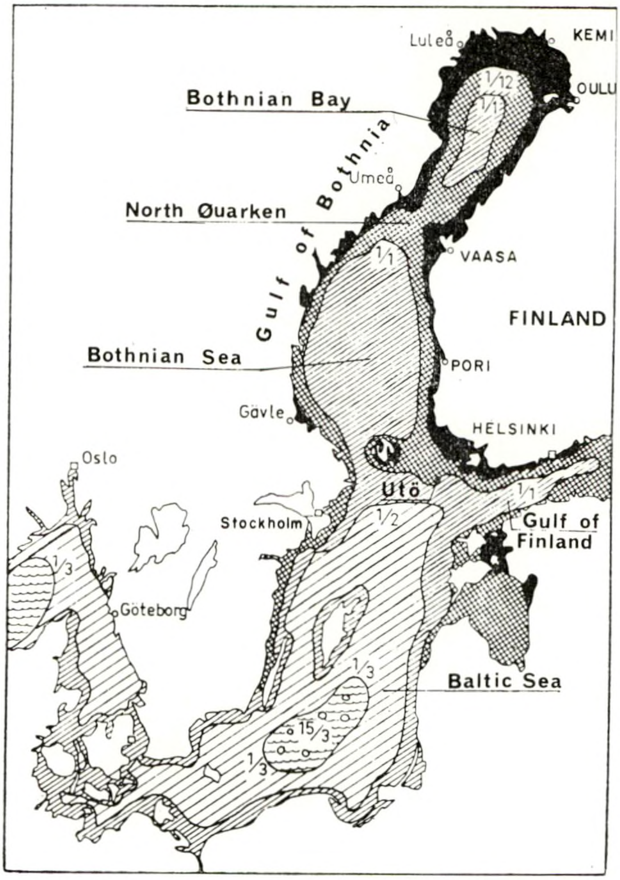

Fig. 4.

The progress of freezing from December to maximum in hard winter.

forming a wall of pack ice. Sometimes, the edge of moving ice may force itself in a solid state below or above solid ice for more than ten metres before ice slabs are formed. When the open sea is not yet frozen, the edge of solid ice may also be broken by storm and ice slabs may be pushed into pack ice at the edge of the ice field.

Formations of pack ice are thus dependent primarily on winds. The locations and size of pack ice formations therefore vary from year to year and their properties are determined on the basis of winds prevailing at the time of freezing.

The prevailing winds in the coast of Finland blow between south and west. Therefore, the most difficult formations of pack ice are encountered regularly in the northern part of the Gulf of Bothnia, in the North Quarken (The contracted sea area between the Bothnian Bay and the Bothnian Sea, see Fig. 4) and the northern part of the Baltic.

The structure of pack ice formations has been investigated locally in Finland. As their size, form and location vary annually, no general definition of their structure cannot be presented. In the investigations carried out the walls of pack ice have been observed to extend frequently down to the bottom when the depth of water has been 10...15 m. Even for ice-breakers, breaking such ice formations is a difficult task.

Winds have a very significant effect on ice conditions in winter. With respect to winds the changes in ice conditions mainly depend on the direction and force of the wind. Winds particularly troublesome for winter navigation are those blowing towards the coast and making difficult the keeping open of channels into harbours used in winter.

The circumstances in which solid ice can be broken in a certain area can be determined even afterwards by making observations about conditions at the time of formation of ice walls. In this way, necessary information is obtained for the assumptions of loading of structures. Formations of pack ice are not in themselves dangerous to structures as the ice slabs are fully loose except for their surface part. On the other hand, formations of pack ice are a proof of strong movement of ice in certain stage of freezing.

2.4. **Thickness of Ice.**

The maximum thickness of solid ice is at its highest in the coastal zone of solid ice. In the northernmost part of the Gulf of Bothnia off the towns of Kemi and Oulu the thickness of solid ice may be 80...100 cm. In the Bothnian Bay the thickness of ice is at most 60...80 cm. In the North Quarken the thickness may reach 50...60 cm and the same thickness may be reached in the eastern part of the Gulf of Finland beyond Helsinki. In the coastal section Pori-Helsinki, the thickness of solid ice does not reach 50 cm even in hard winters.

2.5. **The Degree of Saltness of Water.**

As known the degree of saltness of water has a considerable influence in the strength values of ice. The strength of ice decreases as the degree of saltness increases.

The Baltic Sea has a very low degree of saltness, which even decreases the further we go from the Danish Sounds. The following approximate values of the degree of saltness can be given :

— the northernmost part of the Gulf of Bothnia under	1 ‰
— the North Quarken	3...4 ‰
— the northern part of the Baltic	5...6 ‰
— the eastern part of the Gulf of Finland	3...5 ‰
— the southern part of the Baltic	8..10 ‰

2.6. **Strength of Ice.**

In laboratory and field tests the average compressive strength of ice in the northern part of the Gulf of Bothnia (degree of saltness under 1,0 ‰) at right angles to the direction of growth has been found to be 28 kg/cm² at a temperature of + 0 °C (2). In tests, a value of 4,1 kg/cm² °C has been obtained for the change coefficient of ice strength. The laboratory tests were made with 10 × 10 × 10 cm³ test cubes and the field tests by pushing cylinder halves, dia 40 cm and 80 cm, horizontally so that ice in front of the cylinders was broken.

The bending strength of ice been investigated in Finland for the design of ice-breakers. The bending strength has been found to vary between 3...6 kg/cm² depending on the temperature and degree of saltness of ice.

2.7. **Temperature of Ice.**

The compressive strength of ice is strongly dependent on its temperature. In determining the ice loading of structures, the temperature of ice at the moment of loading must therefore also be assessed.

The largest ice loading occur when ice is moving as an effect of strong winds Then, there is a depression and the temperature in Finnish conditions cannot be below –10...–15 °C. The maximum loading also means that the thickness of ice must be at its largest, which is the case at the latter half of March. Ice is always then covered with snow, which moderated the changes in ice temperature. Furthermore, strong winds are rare in March and the average daily temperature is clearly higher than that of midwinter.

On the basis of field observations and the above factors temperature values of 0...–2 °C have been used in assessing loadings.

3. INFLUENCE OF ICE ON NAVIGATION TRAFFIC

3.1. **General.**

In 1970, the import and export of Finnish harbours, including coastal traffic was only 46 million tons. As the same time the ice-breaker fleet consisted of eight vessels with an overall engine power of 73,500 shaft horse powers (3).

In addition to the ice-breakers owned by the state (see Table 1), harbours have their ice-breakers, fifteen in all in 1970.

The power of the Finnish ice-breaker fleet in relation to the volume of traffic is probably the highest in the world, which is a clear proof of the difficulties encountered by navigation in the coastal waters of Finland in winter.

In normal and severe winters the entire navigation in Finland is dependent on ice-breaker operations. The primary objective of these operations in the last few years has been to kept the southern harbours open throughout the winter. This means that sea transport in the northern part of the Gulf of Bothnia has been assisted in times when ice-breakers have not been needed in the south.

TABLE I

Ice-breakers used or ordered in winter 1970-1971

Name	First year of use	Purchase price Million Fmk	Engine power HP	Crew	Operating speed knots	
					open sea	assisting
Sisu (to be removed in 1975)	1939	8,30	4.500	43	10-11	assisting
Voima	1954	15,09	10.500	56	14	speed
Karhu	1958	14,73	7.500	51	13-14	of all ice-
Murtaja	1959	15,54	7.500	51	13-14	breakers
Sampo	1960	15,74	7.500		13-14	in various
Tarmo	1963	26,56	12.000	56	16	ice
Varma	1968	32,20	12.000	52	16	conditions
Apu	1970	32,10	12.000	52		– easy
In order	(1975)	68,00	(20.000)	(52)	(16)	10 knots
In order	(1976)	68,00	(20.000)	(52)	(16)	– other
						8 knots
		Total	73.500 (113.500)	412 (516)		

In normal and severe winters the harbours of the northern part of the Gulf of Bothnia have been closed for a few months and goods have been transported by rail to the harbours of Southern Finland. In mild winters, more than two-thirds of the usage hours of ice breakers have been used in northern harbours. In severe winters their proportion has remained to about 10 per cent since ice-breakers have been used in southern sea areas (3).

3.2. **Navigation in Winter.**

In normal winters, traffic in the Gulf of Bothnia has been arranged mainly as follows :

— The assistance of the northernmost harbours of Kemi and Oulu is started on an average at the beginning of December.

— In December, the strongest vessels can sail alone to a distance of 60-70 sea miles from Kemi. Weaker vessels need additional assistance of ice-breakers, particularly near the North Quarken. Navigation proceeds in convoys of several vessels.

— During the first three weeks of January vessels are assisted from Kemi to the North Quarken in convoys. Strong vessels are able to continue on their own while weaker ones (certain navigation restrictions are naturally in force then) need assistance, sometimes down to Utö, see Figure 4.

— In the last week of January the situation becomes so difficult that 1-2 vessels at a time are assisted north of North Quarken and south of the strait vessels (if there are enough of them) move in convoys of 5-7 ships. The northernmost harbours have been closed normally by the beginning of February, Pietarsaari and Kokkola a couple of weeks later.

— After the first week of March the situation starts to become easier. At the beginning of April ships may sail to Pietarsaari and Kokkola. First, 1-2 vessels are assisted, and gradually larger convoys and at the end of the month the channel to Kemi and Oulu is opened.

— After mid-May vessels can proceed freely. Then, the movement of ships is only safeguarded by ice-breakers.

In spring, navigation is hampered by wind and movements of ice masses. Vessels have often to be conveyed along the Swedish coast. Helicopters are then used in order to find suitable routes.

In normal winters, there are no larger difficulties in navigation to the harbours of the Gulf of Finland. The Baltic is open close to the coast in the north and to the mouth of the Gulf in the east. At the beginning and the end of winter ships are assisted from the harbour directly to the open sea. One and the same ice-breaker often takes care of navigation of neighbouring harbours.

In mid-winter vessels are using the winter channel protected by islands (Fig. 5). Traffic from harbours then joins at certain spots and continues as a

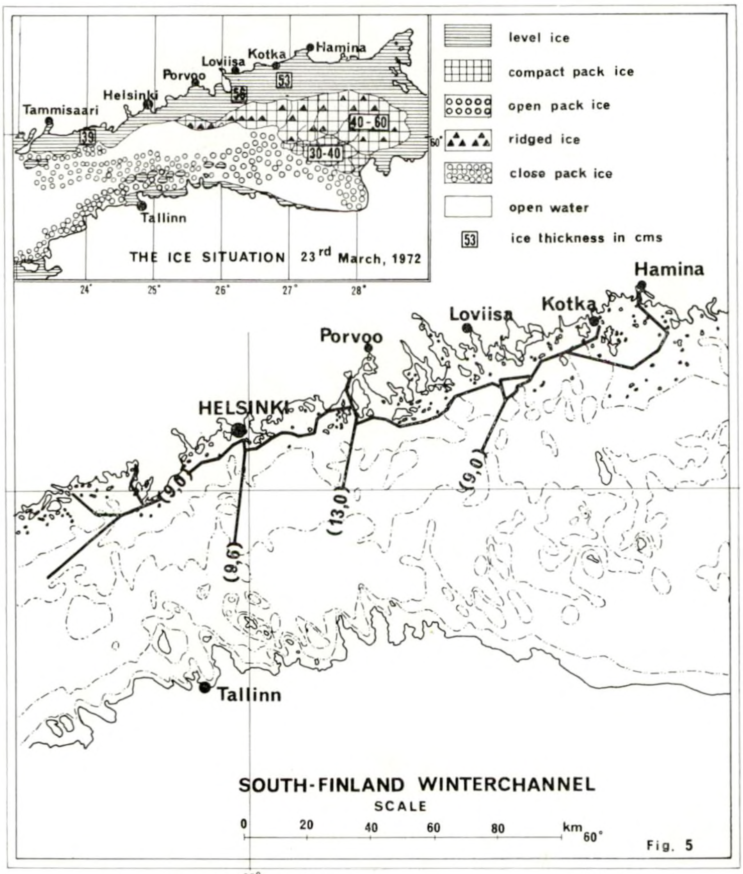

Fig. 5

convoy to the open sea. The convoy is normally assisted by ice-breakers only at difficult spots. Traffic between the meeting point and the harbour takes place either individually or in small groups depending on the situation. The emphasis of ice-breaker action is on the open sea and at the mouth of the island channel.

3.3. Accidents in Winter.

Navigation in ice brings about certain risks although it can also be considered to remove some of them. The channel cut in ice in a zone of solid ice is laterally limited and this prevents vessels from moving off the channel. It has been observed that this has clearly decreased the number of groundings in winter (4).

Navigating in a narrow channel and in convoys however brings about other kinds of accidents : collisions and stern collisions.

Owing to the low density of traffic, collisions in Finnish channels in summer are rare whereas the maximum is reached clearly in winter. Of the collisions of two vessels, 70...80 per cent occur in winter. Navigating in convoys in narrow ice channels brings about the risk of stern collision, as the vessel ahead, even an ice-breaker, may at any time get stuck in ice. Similarly, a critical situation arises when vessels meet because giving way in a slushy and narrow channel is difficult. On the other hand, these situations can be anticipated and therefore, damages in winter collisions have been slight.

The problem has not given grounds for any measures so far. On the other hand, it is obviously difficult to find a good solution for the problem. Anyhow, the measure would call for an increase in the number of ice-breakers which is obviously not economically justified at today's volume of traffic. Moreover, opening parallel channels is most often impossible because of natural obstacles.

Stern collision can probably be decreased only by increased caution and improving the internal communications of convoys.

In the open sea, a merchant vessel, in particular a stopped one, always faces the risk of getting pressed by ice. Although the vessel were reinforced against ice it cannot resist lateral stresses to the extent created possibly by an ice field pushed by wind. As a consequence, in difficult conditions ice-breakers must assist individual merchant vessels since safe navigation calls for continuous movement ahead.

4. INFLUENCE OF ICE ON NAVIGATION ROUTES

As mentioned above, the fluency of navigation, its safety and efficient ice-breaker action mean that winter navigation should use the area of solid ice as much as possible. In this way, a plan for a winter channel of Southern Finland was originated. A part of this channel has been shown in Figure 5. The depth of the channel is 9 m corresponding the water depth of 10,5 m.

Winter channels are used mainly in winter only, but they are useful also in summer for coastal traffic and for smaller vessels desiring to use protected coastal channels.

Planning winter channels must be based on long-time ice observations the principal purpose of which is to find the location of pack ice formations and the edge of the zone of solid ice.

5. INFLUENCE OF ICE ON DESIGN AND CONSTRUCTION OF MEANS FOR NAVIGATION AIDS

5.1. General.

Finnish conditions are often very difficult for navigation. Particularly in autumn and winter when the daylight period is short, the weather is also frequently unfavourable. Rains — sleet and snow — restrict visibility to the minimum and make the use of radar difficult. When the bending and narrow channels and the dangers of rock shallows are mentioned — it is obvious that the aids to navigation — both in vessels and channel — should be better than average.

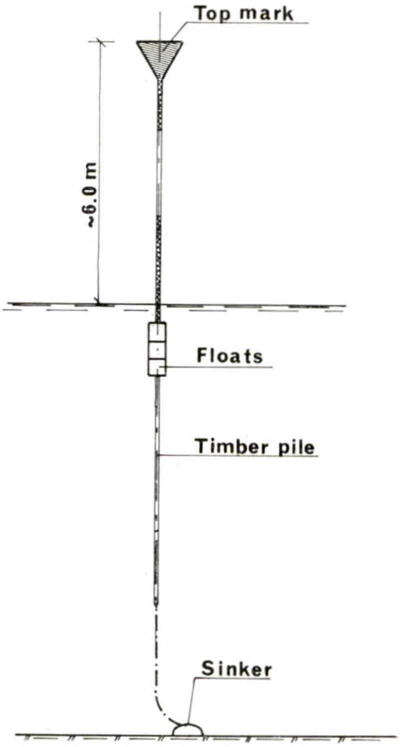

Fig. 6.

Anchored beacon.

Nevertheless, the actual situation on the channels has been in a sense converse, as ice has formed an obstacle for erecting permanent navigation aids in water. As a consequence, anchored beacons have been used (Fig. 6) which owing to their temporary nature, poor visibility, movements etc. cannot be regarded as actual navigation aid.

Anchored beacons are used to indicate the shallows in proximity of the channel. Staying in place of beacons is not certain although they are weighted moderately well. It has been noticed that even a very thin layer of sludge can move anchored beacons. Their dimensions are also so small that their visibility both optically and in radar is very poor. In other words, anchored beacons are useful only in good visibility, when navigation by means of line marks is possible. As it has also been found in the investigations of groundings that accidents have been caused mainly by errors in the determination of ship's position, developing channels beacons that stay in place in ice has been considered necessary.

5.2. **Radar and Radar Reflectors.**

A ship radar is principally an anti-collision device that has not originally been designed for navigation in island channels. Although a ship radar is not so suitable for channel navigation it has to be used frequently as an instrument of determination of ship's position in poor weather conditions because there simply are no better device for that purpose in island navigation.

More difficulties are encountered in the use of radar in island channels in winter because pack ice formation can be seen in radar as well as islands and other permanent objects. As the formations of pack ice have a different shape every year and their location varies, no reliable radar picture map cannot be drawn up for winter navigation.

As a matter of fact the ship radar today is the only electronic device for determination of ship's position used generally in ships and suited to channel navigation. When the navigation aids of the channel are examined from this point of view the conclusion can be formed that channel aids to navigation should be developed so that the direction of the channel can reliably and as easily as possible be determined from radar. As regards channel navigation aids, this means, among other things, as follows :

— The edges of the channel shall be indicated, at least at critical spots, by permanent structures that can be clearly seen by radar. Large-diametre winter buoys fixed to the bottom (Fig. 7) may be considered such device provided that ice is not so movable that the buoys can be sunk by its pressure. However, only fixed channel edge beacons designed for ice forces can be considered navigation aids (Fig. 8 and 9) meeting the requirement of winter navigation.

— Structures shall be provided with efficient radar reflectors in order to distinguish them from other echoes seen in radar. An additional advantage offered by active radar reflectors (Racon) is the indication of the side on which the beacon is located. The use of Racon in edge beacons has not yet been experimented in Finland.

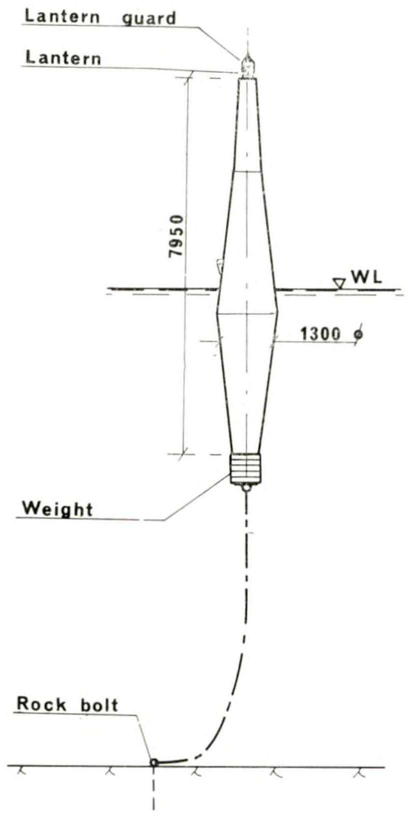

Fig. 7.
Winter buoy.

In determining the locations of radar

reflectors radar picture maps should be used, when necessary. The best echoes are naturally obtained from reflectors erected in water. However, care shouls then be taken in order that formations of pack ice are not formed around reflectors to make the localization of the echo difficult.

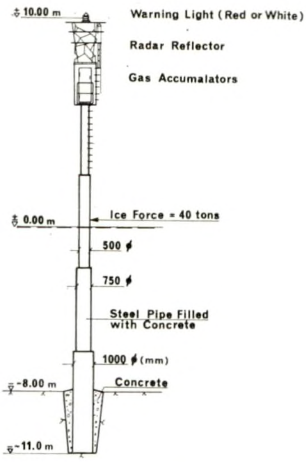

Fig. 8.

Innamo channel edge beacon.

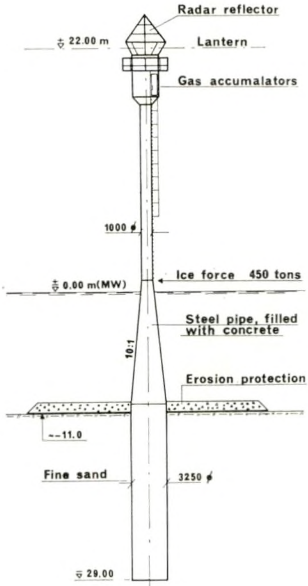

Fig. 9.

Nukkujanmatala lighthouse.

5.3. **Visual Navigation Aids.**

However, all accidents do not occur in poor visibility. Accidents taking place in good weather show that there are errors both in the marking of the channel and in light buoys, which together with weak bridge action may result in erroneous navigation. The deficiencies of day markings may be combined with the notion that the channels lack optical guidance. For instance, the bends of channel lines have not so far been indicated in the terrain. However, it should be possible to determine the ship's position at the turning point because information if the visibility of the channe! section after the turn is obtained generally only in the turning zone. In the case that the beacons of the following channel section cannot be seen for one reason or another, it is too late to stop the vessel.

The cardinal marking system used in Finland also in island channels is most confused with respect to optical guidance and erroneous manœuvres may result even in good weather.

In regions where ice moves only at the time of freezing and melting, winter buoys (Fig. 7) can also be used. The buoys must however be fixed, for example, by rock bolts into a certain spot to that any displacement need not be taken into account in navigation. Low price (about 10,000 Fmk + fixing into the bottom) is an advantage as well as the fact that buoys can also be placed in deep water to indicate the turn point of channel lines.

A fixed channel edge beacon, correctly implemented, also improves optical guidance. The different sides of the channel can also be indicated by various colours and structures.

In the dark, the location of the channel is indicated in Finland by leading lights or sector lights placed at the sides of the channel. Navigation by leading lights is unambiguous, whereas navigation by sector lights always is a sort of guesswork and contain a larger risk. Moreover, the edges of the sector may be displaced owing to ice accumulated in glass. The sector light cannot be taken as a reliable navigation aid which is shown by numerous accidents attributable to it.

Sector lights will gradually be replaced by fixed channel edge beacons founded in water. The fixed channel edge beacons are to be provided only with warning lights with different symbols at the right and left side of the channel. Lighting the face of the beacons would be advantageous but in general, it is not possible owing to the lack of energy.

5.4. **Fixed Channel Beacons Founded in Water.**

5.4.1. *General.*

Depending on conditions, fixed channel beacons founded in water may function either as range structures, channel edge beacons or lighthouses. A common factor for all is that they have been designed to resist ice loadings, too. So far, structures to be characterised mainly as lighthouses have been built in Finland.

The nature of the structure must be taken into account in their design. It is not sensible to use the same safety coefficients for open sea lighthouses and channel edge beacons. The equipment of a lighthouse may be as expensive as the structure itself while the share of the safety device of a beacon is most often only 5...15 per cent of construction cost. When the cost of the structure is dominant, it is no use to overdimension the structure particularly when several beacon structures allow small deformations without any disturbances of operation.

5.4.2. *Structure Types.*

As mentioned before, the safety of navigation calls for a considerable increase in beacons to be founded in water. Structures have therefore been developed that are so inexpensive that a much larger number of beacons can now be erected.

Until recently, the channel beacon structures founded in water were made of reinforced concrete. The dominant type has been a massive caisson lighthouse but structures anchored by prestressing steel into rock have also been constructed.

Earlier, the structure had a conical form at water-line but for cost reasons the latest lighthouses were built by using cylinder surfaces. As known, ice is cut easier by a conical than a cylindric structure owing to the large difference between the compressive strength and bending strength of ice.

However, it has not been possible so far to reduce the loadings of a conical structure since ice loading cannot be determined in cases when the ice field has frozen to lighthouse if the adhesion between ice and concrete is not known. The structure gets the largest ice loadings at the moment the fixed ice field starts moving and the contacting surface between the structure and ice is 100%.

Primarily, the structural types are determined on the basis of bottom conditions and ice forces. The need of space in most lighthouses is so small that is has not much influence in structures.

Particularly in sea areas, ice loadings have a decisive impoitance in design. On the other hand, it is known that the volume of ice forces is a function of the diameter of the structure at water-line. It has been found in tests that ice loadings decrease considerably to the point where the diameter of the structure is approximately equal to the thickness of ice. Therefore, the diameter of the structure at water-line should be 80...100 cm in the area of the northern part of the Gulf of Bothnia, 60...80 cm in the Bothnian Sea and the Gulf of Finland and 40...60 cm in the inner archipelago where ice is not actually moving after having reached a thickness of 20...40 cm. As a consequence of so small structural dimensions, reinforced concrete will be replaced by steel. On the other hand, using steel in Finnish conditions will not bring about new problems because owing to the low degree of saltness of water corrosion is not a problem. It can be taken into account by increasing the thickness of steel plates correspondingly. The rapid development of machinery and working methods has naturally made it finally possible to use new structure types.

5.4.3. *Structure Anchored to Rock.*

Particularly in Southern Finland, the firm primary rock often is exposed at spots where channel beacons have to be built. The compressive strength of the most common mineral types is 1,500...3,500 kg/cm^2 and transferring even large concentrated forces into rock is possible.

Figure 8 shows a solution used for channel edge beacons. The steel structure acting as a projection has been soldered with concrete over a length of about 3 m into rock. The necessary shaft has been excavated by tunnel excavating method. A mammoth pump was used in removing broken rock. Naturally, when excavating methods are developed the shaft may also be made by a tunnel borings machine but even considerably larger shafts, for example, for lighthouses, can be excavated by today's methods.

In series production, the cost of the structure is about 100,000 Fmk of which 50 per cent are formed by founding cost.

5.4.4. *Structure Driven in Ground.*

The structure driven in ground differs from a system founded in rock only so that transferring forces into the ground calls for a much longer fixing.

Figure 9 shows a principal solution of a structure fixed in the ground. It can be taken as rather common since the size of the substructure is not much changed by alterations in the superstructure unless there are changes in ice forces or safety coefficients.

The structure shown in Figure 9 will be erected next summer in the northernmost part of the Gulf of Bothnia where ice conditions are most difficult in the whole country. The structure has been designed for an ice force of 450 tons but it can take momentary impulses of less than 550 tons. In that case, the stress of steel is at the liquid limit. Fill concrete used to prevent buckling nad internal corrosion has not been taken into account when stresses have been calculated.

Loading of moving ice is impulsive in which the duration of loading peaks depends on the speed and plasticity of ice. In fast movement, such as in rivers, the loading time is only a few thousandths of seconds (5). The bearing capacity of underwater ground in such momentary loading peaks is considerably larger than during permanent loading (coefficient $= \gamma/\gamma'$) which is well suited to the nature of loadings.

The cost of this structure is about 600,000 Fmk and the price of lighting device about 50,000 Fmk.

5.4.5. *Caisson Lighthouse.*

The lighthouse of telescopic caisson type shown in Figure 10 developed in

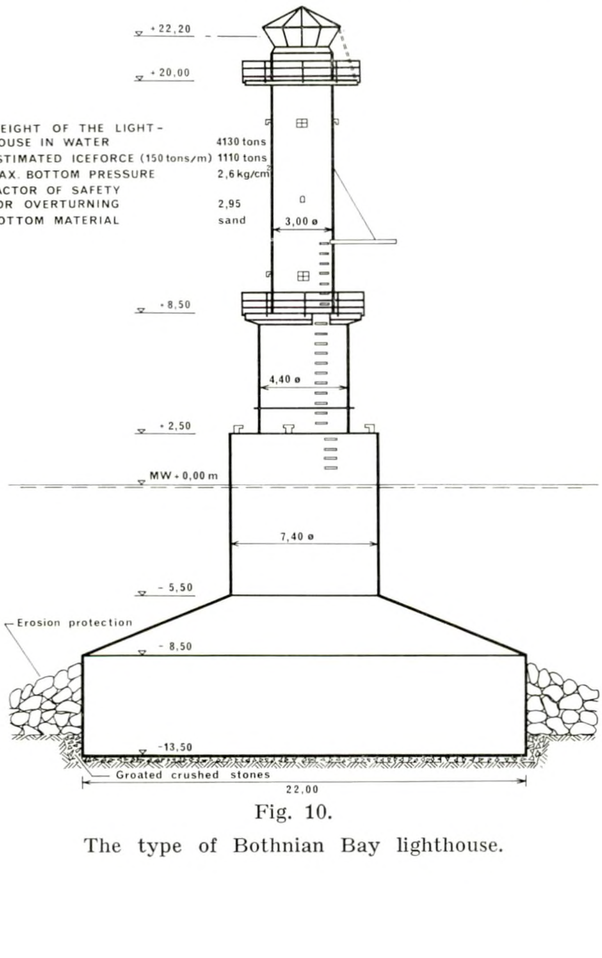

Fig. 10.

The type of Bothnian Bay lighthouse.

Sweden is presented here only as an example of earlier practice. There are four such lighthouses in the area of the Bothnian Bay, built in 1964-1965. The cost of construction of this type at the 1972 price level is about 2,000,000 Fmk. If this structure has to be built for a light device of 50,000 Fmk, the cost of the frame can be considered unreasonable.

In the design of the structure, an ice load of 1,110 tons (150 ton/m) has been used. This has been proven safe in practice.

5.4.6. *Range Structure.*

In order to supplement the overall situation, an example is presented from inland waterways, the total length of which is about 6,600 km.

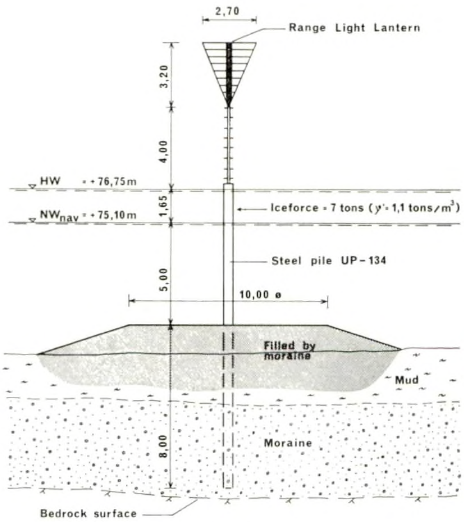

Fig. 11.

Heinsalmi range structure.

The range structure of Heinsalmi (Fig. 11) shows very clearly the enormous difference there is in ice loadings between the sea and inland waterways. The structure represents the most difficult ice conditions encountered in inland water systems. Nevertheless, a design load of 7 tons has proved safe.

The thickness of solid ice in inland waterways varies between 50 and 70 cm depending on conditions.

5.5. **Loadings.**

The most important loading of structures is ice pressure. The safety against sliding of lighthouses of telescopic caisson type only has to be checked with respect to loading by waves. The wind pressure, about 150 kg/m² in Finnish conditions, naturally decides the design of the structure above water.

The size of ice loading fully depends on the conditions at the location of the structure. Design loads may vary widely. In examples, the range is 14 ton/m... 450 ton/m, which can be taken as a maximum in Finnish conditions. The lower limit may naturally be zero in exceptional cases.

In lakes, where the thickness of ice is 50...70 cm, channel beacon structures designed for a horizontal load of 14 ton/m have stood in their place. The low loading can be explained by the fact that in lakes, the horizontal movements of ice are due only to changes in temperature and are slight. Variations in the water level are most often slow, too. In spring, ice melts nearly without moving and the strength of ice when it finally starts to move is very low.

In sea areas the ice loading of cylindric structures is determined from the formula :

$F = k \,.\, h \,.\, b \,.\, \delta$ in which.

h = thickness of ice.

b = diameter of the structure.

δ = compressive failure strength in a temperature T.

k = coefficient in which the shape and size of structure in relation of ice thickness is taken into account.

The value of k is obtained from Figure 12. The loading situation means that the contact between the structure and ice is completed. Such a contact is encountered only when a field of ice frozen to the structure starts to move. After the first rupture the contact is no more complete and as a consequence, ice loading decreases. On the other hand, a moving ice field causes impulses which have to be taken into account, particularly in design of equipment.

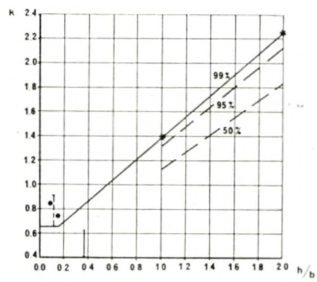

Fig. 12.

Dependence of coefficient K of ration H/B.

LEGENDS :

* Values obtained in field measurements (11). The thickness of ice 80 cm and the degree of saltness of water 0.0‰.

● Values correspond to the design loads 200 Ton/M and 150 Ton/M of lighthouses in the Bothnian Bay and the Bothnian sea at ice thicknesses 80 cm/60 cm.

—— Load at the failure of the Nygran lighthouse 110-170 Ton/M (thickness of ice 90 cm).

- - - - Load at the sliding of the Tainio lighthouse 80-110 Ton/M (owing to the small thickness of ice, 30-50 cm. The result is uncertain).

K = 0.67 is a value used generally for a cylindric structure (6).

99 % Safety limit for K calculated from the results of field tests.

6. CONCLUSION

Problems caused by ice vary widely depending on location and conditions. The optimum solutions therefore call for knowledge of local conditions in addition to sound basic information.

At the moment, our knowledge of ice, its structure, strength properties, formations and movements is narrowly sufficient for the solution. of present problems. As shipping and its related activities will certainly develop powerfully in the future, finding out the effect of ice in advance will be more and more important in Finnish conditions. Investigations of ice should therefore be planned in advance in order that information obtained could be used as extensively as possible for navigation and water construction.

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RÉSUMÉ

1. — Généralités.

2. — On examine dans ce chapitre les conditions qui règnent dans la zone de la mer Baltique en ce qui concerne la formation des glaces : glaciation, étendue de la couche de glace, formations de banquises, épaisseur de la glace, salinité de l'eau, résistance et température de la glace.

3. — On considère ici l'influence de la glace sur la navigation finlandaise entre autres en décrivant le déroulement du trafic en mer Baltique et dans le golfe de Botnie par un hiver normal. On examine en outre les accidents qui surviennent en hiver et les possibilités d'en réduire le nombre. Le Tableau I présente les brise-glaces finlandais.

4. — On examine brièvement dans ce chapitre l'effet des glaces sur les routes suivies par les navires.

5. — On traite dans ce chapitre des dispositifs de sécurité de la navigation dont on dispose actuellement en Finlande et de la sûreté de leur action. On y expose en même temps les principes selon lesquels on s'efforce d'améliorer la sécurité de la navigation dans les chenaux de l'archipel et du littoral. On constate que pour résoudre ce problème il est nécessaire d'augmenter considérablement le nombre des constructions permanentes à installer dans l'eau. On présente divers modèles de signaux permanents et adaptés aux conditions créées par les glaces. Pour finir, on décrit les charges de glace dont on doit tenir compte dans le choix des dimensions des constructions.

S. II - 4

RAPPORT

par

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On assimile souvent la France continentale à un hexagone, dont les diagonales nord-sud et est-ouest ont environ, respectivement, 970 et 940 km. Trois des côtés de cet hexagone sont baignés par la mer : la longueur des côtes atteint 1.100 km au nord, sur la Manche et la mer du Nord, 1.380 km à l'ouest, sur l'Océan Atlantique, et 635 km au sud, sur la Méditerranée, au total 3.115 km. Par ailleurs, la France continentale se situe entre les 43e et 51e parallèles (voir fig. 1).

L'ensemble de ces circonstances lui vaut un climat que l'on considère comme « essentiellement tempéré » et explique que les phénomènes de gel, dont l'intensité varie d'ailleurs beaucoup d'une année à l'autre, soient relativement peu sensibles au voisinage des côtes et de plus en plus virulents au fur et à mesure que l'on s'en éloigne.

Il arrive même que, certaines années parmi lesquelles on peut citer 1955, 1959 et 1969, la navigation ne soit interrompue par les glaces ni sur les voies navigables intérieures, ni *a fortiori*, dans les ports maritimes.

Par contre, d'autres hivers sont particulièrement rigoureux, tels ceux de 1954, 1956, 1963 et 1971. La navigation est alors interrompue, essentiellement sur certains canaux et sur certaines dérivations de cours d'eau canalisés, pour des durées qui, en 1963, ont atteint 87 jours sur le canal de la Marne au Rhin et 83 jours sur le canal des Houillères de la Sarre, voies situées au nord-est du pays, dans une région où les hivers sont souvent rigoureux.

D'après des statistiques portant sur les années 1947 à 1968 et sur les voies où se produisent des interruptions de navigation, (de telles interruptions sont rares sur les grandes voies) celles dues au gel représentent, en moyenne, un tiers du total de leur durée. Sans doute sont-elles un peu moins importantes que les « chômages », interruptions volontaires nécessitées par l'exécution des travaux d'entretien, qui exigent un abaissement du niveau des biefs ou même leur vidange, et qui correspondent à 40 % de ce même total; mais ces chômages sont prévus à l'avance, ce qui diminue considérablement la gêne qu'ils apportent aux utilisateurs; au contraire, l'incertitude quant aux possibilités de trafic hivernal sur certaines

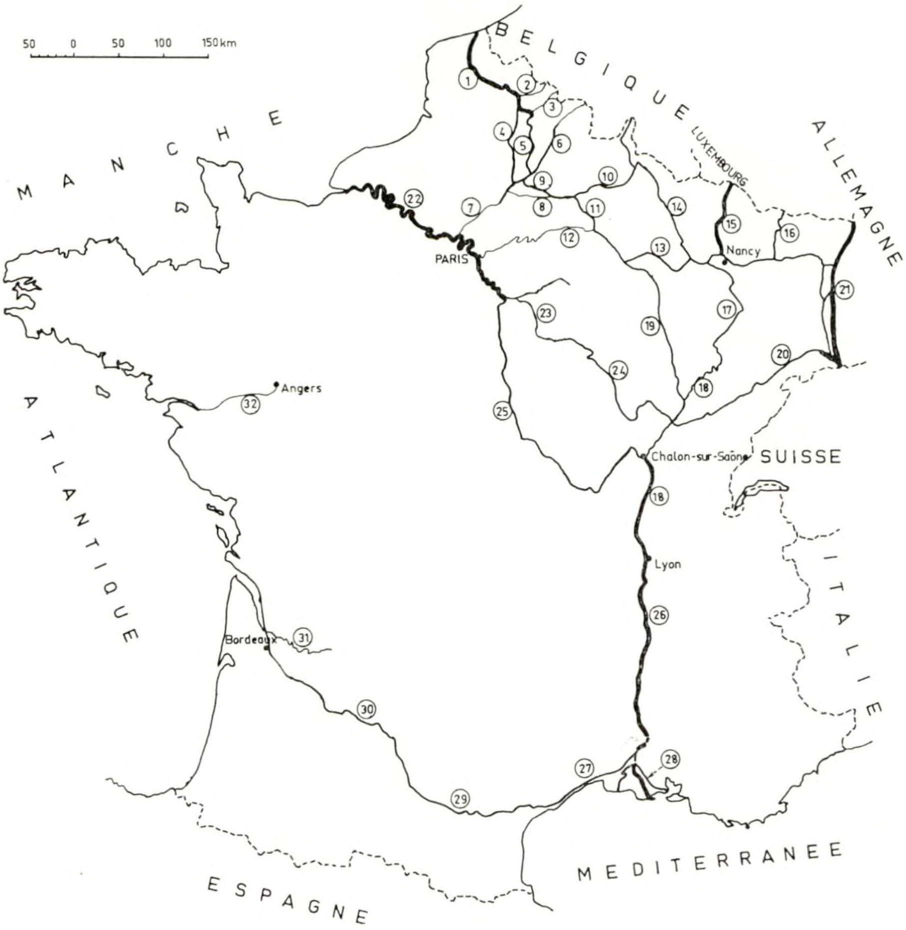

Fig. 1.

Carte des voies navigables de France
Map of France's Navigable Waterways

LÉGENDES

——————— petit gabarit

——————— grand gabarit

1. Canal Dunkerque-Denain.
2. Scarpe (R.).
3. Escaut (R.).
4. Canal du Nord.
5. Canal de Saint-Quentin.
6. Canal de Sambre à l'Oise et Sambre (R.).
7. Oise (R.).
8. Aisne (R.) et Canal latéral à l'Aisne.
9. Canal de l'Oise à l'Aisne.
10. Canal des Ardennes.
11. Canal de l'Aisne à la Marne.
12. Marne (R.) et Canal latéral à la Marne.
13. Canal de la Marne au Rhin.
14. Canal de l'Est (branche nord).
15. Moselle (R.).
16. Canal des Houillères de la Sarre.
17. Canal de l'Est (branche sud).
18. Saône (R.).
19. Canal de la Marne à la Saône.
20. Canal du Rhône au Rhin.
21. Rhin (F.) et Grand Canal d'Alsace.
22. Seine (F.).
23. Yonne (R.).
24. Canal de Bourgogne.
25. Canal du Loing, de Briare et du Centre.
26. Rhône (F.).
27. Canal du Rhône à Sète.
28. Canal d'Arles à Bouc.
29. Canal du Midi.
30. Canal latéral à la Garonne et Garonne (F.).
31. Dordogne (R.).
32. Loire (F.).

voies navigables françaises, qui, comme nous venons de le voir, comporte une marge d'interruption pouvant varier, suivant les hivers et les voies, de 0 jour à 3 mois, se trouve être particulièrement gênante.

Nous rappelons que cette question a fait l'objet d'intéressantes communications au XIXe Congrès International de Navigation (Londres 1957 - SI-C3) et en particulier d'un long rapport de notre regretté camarade René Siegfried, Ingénieur en Chef des Ponts et Chaussées, alors Directeur des Ports de Nantes et de Saint-Nazaire; nous limiterons donc notre étude, dans ce qui suit, aux trois points définis par le programme du sujet :

— Action des glaces sur les ouvrages de navigation,

— Moyen de prévenir leur formation,

— Maîtrise de leur déplacement.

Nous tenons à remercier, pour les renseignements qu'ils nous ont fournis, la Direction de la Production et des Transports d'Electricité de France, la Compagnie Nationale du Rhône, le Laboratoire National d'Hydraulique de Chatou, les Ingénieurs Généraux et les Ingénieurs en Chef des Ponts et Chaussées dont les attributions concernent les ports maritimes et les voies navigables et, tout particulièrement, MM Gilbert, Ingénieur Général des Ponts et Chaussées en retraite et Valeteaud, Ingénieur Divisionnaire des Travaux Publics de l'Etat en retraite, qui ont bien voulu nous faire part de la grande expérience qu'ils avaient acquise, tout au long de leur carrière, des problèmes de l'espèce concernant la Seine.

I. — ACTION DES GLACES SUR LES OUVRAGES DE NAVIGATION

L'action des glaces sur les ouvrages de navigation peut résulter de l'une de ses trois propriétés suivantes : la dilatation qui se produit lors de sa formation, son adhésivité, sa dureté.

I.1 La transformation d'eau en glace se fait avec augmentation de volume de l'ordre de 10 %. Si cette dilatation est contrariée par un obstacle rigide, il se produit, au droit de cet obstacle, des contraintes considérables susceptibles notamment de provoquer l'éclatement de l'enceinte à l'intérieur de laquelle l'eau se trouve enfermée.

Ce peut être notamment le cas des maçonneries qui, lorsqu'elles sont poreuses ou fissurées, sont susceptibles d'être imprégnées d'eau; il est donc nécessaire de vérifier soigneusement et de maintenir en bon état l'étanchéité de leurs parements, ainsi que de ne pas y laisser subsister de vide intérieur où l'eau pourrait pénétrer; à défaut de ces précautions, des dislocations se produisent, au moment du gel, qui obligent à les refaire après le dégel, en allongeant ainsi la durée de l'interruption de navigation.

Des dégâts analogues se sont produits, en février 1956, sur des matériaux crayeux relativement poreux, formant revêtement de certaines digues ou de certains perrés du port de Rouen.

On en a même constaté sur des digues ou berges revêtues, mais dont le revêtement n'était sans doute pas assez étanche : c'est ainsi qu'à la même date et dans le même port, un gonflement de la partie interne de digues, constituée par un arrimage de matériaux crayeux, a provoqué l'éclatement du revêtement bétonné qui les protégeait et l'éboulement consécutif de certaines parties de ces digues. Un phénomène de même nature s'est produit sur les berges du canal du Nord au cours de l'hiver 1970-1971, entraînant, sur une longueur d'environ 2.000 m, la destruction du revêtement en béton bitumeux qui présentait, d'autre part, des traces de cisaillement au droit de la butée des glaces.

Cet effet du gel pose, en France, des problèmes d'entretien d'autant plus importants que la plupart des très nombreux ouvrages de tous les anciens canaux français sont beaucoup plus que centenaires.

I.2 La glace adhère aux objets au contact desquels elle se forme, et des fragments de glace se soudent entre eux sous une très faible pression.

De ce fait, la manœuvre des parties mobiles des ouvrages se trouve pratiquement bloquée lorsqu'elles sont prises par la glace, et les corps qui ne peuvent résister aux efforts de traction, tout particulièrement les organes d'étanchéité en néoprène, risquent d'être déchirés lorsque l'on cherche à arracher la glace qui y adhère; d'autre part, l'accumulation de blocs de glace, lorsqu'ils se trouvent, pour une raison quelconque, arrêtés dans le lit d'un cours d'eau, peut constituer de véritables banquises d'un volume considérable.

I.2.1 L'adhésivité de la glace sur les objets en contact desquels elle se forme empêche ou du moins rend très difficile tout déplacement de ces objets, et, en particulier, toute manœuvre des organes mobiles des ouvrages de navigation.

C'est ainsi, par exemple, que les barrages mobiles se trouveraient hors d'état de manœuvrer, si des précautions spéciales n'étaient prises en vue d'éviter les conséquences d'un tel blocage; celles-ci seraient particulièrement graves en cas de crue de débâcle ou de crue survenant avant que le dégel ne soit complet; la maîtrise du niveau des eaux est, en effet, une condition essentielle de la sécurité d'un cours d'eau canalisé.

Nous examinerons en II.1.1 et II.1.2 les techniques utilisées pour éviter la formation de glace sur les surfaces où les parties mobiles et les parties fixes de ces ouvrages sont en contact.

Dans le même ordre d'idées, il convient de prendre des précautions pour éviter que le froid ne bloque, bien qu'elles soient situées à une certaine profondeur, les vannes servant à l'alimentation ou à la vidange du sas des écluses.

Le gel peut aussi arrêter le fonctionnement des ponts mobiles; mais, comme ceux-ci n'existent que sur des voies relativement peu fréquentées, où la navigation est rapidement interrompue, il n'y a aucun inconvénient à maintenir ces ponts, pendant la période du gel, dans la position permettant le passage de la circulation routière.

I.2.2 La facilité avec laquelle des blocs de glace se soudent entre eux peut entraîner la formation d'embâcles, et, dans les estuaires soumis à la marée, — où le courant de flot sous la couche embâclée crée une accumulation des glaces antérieurement passées à l'aval et des glaces d'amont en charriage —, de véritables « packs ».

C'est en fait la formation et surtout la débâcle de ces « packs » qui constituent la cause essentielle des gênes que subissent les ports maritimes du fait des glaces; les ports d'estuaires, Bordeaux sur la Gironde et Nantes sur la Loire, connaissent épisodiquement de telles perturbations. Le port de Rouen sur la Seine en a connu également dans le passé, mais pour les raisons qui sont indiquées plus loin (§ II.1.1.1) aucune formation de glace en Basse-Seine n'a été constatée depuis 1956. Dans des conditions voisines, et bien qu'il ne soit pas un port d'estuaire, le port de Dunkerque a été embâclé, en 1954 et en 1963, par des glaces provenant probablement de l'embouchure de l'Escaut, poussées le long des côtes, tant par les courants maritimes que par un fort vent d'est, jusque dans l'avant-port, où, du fait de la tranquillité de l'eau, elles avaient tendance à se souder entre elles. En 1954, l'exploitation de ce port a été interrompue pendant une demi-journée; dans les deux cas, elle a été gênée pendant environ 3 jours.

Indépendamment des problèmes de désagrégation de ces embâcles ou « packs », qui seront examinés en III.2, leur présence peut entraîner des conséquences graves sur les ouvrages sur lesquels ils prennent appui.

L'eau non gelée qui continue de s'écouler doit en effet trouver passage, généralement entre le bloc de glace ainsi formé et le fond du lit. Il s'ensuit un rétrécissement de la section d'écoulement, accompagné d'une augmentation de vitesse et, par suite, une érosion du fond du lit. Cette érosion peut entraîner des désordres dans les fondations des ouvrages voisins. Ce fut le cas d'un pont situé en amont du port de Nantes, où, au cours de l'hiver 1956, les fonds naturels ont, en moins de 20 jours, été creusés, de la cote — 3,50 à la cote — 7,00, détruisant en partie les défenses en enrochement qui protégeaient le pied des piles de l'ouvrage.

Inversement, les embâcles sur barrages fixes entraînent une surélévation de l'eau à l'amont et par suite, une augmentation de la chute qui peut, dès lors, affouiller, par l'aval, les fondations de ces ouvrages.

D'autre part, au fur et à mesure que l'embâcle grossit, sa poussée sur l'obstacle qui le retient devient de plus en plus forte : dans certaines circonstances il peut y avoir risque de renversement de l'ouvrage lui-même.

Sans aller jusqu'à la formation d'embâcle, les glaces peuvent obstruer les prises d'eau et provoquer des gênes sérieuses aux industries qui les utilisent.

I.3.1 La glace est un corps dur qui, lorsqu'il présente un volume suffisant et qu'il est animé d'une certaine vitesse, — ce qui est souvent le cas sur les cours d'eau, — peut, tant par sa force vive que par le tranchant de ses arêtes, causer de graves dégâts aux ouvrages dont la résistance n'est pas suffisante.

C'est particulièrement le cas du balisage flottant qui, dans toute la mesure du possible, doit être retiré lorsqu'est prévue une débâcle de glace. A défaut de cette précaution, — qui constitue d'ailleurs une opération très difficile à réaliser rapidement, et qui entraîne, d'autre part, une gêne considérable à la navigation, sinon son arrêt, — les bouées sont enlevées ou déplacées. Lors de la débâcle de 1956, on a observé, sur la Gironde, des déradages de bouées pouvant atteindre jusqu'à 5 km.

Dans un ordre d'idées analogue, des blocs de glace dérivant sur la Seine, en février 1956, ont causé d'importants dégâts à divers ducs d'Albe et supports de passerelles en bois existant encore au port de Rouen. Des dégâts analogues ont été causés, à plusieurs reprises, à des espars par des débâcles sur la Saône.

I.3.2 Par ailleurs, la dureté de la glace la rend susceptible de s'opposer du seul fait de sa présence et en dehors de tout phénomène d'adhésivité, à la manœuvre d'organes mobiles, et notamment à celle des portes d'écluses à vantaux busqués, ainsi d'ailleurs qu'au déplacement des bâtiments qui peuvent être coincés par des blocs. Aussi, au moment de la reprise de la navigation, est-on obligé d'évacuer préalablement l'essentiel des blocs de glace qui s'accumulent au voisinage des portes amont, où elles viennent naturellement s'amasser en raison du très léger courant d'eau qui, ne serait-ce que par suite de faibles fuites, traverse à peu près en permanence l'écluse. Dans la plupart des cas cette évacuation nécessite de leur faire traverser le sas par de fausses bassinées. La manœuvre des portes busquées doit alors être faite avec suffisamment de souplesse pour qu'elles ne risquent pas de se trouver bloquées par des glaces retenues entre les vantaux et les chambres des portes; cela nécessite l'intervention directe de l'éclusier, car la poursuite intempestive de la manœuvre d'ouverture risquerait d'entraîner de graves détériorations des mécanismes, — qui sont pourtant calculés pour supporter une certaine surcharge pouvant atteindre 10 à 20 %, — si ce n'est des vantaux eux-mêmes. L'évacuation des glaces se fait ensuite en envoyant un léger courant d'eau à partir de l'amont. La nécessité de pouvoir exécuter cette manœuvre oblige à prévoir dans les écluses, la possibilité de chasses qui permettent, d'une part, d'attirer les glaces de l'amont dans le sas, d'autre part de les évacuer. A défaut de cette possibilité, l'évacuation des blocs de glace doit être guidée manuellement.

Dans certains cas, d'ailleurs relativement rares, les glaces accumulées devant la porte amont peuvent être évacuées en les rejetant au dehors de la voie navigable par des déversoirs latéraux au chenal, situés à faible distance de la porte amont. Il est nécessaire qu'en aval de ces déversoirs, la glace puisse être accumulée sans causer de dégâts aux riverains, par exemple dans des contre-fossés de volume suffisant.

Enfin la pression des blocs de glace à l'intérieur du sas, notamment lorsqu'un bâtiment pénètre dans l'écluse, a, dans certains cas, détérioré les échelles installées dans les bajoyers pour permettre de passer d'un bâtiment sur le terre-plein.

Les portes à secteur cylindrique à axe vertical, dont sont munies certaines écluses du nord de la France, ne nécessitent pas de telles précautions et permettent une évacuation facile des glaces. Il en est de même de divers autres types de portes.

II. — MOYENS DE PRÉVENIR LA FORMATION DES GLACES

On peut concevoir trois méthodes pour prévenir la formation des glaces : la première consiste à réchauffer l'eau, la seconde à la maintenir en état de surfusion, la troisième à en abaisser le point de congélation.

II.1.1.1 Sur les cours d'eau en bordure desquels existent des usines — tout particulièrement des centrales thermiques classiques ou nucléaires destinées à la production d'énergie électrique —, dégageant suffisamment de calories et dont l'eau de refroidissement y est rejetée, la glaciation devient d'autant plus difficile que le débit généralement faible, en période de gel, permet une élévation plus forte de la température de l'eau : on peut actuellement admettre qu'en dehors des dérivations ou des bassins portuaires, des fleuves comme la Seine en aval de Vitry-sur-Seine (localité située en amont de Paris) ou des rivières comme la Marne en aval de Vaires, la section française de la Moselle en aval de Blenod-les-Pont-à-Mousson, l'Oise en aval de Compiègne, sont pratiquement à l'abri du gel. Il s'agit là d'assez importantes sections, longues d'environ 200 km sur la Seine, 20 km sur la Marne, 90 km sur la Moselle française, 100 km sur l'Oise. Le développement de l'industrialisation et des centrales thermiques laisse espérer que, sur les cours d'eau, les problèmes posés par les glaces seront de moins en moins graves. Seules les débâcles de glaces provenant de l'amont pourront continuer à apporter certaines gênes localisées. Ainsi, ce que l'on désigne parfois, souvent d'ailleurs improprement, sous le nom de « pollution thermique » est, en hiver, un facteur extrêmement favorable à la navigation et à la bonne tenue des ouvrages.

En dehors de ces circonstances, assez rares sur les canaux, l'apport de calories extérieures à l'eau elle-même ne peut être que très limité.

On peut citer, dans ce sens, les cas isolés où le bief d'un canal est en liaison directe avec une nappe phréatique, dont le volume, et, par la suite, les réserves en calories, sont grands; la formation des glaces se trouve alors retardée ou même supprimée dans la partie du bief qui communique avec la nappe.

Dans le même ordre d'idées, il peut être intéressant de faire transiter, dans un canal latéral à une rivière, l'eau généralement moins froide de celle-ci, ou même de pomper des eaux souterraines plus chaudes, comme c'est le cas pour certains biefs du canal de Saint-Quentin où l'on peut amener des eaux, en quantité malheureusement extrêmement limitée, dont la température est de l'ordre de 11° C.

Enfin on a noté que la présence de neige à la surface de l'eau la protégeait du froid et que l'épandage, sur la glace, de matériaux inertes, tels que de la poudre de charbon, permettrait un réchauffement par les rayons solaires et une fusion plus rapide au moment du dégel. Il ne s'agit là que de procédés dont l'utilisation est très limitée.

II.1.1.2 Si le problème de l'apport de calories extérieures destinées à faire fondre de grandes quantités de glace n'est guère soluble en dehors des cas particuliers susvisés, il devient relativement facile à résoudre lorsqu'il s'agit seulement d'empêcher la glace de se former sur une surface très limitée et localisée. C'est essentiellement le cas lorsqu'on veut maintenir à tout moment la possibilité de manœuvrer les organes mobiles de certains ouvrages et notamment de barrages.

Dans ce but, on incorpore dans le parement des maçonneries, au moment de la construction de l'ouvrage, des résistances électriques suffisamment puissantes pour maintenir, sur toute leur longueur, la température au-dessus de 0°C, ce qui, entre autres avantages, maintient les étanchéités en néoprène en dehors de toute action du gel.

De tels dispositifs ont été réalisés sur tous les barrages mobiles du Rhin (à l'exception de celui de Kembs, construit il y a une quarantaine d'années) et du Rhône, sur les nouveaux barrages de la Seine à l'amont de Paris et de la Saône, ainsi que sur tous ceux de la Moselle construits depuis 1956. En ce qui concerne ces derniers, les résistances électriques absorbent, en général, une puissance de l'ordre de 0,25 à 0,3 kw par mètre de longueur. La protection des vannes segments comporte, de chaque côté de la passe un élément d'environ 10 m de longueur, qui suit la circonférence sur laquelle les bords de la vanne s'appuient sur les maçonneries et dont la puissance est de l'ordre de 6 kw par passe. La protection des vannes clapets, qui balaient une certaine surface de maçonnerie, comporte de chaque côté la présence de 4 éléments chauffants ayant respectivement 2,6; 3,2; 4 et 5,6 m de longueur, soit au total 15,4 m, et dont la puissance est de l'ordre de 8 kw par passe. L'alimentation se fait par un transformateur 380/125 volts. Les résistances sont constituées par des conducteurs spéciaux, à âme en alliage nickel-chrome, isolés et noyés dans une gaine en acier inoxydable. Les éléments chauffants sont raccordés par des câbles non chauffants à des boîtes de jonction qui, après montage et mesure de l'isolement, sont remplies d'une graisse neutre spéciale. Dans tous les cas, lors du montage des câbles chauffants, il convient d'apporter un soin particulier à la confection des joints entre éléments, afin d'obtenir une étanchéité parfaite et un bon isolement.

Sur le Rhin où les chutes sont beaucoup plus fortes, les résistances installées de chaque côté des pièces fixes des vannes segments ont une puissance de 40 kw. Au barrage de Kembs, qui, du fait de son ancienneté, n'est pas muni de dispositifs incorporés de chauffage électrique, des essais d'insufflation d'air chaud dans une gaine en tôle plongée dans la rainure d'une vanne semblent donner de bons résultats.

On pourrait d'ailleurs imaginer d'autres procédés, tels que des jets de vapeur, ou même d'eau chaude sous pression.

Si l'incorporation de tels dispositifs de réchauffement paraît, *a priori*, parfaitement indiquée sur le Rhin, la Moselle et la Saône, situés au nord-est ou à l'est de la France, on peut se demander pourquoi on en a également prévu sur le Rhône, dans une région située aux environs du 45° parallèle, dont le climat est presque méditerranéen. La raison en est essentiellement qu'en hiver la vallée du Rhône

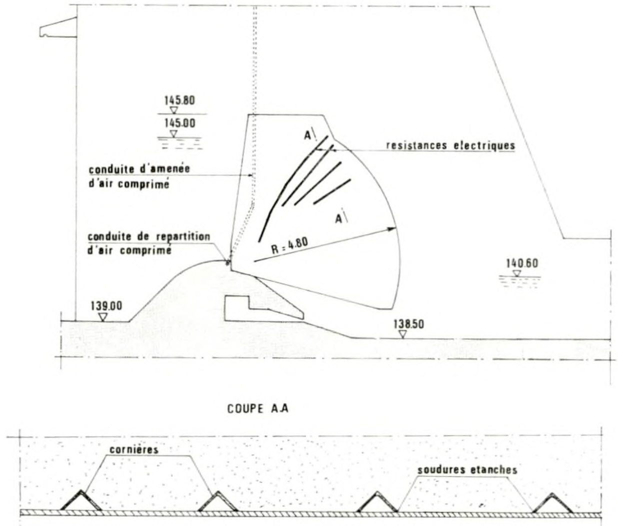

Fig. 2.
Barrage d'Apach — Vanne clapet — Boucliers latéraux.
Apach barrage (dam) — Needle valve — Lateral shields.

LEGENDES

Conduite d'amenée d'air comprimé	=	Compressed air supply-pipe.
Résistances électriques	=	Electric resistances.
Conduite de répartition d'air comprimé	=	Compressed air distributing pipe.
Cornières	=	Angle bars.
Coupe A.A	=	Section A.A
Soudures étanches	=	Watertight weldings.

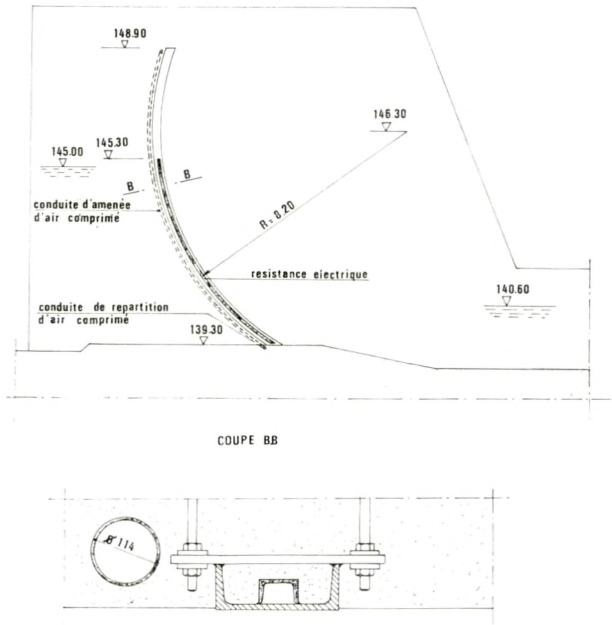

Fig. 3.
Barrage d'Apach — Vanne segment — Pièces fixes.
Apach barrage (dam) — Sector gate — Steady parts.

est balayée par des vents du nord extrêmement froids et très violents, connus sous le nom de « mistral », dont la vitesse dépasse 16 m/s pendant 135 jours au nord d'Avignon. De ce fait, les températures hivernales peuvent atteindre — 15° (en 1956). Au cours des 20 dernières années, la navigation sur le Rhône a été interrompue 3 fois par le gel, 6 jours en 1954, 21 jours en 1956 et 12 jours en 1963.

Par contre, de telles mesures n'ont pas été adoptées, ni sur la Seine, en aval de Paris, ni même sur l'Oise, où le réchauffement résultant de la présence de plusieurs importantes centrales thermiques a été jugé suffisant.

Des dispositions analogues ont été réalisées sur la plupart des écluses du Rhin et sur quelques écluses du Rhône. La puissance installée sur le Rhin est, par écluse, de l'ordre de 4 kw pour une largeur de 12 m et de 8 kw pour une largeur de 24 m. Sur le Rhône, elle atteint 1,5 à 2 kw par mètre linéaire de joint.

On trouve également des résistances chauffantes aux portes de l'élévateur transversal de Saint-Louis-Arzviller, sur le canal de la Marne au Rhin.

On a toutefois constaté, du moins sur le Rhône, que le gel des canaux de dérivation interrompait toujours la navigation avant que la manœuvre des écluses ne soit elle-même devenue difficile. Aussi, par mesure d'économie, les écluses nouvellement construites sur ce fleuve ne sont-elles plus munies de dispositifs chauffants. Une constatation analogue a également été faite sur le canal de la Marne au Rhin au droit de l'élévateur susvisé.

Par ailleurs, l'utilisation, de plus en plus généralisée, sur tous les ouvrages nouvellement construits, de vérins à l'huile incongelable permet d'en poursuivre la manœuvre quelle que soit la température extérieure.

Certaines écluses de chute importante comportent des bollards flottants. Pour éviter qu'ils ne se bloquent du fait du gel, on les relève et on les maintient hors d'eau en dehors du passage des bâtiments. Ils n'ont évidemment pas de dispositifs de chauffage incorporé.

II.1.2 En dehors de ces cas particuliers, il faut, pour éviter ou retarder la formation des glaces, faire appel aux calories contenues dans l'eau de la voie elle-même, et à cet effet, agiter cette eau de manière à assurer le mélange des zones moins froides, situées en profondeur, et des zones de surface soumises directement à l'action du froid. Il est bien évident que l'importance de cette source de chaleur croît avec la profondeur d'eau dans le bief, et, de ce fait, la canalisation d'un cours d'eau et l'approfondissement des biefs ont un effet très bénéfique sur la possibilité de maintenir la navigation. Dans les estuaires, les surprofondeurs permettent, d'autre part, à la marée de se faire sentir plus profondément.

Cette agitation se produit naturellement dans les cours d'eau où elle est entretenue par le courant, mais où, assez fréquemment, des phénomènes de glaciation de fond, dont il sera parlé plus loin (II.2) viennent se superposer, ou souvent préexistent au gel de surface. Elle peut résulter du vent, même froid mais qui, généralement, s'affaiblit pendant la nuit. Elle peut également résulter des dénivellations que l'on fait subir au plan d'eau et qui disloquent la glace, mais peuvent causer des dégâts aux bateaux et aux berges où la glace adhère.

Elle peut surtout être obtenue par la circulation continue des bâtiments, dont la navigation de nuit, si elle est suffisamment intense, retarde sensiblement la formation des glaces. A ce point de vue, on a constaté que, sur le Rhin, dont la partie aval est à courant libre, les basses eaux qui accompagnent généralement les phénomènes de gel constituent un obstacle à la navigation et facilitent la prise des parties amont, surtout en canal latéral. Lorsque la navigation des bâtiments de commerce n'est pas suffisante — les convois poussés, qui sont les bâtiments les moins sensibles à l'action de la glace, s'arrêtent en général, suivant les voies, lorsque son épaisseur atteint de six à dix centimètres — on est souvent conduit à utiliser des brise-glace, sortes de bateaux dont le fond plat, incliné à l'avant sur l'horizontale, monte sur la glace, la cisaille et la réduit en blocs qui fondent plus facilement au contact de l'eau. Ils n'agissent plus guère lorsque l'épaisseur de la glace dépasse 30 à 40 centimètres.

Sur les canaux étroits, les brise-glace sont tirés à partir de la berge par des tracteurs agricoles ou forestiers d'autant plus efficaces que leur puissance est plus élevée (il est bon de disposer de 50 à 75 CV); il convient alors d'éviter que les tracteurs ne détruisent les chemins de halage et ne glissent en cas de verglas et, à ce point de vue, l'utilisation de tracteurs à chenilles est peu recommandé, même si des précautions sont prises pour en éviter l'agressivité. Sous ces réserves, la traction des brise-glace à partir des berges est considérée comme un moyen relativement économique sur les voies où elle est possible. Encore faut-il, bien entendu, qu'il existe, en bordure de ces voies, des chemins de service accessibles.

Sur les voies plus larges, ils sont poussés par des pousseurs de route, normalement utilisés pour convoyer les barges.

Dans l'un et l'autre cas, les engins de traction ou de poussage et leurs conducteurs sont généralement pris en location par l'Administration, qui n'aurait pas intérêt à en disposer en propriété, étant donné leur usage très intermittent.

Seuls les brise-glace eux-mêmes lui appartiennent. Ils ont souvent une dizaine de mètres de longueur et une largeur (5 à 10 m) adaptée à celle des écluses en service sur la voie. On étudie leur standardisation; il est d'ailleurs possible, sur les voies à grand gabarit, de pousser côte à côte deux brise-glace de 5 m, — relativement nombreux dans les services de navigation français, compte tenu de l'importance kilométrique des voies à petit gabarit,—.

De même que l'on peut empêcher la formation localisée de glace par les dispositifs examinés en II.1.1, on peut également placer, dans le radier des barrages ou des écluses, des conduites de distribution d'air comprimé qui permettent de créer une agitation empêchant ou gênant la formation de glace, en entraînant vers le haut l'eau moins froide du fond du cours d'eau. De tels dispositifs ont été installés sur les barrages du Rhin, du Rhône et de la Saône, sur deux des barrages de la Moselle, sur les écluses du Rhin et sur celles du Rhône, à l'exception des plus récentes, pour la même raison que celle indiquée en II.1.1.2.

Enfin, et notamment lorsque les ouvrages ne sont pas munis de dispositifs de chauffage ou de canalisations d'air comprimé, on peut retarder et, généralement, supprimer complètement la prise de glace en les manœuvrant aussi souvent que nécessaire, ce qui nécessite évidemment une surveillance très attentive.

Dans les autres cas, on est conduit à casser la glace manuellement, comme le font les mariniers autour de leurs bateaux, sous réserve, bien entendu, de ne pas endommager des étanchéités trop fragiles.

En tout état de cause, si un froid de l'ordre de — 10° centigrades persiste assez longtemps, plus de trois ou quatre jours par exemple, la navigation finit par devenir impossible, du moins sur les petits canaux.

II.2 Le phénomène de glaciation de fond dans les cours d'eau est plus complexe : la turbulence et parfois le vent peuvent amener une surfusion de l'eau, entraînant une baisse de sa température à — 1 ou — 2 degrés centigrades (° C) et s'opposant, dans certains cas, à sa prise superficielle. Ce phénomène de surfusion peut entraîner, par températures de l'ordre de — 10° C, la formation de glaces de fond, dont la présence est constatée sur de nombreux cours d'eau, surtout à courant libre, — car elles se produisent de préférence en des points où la profondeur est faible, — mais également canalisés : elle a été observée sur la Loire depuis plus d'un siècle; la glace de fond reste assez longtemps à l'état pâteux; il se forme une sorte d'émulsion de glace et d'eau, mélangée parfois de sable ou de vase arrachés au fond du cours d'eau, qui ressemble à des paquets de neige à gros cristaux semi-immergés, susceptibles d'obstruer certaines passes de barrage (notamment en ce qui concerne les barrages à ouvertures fines de type « à aiguilles ») et même d'adhérer à des seuils fixes ou de constituer des amas. Leur consistance les fait parfois comparer à une « glace de sorbet ». On considère généralement comme pratiquement impossible d'avoir une action sur la formation de cette glace de fond. Tout au plus peut-on essayer de la prévoir en fonction des indications données par la météorologie et qui sont particulièrement précieuses pour définir, dans toute la mesure du possible, les mesures à envisager.

Dans un ordre d'idées basé sur des principes voisins, certaines études avaient été faites, il y a une trentaine d'années, sur l'effet retardateur à la prise de glaces de certains produits saponifiables, et notamment de l'alginate de soude mélangée au stéarate de zinc, qui favorisent l'apparition de cristaux de neige au détriment de la glace compacte. Le fait que ces produits sont difficiles à pulvériser et l'obligation de renouveler cette pulvérisation après chaque passage de bateaux fit renoncer à donner une suite pratique à ces études, par ailleurs concluantes. Il est d'autre part probable que la sensibilisation actuelle des esprits aux problèmes de pollution conduirait à éviter de tels procédés, s'ils avaient pu réussir.

II.3 Le point de congélation de l'eau s'abaisse avec sa teneur en diverses matières et notamment en sels. La prise par le gel d'eaux qui en sont chargées se fait donc par des froids plus intenses que celle d'eaux plus pures. C'est le cas notamment des affluents urbains, ou des chlorures que peuvent rejeter certaines soudières et qui retardent la prise de certaines sections de rivières (Meurthe) ou de canaux (Canal du Rhône au Rhin). De même la prise des eaux maritimes nécessite des froids sensiblement plus vifs que celle de l'eau douce.

Il est bien évident que ces pollutions sont peu souhaitables en elles-mêmes et qu'il y a intérêt, dans toute la mesure du possible, à les réduire.

II.4 Quels que soient les moyens mis en œuvre, il peut arriver, notamment sur les canaux ou les voies à faible trafic, que l'épaisseur de la glace atteigne une valeur telle qu'il ne soit plus économiquement possible de poursuivre la navigation. On est alors conduit à l'arrêter et à attendre le dégel pour la rétablir. A ce moment l'aspect cristallisé de la glace change; sa contexture devient molle et spongieuse. On dit souvent qu'elle « pourrit ». C'est alors que l'on peut envisager la reprise de la navigation et entreprendre son cassage, par le passage de brise-glace, à condition que son épaisseur ne dépasse pas 30 à 40 cm et que les températures ne restent pas en permanence inférieures à environ — 5° C.

III. — MAITRISE DU DÉPLACEMENT DES GLACES

Nous avons évoqué, à propos de l'action des glaces sur les ouvrages de navigation, les méthodes utilisées localement pour les déplacer dans le sas ou en amont des écluses. Ces méthodes sont valables aussi bien sur les canaux que sur les cours d'eau canalisés.

D'une manière générale, sur les canaux, la reprise de navigation, qui, — comme nous venons de le voir en II.4 — a lieu après un radoucissement de la température, entraîne une disparition relativement rapide des blocs de glace qui fondent progressivement tant par suite de la relative chaleur de l'air qu'en raison des chocs qu'ils reçoivent à l'occasion du passage des bâtiments.

Sur les cours d'eau, les problèmes se présentent sous un aspect plus délicat du fait que, dès qu'elles ne constituent plus un ensemble joignant l'une et l'autre rives, les glaces sont entraînées par le courant et risquent de s'arrêter et de se ressouder dès qu'elles rencontrent un obstacle quelconque tel que les piles d'un pont ou d'un barrage ou simplement une faible profondeur sur les rivières à courant libre. Indépendamment de l'action du courant, les blocs de glace sont sensibles à celle du vent et peuvent s'accumuler sur le bord du cours d'eau vers lequel souffle celui-ci. Ce phénomène est particulièrement net sur la Loire.

La maîtrise du déplacement des glaces comporte plusieurs types d'opérations.

III.1 Si les barrages de type moderne, — notamment lorsque les dispositions décrites en II.1.1.2 et II.1.2 ci-dessus sont prises pour permettre à tout moment leur manœuvre, — peuvent généralement être maintenus dans la position qui correspond au débit instantané du cours d'eau, il n'en est pas de même pour les barrages de type ancien, dont de nombreux existent encore sur les voies à petit gabarit construites il y a un siècle et plus, et tout particulièrement sur les barrages du type à « aiguilles et fermettes ». Ces derniers, de construction très économique, permettent un réglage précis du niveau d'eau. Ils comportent essentiellement des éléments de bois de section carrée d'environ 7 cm de côté, placés dans un plan vertical parallèle au lit du cours d'eau et qui s'appuient, à leur base, sur une encoche ménagée dans le radier, et vers leur partie supérieure sur une poutrelle métallique légère reposant elle-même sur une série de petites fermes métalliques, appelées « fermettes »; lorsque le barrage est complètement démonté, les fermettes peuvent pivoter autour d'un axe horizontal, parallèle au lit du cours d'eau situé à leur base et être ainsi escamotées dans une longue rigole horizontale, perpendiculaire au lit du cours d'eau, ménagée au fond du radier dégageant ainsi complètement le passage des crues. Il est bien évident qu'à partir du moment où les aiguilles maintenues en place sont prises par les glaces, leur manœuvre manuelle, toujours délicate et dangereuse en temps ordinaire et qui nécessite impérativement le port d'un gilet de sauvetage, n'est pratiquement plus possible; le barrage devient alors un véritable seuil fixe susceptible de relever le niveau de l'eau à l'amont et de provoquer des inondations. Aussi, pour ce type de barrage, — dont, évidemment, on ne construit plus de nos jours, — est-on conduit, lorsqu'il y a une menace grave de gel, à effacer préalablement les éléments (aiguilles, poutrelles, fermettes) de manière à donner à l'écoulement de l'eau une section maximale. Celà entraîne évidemment l'abaissement du niveau amont et l'arrêt total de la navigation. Les bâtiments qui n'ont pu sortir à temps des sections intéressées sont alors échoués dans des dérivations sans courant, autant que possible sur un fond plat de manière à limiter les conséquences néfastes de cet échouement; ces dispositions ne s'appliquent qu'à des bâtiments relativement petits.

En dehors des inconvénients de l'échouement des bateaux, ce type de manœuvre entraîne de longues interruptions de navigation, car la remise en eau des biefs au dégel, à une époque où le débit du cours d'eau risque d'être très faible, peut durer fort longtemps. Il était autrefois pratiqué entre Montereau et Paris sur certains biefs de la Seine où existent encore des barrages vétustes, mais, depuis 1954, on a pris l'habitude de ne pas les coucher, pour permettre un rétablissement plus rapide de la navigation et ne pas interrompre l'alimentation des prises d'eau industrielles. Les phénomènes décrits ci-dessus, constitution d'un véritable barrage de glace, montée du niveau d'eau à l'amont, inondations, se sont produits sur certaines des sections intéressées du fleuve, mais sans entraîner de conséquences par trop graves, notamment en ce qui concerne la tenue des barrages eux-mêmes, pour qui on avait a priori des craintes particulières. Le problème se résoud d'ailleurs progressivement, sur la Seine, par la substitution de barrages modernes aux anciens, dont deux seulement restent encore en service actuellement. Il ne semble toutefois pas que les mesures adoptées depuis 1954 sur la Seine puissent l'être sans danger lorsque les cours d'eau canalisés comportent de longs biefs en canal parallèle, car l'existence, dans ces biefs, d'un niveau d'eau supérieur à celui que peut retenir la porte de garde risquerait d'entraîner, dans leur partie aval, des inondations importantes, parfois catastrophiques ainsi que la rupture des digues qui les limitent, si celles-ci venaient à être submergées. Aussi, malgré tous ses inconvénients, la pratique consistant à coucher les barrages à aiguilles et fermettes est-elle maintenue sur les voies, autres que la Seine en aval de Montereau, où existent des barrages de ce type.

III.2 La maîtrise du déplacement des glaces vise tout particulièrement le problème des embâcles de glace. Comme nous l'avons déjà vu, celles-ci se forment par la soudure, — généralement provoquée par un obstacle tel que des piles, ou une insuffisance de profondeur, — des blocs de glace de surface ou de fond provenant de l'amont. Il se produit, devant cet obstacle, une véritable banquise et qui grossit au fur et à mesure que les glaces descendent de l'amont. Ce type d'incident peut avoir les conséquences graves que nous avons énoncées au § I.2.2.

La dislocation non contrôlée et la flottaison au fil de l'eau d'une partie importante de l'embâcle peut, du fait de sa grande masse, entraîner, à l'aval, des accidents graves en cas de heurt d'autres ouvrages ou de bateaux. Elle peut également nécessiter des arrêts de navigation, comme il s'en est produit, très exceptionnellement d'ailleurs, au port de Nantes.

Il semble donc qu'il y ait intérêt à provoquer cette dislocation sous surveillance attentive. Dans les ports maritimes, et notamment à Nantes, on peut le faire en attaquant l'embâcle, qui se produit à l'amont immédiat du port, par le choc de l'étrave de remorqueurs de puissance suffisante. L'action de ces remorqueurs est particulièrement efficace, à l'amorce du dégel, au début du jusant, le courant entraînant les blocs de glace vers la mer. C'est également par le passage de remorqueurs que le port de Dunkerque a résolu le problème des embâcles qui s'y sont épisodiquement produits dans les conditions rappelées ci-dessus (§ I.2.2). Sur les voies de navigation intérieure, où les embâcles se produisent souvent dans des sections non navigables, le seul moyen qui paraisse utilisable consisterait à les ébranler à l'explosif, à les « pétarder », ce qui n'est pas sans présenter des inconvénients assez graves, notamment pour les maisons riveraines dont les vitres risquent d'être brisées par l'explosion, pour les ouvrages eux-mêmes et pour la faune aquatique. Aussi est-on conduit à n'appliquer cette méthode qu'à la dernière extrémité, et notamment si un radoucissement de la température n'est pas prévu.

CONCLUSIONS

Les problèmes posés par la glace sont délicats du fait des multiples et souvent graves conséquences qui peuvent y être apportées.

La connaissance, aussi précise que possible, des prévisions météorologiques constitue une aide précieuse pour le choix des décisions.

L'expérience du personnel, son « tour de main », joue, d'autre part, un rôle considérable.

Il semble qu'il faille chercher à maintenir, dans toute la mesure du possible, la navigation sur les voies à trafic important, telles que la Seine, l'Oise, le Rhin, la Moselle, et, à ce point de vue, la présence, le long de ces voies, de centrales ou d'usines apportant des calories à l'eau, est un atout considérable, qui prend de plus en plus d'importance en raison de la croissance continue et rapide des besoins en énergie électrique.

Sur les petites voies, par contre, il paraît nécessaire d'admettre, ne serait-ce que pour des raisons économiques, qu'au-delà d'une certaine « dose de froid », la navigation doit être interrompue. La reprise de cette navigation au moment où s'amorce le dégel, nécessite des précautions en vue de ne pas causer de dommages aux ouvrages et aux revêtements de berge des biefs.

Sur tous les cours d'eau, il convient de réserver, toutes les fois que cela est possible, la faculté de manœuvre des barrages, soit en assurant cette manœuvre assez souvent pour que les parties mobiles ne risquent pas de faire prise, soit, dans les régions plus froides, en incorporant dans les maçonneries des résistances chauffantes permettant d'amorcer la fusion des glaces. A défaut, et sauf exception, on peut être conduit à effacer les bouchures, ce qui provoque de multiples inconvénients, mais évite le risque d'une catastrophe.

SUMMARY

On account of the mild climate of France, the operation of the seaports in only very exceptionally hindered by frost; only the drift-ice from the upstream river may cause very seldom and very short atmospheric disturbances in estuary ports. On the other hand, according to years, navigation may not be interrupted on any waterways or may be interrupted up to 3 months on some waterways.

I. Frost and ice can bring about the splitting of stone-work or of porous materials, the locking of the movable parts of the structures, the breaking up or the wrenching of their fragile parts, damage to the foundations of structures against which ice-packs are propped, the displacement or the destruction of frail structures (buoys...).

II. On the most important waterways, the reheating of water by steam generating stations, whose development is equal to that of the consumption of electricity, lessens more and more the risks of frost, which are then practically eliminated outside the diversions and the port areas. If that condition proves right, it is desirable to maintain navigation as intensively as possible.

When one fears this reheating may not be sufficient, it is advisable to incorporate, in the fixed parts of dams (barrages), localised electric resistances ensuring, at the contact of the movable parts, a temperature always superior to 0 degree C, and consequently making sure that the operating of those parts always remains possible.

The tossing of water delays ice formation; this is the case of waterways with heavy traffic and twenty-four-hour navigation by day and night. To a certain extent, the insufficient passage of trading boats can be compensated by putting ice-breakers into operation.

The foundation-plates of some structures are equipped with air-pipes supplying compressed air which, by stirring up the water, delays the freezing-up.

Some phenomena of super cooling produce the formation of ground-ice in the waterways.

The presence of certain substances and in particular salts, lowers the freezing point of water.

When, in spite of all the precautionary measures, navigation has to be interrupted, it is advisable to wait for the beginning of thaw before setting it going again. This is the general case with the small waterways.

III. The old type of dams (barrages) have to be retracted as they cannot be operated any more when they are icebound. Provided that adequate precautions are taken, and namely those mentioned above, the modern dams (barrages) have not got this inconvenience which is so troublesome for navigation.

The breaking of ice-packs often sets delicate problems.

S. II - 4

PAPER

by

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CONTENTS

1. EFFECTS OF ICE ON STRUCTURES

1.1 Introduction.

The strain and stress exerted on a structure by ice cannot be exactly computed, as the extent and intensity of the force depend on many factors occurring simultaneously but which in practice are not simultaneously determinable. The strain from ice pressure, which is often decisive in the case of marine structures, therefore has to be determined from natural observations and measurements by the statistical method and analytically evaluated. The first precondition for such natural measurements is the utilisation of a suitable measurement technique both in the instrumental equipment and in the development of the investigations and a possibility of rapidly evaluating the measurement results. Furthermore, it must be borne in mind that, simultaneously with the force measurements, the ice, water and atmospheric conditions are dealt with, so that the measurement results from numerous stations can be interrelated and no misleading conclusions or inferences can be drawn from them.

1.2 **General comments on ice strain.**

In order to be able to judge the stress exerted by ice on structures, the following concomitant factors need to be taken into account : types of ice, mechanical properties of the ice, types of ice formation, ice forces and structural shapes on which the ice exerts its effects. The following types of ice are distinguished :

fresh water ice

salt water ice < sea ice $\geq$ 24.7‰ salt; brackish water ice $\leq$ content (according to Pounder).

The ice hardness is not great. It is located at 1.5 on the hardness scale. The elasticity is also slight. The E module varies between 950 kp/sq.mm parallel and 1,120 kp/sq.mm perpendicular to the freezing surface. These properties are influenced by ice temperature, salt content, pressure and gas content (porosity). In general, the elasticity of sea ice, as the result of its unhomogeneous structure, is less and its plasticity more than that of fresh water ice. In the case of fresh water ice, the mean resistance to pressure is, according to (3), at $\sigma B = 40$ kp/sq.cm; it falls in the case of a larger share of bubbles. In the case of sea ice, it is lower owing to the salt content.

According to Schwarz (2), the resistance to pressure reaches its highest value in the case of a distortion velocity per cm of $\sim 0.003 \frac{cm}{s}$.

Already in the case of slight strain, ice behaves in contrast to other solid bodies, not only elastically but also plastically, insofar as the strain is exerted for a long time and slowly on the ice.

In the stress on structures, a distinction is to be made between the following :

Drift ice = sheets of ice drifting with current and wind;

Pack ice = drift ice closely pressed together and superimposed;

Ice floe = enclosed surface of ice, large in area.

The ice forces exerting an effect on structures operate statically, dynamically or alternately static/dynamic and occur as pressure, impact or thrust forces which are often released by current with additional wind effects :

— Statically as ice pressure = horizontal force, which is exerted by an enclosed, temporarily fixed ice floe with a rise in temperature as a result of expansion.
— Dynamically as ice impact = impact of a drifting ice floe or ice block when it encounters an obstacle.
— Irregularly alternating static and dynamic stress by ice pressure and ice impact = greatly fluctuating flux of force in case of local crushing of a narrow strip of a drifting sheet of ice by an obstacle. In this way, constraints occur which, by the biaxial tension position, result in a higher strain than can be deduced from the resistance to pressure of the ice.

Up to the present, the resistance to pressure of the ice was frequently the point of departure for establishing the ice pressure. The strain values recorded in the coastal zone of the North Sea and the Baltic varied between 5 and 150 Mp/m. In the case of the Eider dam, 15 Mp/m was applied as static ice pressure and 75 Mp/m as dynamic ice pressure for the segmental sluices. The actual ice thickness « h » in the case of impact is also dealt with in different ways. In Sweden, it amounts to h = 0.3 to 0.7 m, in the Netherlands h = 0.4 to 0.5 m and in Germany h = 0.5 to 1 m.

The pressure resistances ascertained in cubic pressure tests cannot, however, simply be converted into the ice load to be applied with hypothesis if a pressure surface, as this would lead to a considerable overdimensioning, but a relationship must be established between actual ice pressure and the ice pressure resistance ascertained.

In the Eider estuary on the west coast of Schleswig-Holstein (North Sea), ice observations and ice pressure measurements lasting several years were carried out in natural surroundings during the construction of the Eider dam Hundeknöll-Vollerwiek (1). They served the purpose of testing the measurement technique used and furthermore were to provide information about ice strain occurring in structures.

1.3 **Ice conditions in the Eider estuary.**

In the tidal flat area of the Outer Eider, which is characterised by channels 15 m deep and extensive sand banks lying in most cases at LLW to LLW + 0.5 m, the air temperature, wind and water level determine the development of ice. When frosty weather sets in, east winds predominate, which result in low water levels and exert a favourable influence on ice formation. Shallow waters on the great stretches of mud flats, which are already high and dry at half tide, bring about a sudden fall in the water and ground temperature and a rapid growth of pack-ice. As soon as the water levels are raised only slightly, the pack-ice floats away and reinforces the ice floes in the channels. As was shown by the ice observations in the winters from 1967-68 to 1971-72, the ice formation

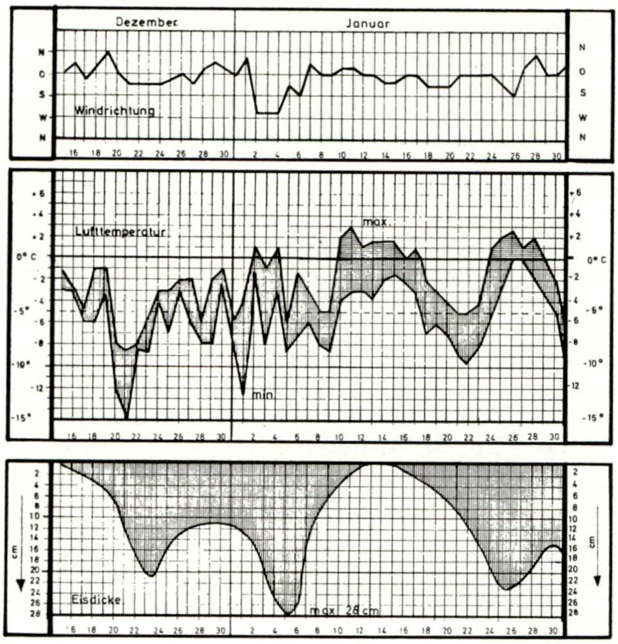

Fig. 1.

LEGENDS

Ice development in the Eider estuary 1969-1970.

Dezember	December
Januar	January
Windrichtung	Direction of wind
Lufttemperatur	Air temperature
Eisdicke max. 28 cm	Ice thickness max. 28 cm

begins regularly at air temperatures below —3 °C and locally on the flat submerged sand banks and on the edges of the tidal flats. A more marked ice growth occurs at temperatures below —10 °C, whereby the water temperature follows with a time-lag of 1 to 2 days, as is clearly shown by the ice development in the winter of 1969-70 (fig. 1). The ice then moves back and forth in large floes with the tide and piles up on the edges of the channels to form pack-ice belts (fig. 2). Maximum values observed :

Size of ice sheets	5,000 sq.m
Thickness of ice sheets	30 — 40 cm
Drift ice velocity	1 m/s.

Basically, ice floes and sheet ice move in the direction of the tide. However, they are strongly influenced in their direction by wind.

When a thaw sets in, the ice blocks lying on the sand banks also float away and move in ice floes or as single blocks with the tide. These ice blocks have a maximum volume of 300-400 cu.m and thicknesses up to 4 m. They are more dangerous for structures than is drift ice. At the beginning of the thaw, which is often accompanied by a change of wind from east to west and by higher water levels, the surface ice also shows a stronger tendency to move from the mud flats into the channels, forming large ice floes with connected sheets, some of which are sandwiched together, which pile up

Fig. 2.
Pack ice belt in the Eider estuary.

on the edges and, when they encounter obstacles, form pack ice belts (up to 8 m in heigth).

1.4 Ice pressure investigations.

1.4.1. *Direct ice pressure measurements.*

The Eider dam was built on an artificial island in the Wattenmeer. A 900 m long steel transport bridge formed the link with the mainland. The bridge panels, placed at a distance of 40 m from each other, consisted of large tubular piles ⌀ 760 mm, which were calculated in the lengthwise panel at 100 Mp ice pressure. During the ice period, the ice pressure on the panel piles and dolphins was ascertained by means of measuring devices and on the basis of distortions. On each of the bridge panels 7 and 8, a pressure measurement device was installed. They were distinguished from each other by their outward form. The measurement device on panel 7 served to measure the ice pressure on a tubular pile, while that on panel 8 measured the ice pressure on a vertical plane surface (fig. 3).

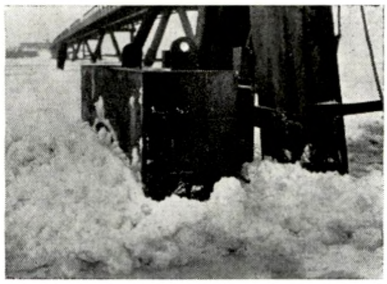

Fig. 3.
Surface pressure measurement device.

The pile pressure measurement equipment consisted of a semicircular pressure scale with 56 pressure indicators, placed in 10 rows one above the other. The pressure indicators operate according to the method of electric resistance measurement, whereby the elastic deformation was measured and recorded as the change in the electrical resistance of glued expansion measurement strips. The measurement values were amplified by 12 carrier frequency bridges and recorded with a direct-recording UV light ray oscillograph (Visicorder).

The plane surface measurement equipment consisted of a large cylindrical pressure measurement chamber ⌀ 1.5 m, the square casing of which was assembled on a double frame rammed in front of the bridge panel. To the cylindrical case of the pressure measurement chamber, active and passive expansion measurement strips were stuck, by means of which the ice pressure exerting its effects on the pressure diaphragm was measured. In this connection, the resistance change of all the expansion measurement strips was added and recorded as a single value. The total pressure could then be calculated immediately by multiplication with the calibration value.

During the measurements with the two measurement devices, all the other interesting data, such as thickness, direction and velocity of the drift ice as well as data about wind, water level and temperature, were measured and recorded at the same time.

The greatest pressure from an ice floe against a tubular pile did not occur at the first encounter, but only after reduction to a lower drifting speed, whereby the prevalent uniaxial tension was converted into a biaxial one. In this cutting phase, the floe was « sawn off » from the panel pile under almost constant total load. When the floe came to a standstill, the greatest ice pressure occurred shortly before the end of this dynamic strain.

The static pressure occurring after the standstill was always smaller than the previous dynamic pressure load.

At the time of « sawing off » of the ice floes (fig. 4), the individual measurement value indicators on the semicircular measurement scale constantly recorded

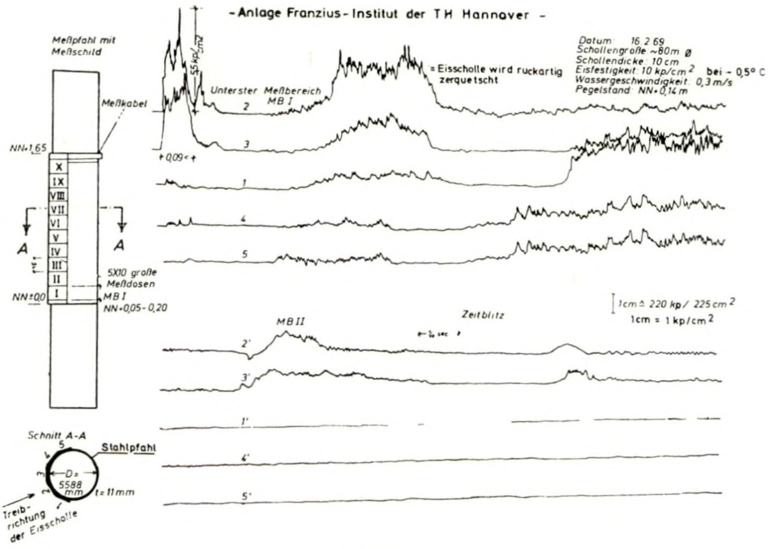

Fig. 4*a*.

Ice pressure measurements at panel 7
— Equipment, Franzius-Institut der TH Hanover —

LEGENDS.

Messpfahl mit Messschild	Measuring pole with measurement dial
Messkabel	Measuring cable
5 × 10 grosse Messdosen	5 × 10 large measuring chambers
MB I	MB I
NN + 0.05 — 0.20	LL + 0.05 — 0.20
Schnitt A — A	Section A — A
Stahlpfahl	Steel pole
Treibrichtung der Eisscholle	Drift direction of ice sheet
Datum :	Date :
Schollengrösse : ∿ 80 m ∅	Sheet size : ∿ 80 m ∅
Schollendicke : 10 cm	Sheet thickness : 10 cm
Eisfestigkeit : 10 kp/cm² bei — 0.5°C	Ice strength : 10 kp/sq. cm at at — 0.5°C
Wassergeschwindigkeit : 0.3 m/s	Water velocity : 0.3 m/s
Pegelstand : NN + 0.14 m	Water level : ll + 0.14 m
Unterster Messbereich	Lowest measurement range
MB I	MB I
= Eisscholle wird ruckartig zerquetscht	= ice sheet is crushed jerkily
MB II	MB II
Zeitblitz	Time-flash

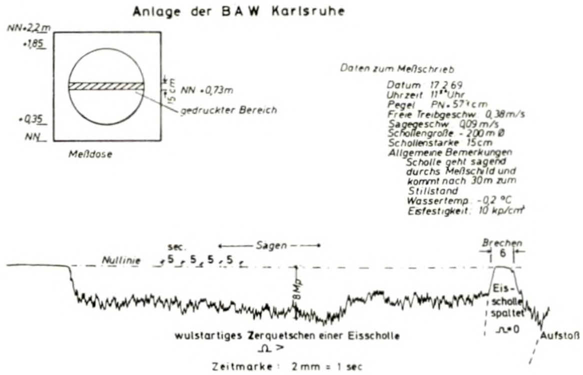

Fig. 4*b*.

Ice pressure measurement on panel 8.

Equipment of the BAW Karlsruhe.

LEGENDS.

gedrückter Bereich	printed range
Messdose	measuring chamber
Daten zum Messschrieb	Data for measurement recording
Uhrzeit : 11.50 Uhr	Time : 11.50 a.m.
Pegel : PN + 573 cm	Level : Datum + 573 cm
Freie Treibgesch. : 0.38 m/s	Free drift speed : 0.38 m/s
Sägegeschw. : 0.09 m/s	Sawing speed : 0.09 m/s
Schollengrösse : bis 200 m ⌀	Sheet size : up to 200 m ⌀
Schollenstärke : 15 cm	Sheet thickness : 15 cm
Allgemeine Bemerkungen :	General remarks :
Scholle geht sägend durchs Messschild und kommt nach 30 m zum Stillstand	Sheet proceeds in sawing motion through measurement dial and comes to a halt after 30 m
Wassertemp. : — 0.2°C	Water temp. : — 0.2°C
Sägen	Sawing
Brechen	Breaking
Nullinie	Datum line
Wultsartiges Zerquetschen einer Eisscholle	Swollen crushing of an ice sheet
Zeitmarke	Time mark
Eisscholle spaltet	Ice sheet splits
Aufstoss	Impact

varying local loads, while the ice pressure on the large measurement chamber varied to a much more limited extent. The ice pressures measured on both measurement apparatuses varied in some cases considerably according to the temperature, structure and thickness of the ice, so that utilisable results can be obtained only from frequency distributions.

Both measurement devices proved to be correct and usable and for the first time rendered possible informative measurements which throw light on the problems of ice pressure.

The maximum ice pressure on both measurement devices varied, according to the ice strength, as well as the form and dimensions of the measurement equipment, around 30 Mp total load, whereby individual peak pressures of up to 20 kp/sq. cm occurred. Cubic pressure tests (10 × 10 × 10 cm) in the direction of growth of the ice yielded as mean pressure resistances, depending on the ice temperature with a deformation velocity per cm of $0.003 \frac{cm}{s}$:

— 0.5°C = 17 kp/sq.cm;
— 7°C = 30 kp/sq.cm;
— 10°C = 40 kp/sq.cm.

Well-defined relations in respect of size and dependence of the ice pressure of drift ice can only be found by the statistical method from numerous measurements. The formula postulated by Schwarz (2) for the calculation of ice pressure is only valid for circular tubular dolphins with a diameter of about 60 cm. For all other forms and dimensions of structures, it can only apply approximately.

1.4.2. *Indirect ice pressure investigation.*

Further computational conclusions about the magnitude of the ice pressure could be drawn from the deformation of isolated steel tubular dolphins in the navigational opening of the transport bridge as a result of the effects of drift ice. The steel pile ($\varnothing$ = 812.8 mm, t = 12.7 mm), in St 52 steel, was 25 m long, 11 m of which are fixed in the ground. After the ice impact, the pile showed an upper deflection of 1.55 m. With simplified hypotheses of the deformation line and form stability under rigid fixing in the ground, a total ice pressure of about 30 Mp resulted, which corresponded to the values subsequently measured.

The ice pressure measurement device on panel 8 was destroyed in the night at the time of powerful ice motion (flood current). The nominal rupture spots were placed at 60 Mp, and they were exceeded by the ice pressure.

1.5 **Ice impact and ice abrasion.**

The ice blocks (300-400 cu.m in volume) which become detached from the mud flats when the thaw sets in drift with the tidal current. In case of collision with a structure, the stored kinetic energy is decisive, as the ice pressure resistance plays no determinant role owing to the great thickness. The extent of the ice impact depends on the volume of the ice block, the drift velocity and an impact factor which is to be applied more or less as in the case of ship impact. The drift direction of the ice block adjusts itself to the tidal current, as the deeply submerged ice block offers practically no effective working surface to the wind.

In the case of the Eider dam, it was observed that the stone embankment of the dam immediately at the water's edge was submitted to abrasion by longitudinally shearing ice floes. The tips of the projecting granite stones were rounded off after an icy winter. Pulling up or lifting of the stones was prevented by casting the joints with Colcrete mortar. In case of occurrence of such ice movements, it is advisable not to provide any open-joint embankment.

1.6 **Summary.**

The observations and measurements available make it possible to discover in which order of magnitude the ice stress occurs. It is however difficult to deal with the impact of the drifting ice blocks in its absolute magnitude, for it is decisively influenced by the flow with which the ice block encounters an obstacle. Naturally, it is appropriate to plan the structures beforehand in such a way that, by their position and design, they would to a large extent exclude the possibility of ice attacks or greatly decrease them. As far as possible, ice floes should break up by their own weight with a free linear or narrow surface strip foundation. It should be borne in mind that the direction of the ice attack depends not only on the current but essentially also on the wind direction; an exception to this are ice blocks. It seems sensible systematically to investigate geometrical shapes — as in the case of flow against piers — in the case of ice attack as well. Sloping, round or angular working surfaces are in any case more favourable than plane surfaces placed obliquely to the direction of the drift ice.

2. EFFECTS OF ICE ON NAVIGATION

2.1 General.

Traffic on the shipping lanes can today be maintained, even in unfavorable ice conditions, by using more powerful and improved ice breakers. Small ships and inland waterway traffic are however still hampered by drift ice and frequently have to be suspended in winter for several weeks. Traffic on the ship canals is affected most seriously, as the removal of the ice by means of ice breakers and when the thaw sets in is held up, through lack of a continuous longitudinal current, on reaches of anything up to 200 km in length. If traffic is brought to a standstill by ice on these canals, then — in contrast to what happens in flowing waters— it often proves impossible to resume it, even during interim periods of thaw. Furthermore, the ice may also immediately prove an obstacle to overland traffic if the latter crosses the shipping route with ferries.

The following comments consider some of the many questions arising in connection with the effects of ice, deal with experiments and attempts to limit ice obstacles by improved ship design and examine ice control on a tidal river, taking the Elbe as an example.

2.2 Model tests for ice-breaking bulk carriers.

2.2.1. *General.*

The development of mineral resources which had hitherto been inaccessible in the desolate regions of Canada and Alaska led to a demand for appropriate ships as means of transport. Owing to the altogether extreme climatic and hydrographic conditions in the Arctic waters, and owing to the navigational obstacle of ice, special ships had to be designed which are proof against the special strains and also remain utilisable in the Arctic winter under extremely adverse ice conditions.

In addition to a higher carrying capacity, a sufficiently large propulsion power (in both directions) is required so as to enable, for example, in case of barriers of vast glacial islands of ice and similar obstacles which are difficult to surmount, the ship to make repeated start-ups.

For the design of traditional polar ice breakers, a number of data are now available which were obtained by means of practical operating experience and theoretical calculations. Their applicability depends on the extent to which the ice conditions are reproducible, the type of ship and its relevant size and capacity. Naturally, for ice-breaking bulk carriers 200-400 m long, in case of navigation in ice thicknesses of 3-6 m, these data can be applied only to a very limited extent.

A purely theoretical determination of the ship's resistance when breaking ice, as well as the calculation of the lateral strains from ice pressure are only possible to a restricted degree, as the data with respect to the actually occurring values of ice resistance and the coefficients of friction, which depend greatly on age, salt content, temperature, crystal structure and, as the case may be, the snow coating, are still inadequate. It is difficult to obtain by means of model tests a sufficiently reproducible picture of the strains to which an ice breaker and more particularly a bulk carrier are subjected. The physical similarity laws for the conversion of the resistances measured on the model in the case of ice breaking and surmounting of frictional drag, as well as their reciprocal influence, are still largely unexplained. The difficulties in the planning of suitable model tests stem from the multifarious nature of the processes on the ship when engaged in ice breaking.

2.2.2. *Processes on the ship when ice breaking.*

When the ship advances against an enclosed ice surface, compressive and bending strains are produced in the ice which, according to the inclination of the stem, shape of the frame, acuteness of the angle of waterline entry, lead — in the case of sufficiently large propulsive capacity of the ship — to breaking of the ice. A sloping stem accompanied by protruding frames mainly subject the ice to bending strains, while vertical frames and stems mainly cause compressive and buckling stresses. In the case of a homogeneous ice surface, radially disposed cracks occur in the ice, which then breaks up in a circular form around the stem and disintegrates into sheets. The sheets thus produced are, by means of a certain expenditure of energy against their mass inertia, pushed on one side and tipped; they are submerged against their hydrostatic lifting forces or pushed against each other by gravity, whereby sliding friction resistances occur between the sheets on the stem and on the outside plating. The prow is an instrument, the dimensions, shape, surface finish and speed of advance of which determine all stages of the process. A calculation solely of the energy necessary for the kinematics of the sheets already leads to estimates of the ice thickness that is surmountable with the given propeller thrust. By means of using an approximation for the coefficients of friction between the ice and the outside plating, a certain refinement of the calculation is conceivable.

When the ship advances in the channel that has been broken open, frictional forces of the sheets exert their effects on the ship's sides. In the case of ice breakers which always have a doubly curved outside plating, they are mostly of more limited significance, although they form the chief component in the navigational resistance of ice in the case of large bulk carriers with parallel plates that are even over wide surfaces. A reduction of the waterline width aft, which is only possible to a limited extent, or a widening of the prow, as in the case of the « Manhattan », leads to a reduction of the ice-sheet pressures on the long sides of the ship and decreases the frictional forces.

2.2.3. *Difficulties involved in model tests.*

The marked interdependence of the resistance components described adds to the difficulties of carrying out reproducible model tests, even solely for a certain ice navigational situation that is regarded as uniform. For this purpose all the material constants of the « ice » used in the model test would need to have physically correct reduced sizes and it would have to be guaranteed that the proportional resistance magnitudes in the case of a model speed reduced to a certain extent are related to each other in a proportion corresponding to the full-scale model. However, just as in the case of normal ship model tests in open, smooth water the various model laws stipulate entirely different model speeds for frictional resistance due to viscosity and wave resistance due to gravity and hence necessitate in each case a considerable resistance correction by means of a subtraction for frictional correction, so is it to be expected that the model laws, which are partly still unknown, for the breaking, transport and sliding friction of the ice sheets on ice and steel, even in the case of correctly reduced material constants of the model ice used, require in each case different laws for determining the model speed. It must therefore be doubted whether the conversion of the model speed to the ship speed in accordance with the Froude similarity law, used hitherto in ice breaker model tests, led to correct values, as — in addition to the inertia forces — it merely took account of the forces purely induced by gravity on the model. At the commencement of this special model test technique, an attempt should therefore be made to proceed first of all to a certain separation of the partial resistances occurring on the model in the case of ice breaking under various model ice conditions.

The first principles for a calculation of the work in the case of ice breaking on the bows and in the case of transport of ice sheets can be obtained theoretically and on the basis of observations on board the ship (ice breaker formulae according to Vinogradov, etc.). Model tests in broken ice sheets of certain dimensions (Fig. 5) can provide an initial reference value concerning the navigational resistance in the case of specific covering of the fairway with ice.

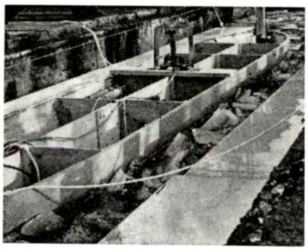

Fig. 5.

Propulsion tests in broken ice sheets of a thickness corresponding to 4-5 m

Furthermore, it seems to be relevant to ascertain separately, on divided models by means of appropriate measuring devices when measuring the overall resistance, the actual breaking resistance in the bows area and the actual frictional resistance on the sides of the model, and hence to make possible a further analysis, at least of the model behaviour.

In view of the difficulties of a model-type performance of tests mentioned above, the investigations which have been customary so far can only represent an initial approach with more or less limited capacity as evidence. Thus, for example, in the case of tests in fresh water ice, modified paraffin and artificial model ice material, an ice thickness linked with reproducible strength is mostly considerably too thin, or conversely, in the case of reproducible thickness and mass of the ice sheets, the strength is too high by a certain multiple, which means that the tests are only very limitedly reproducible.

An advance in the model test technique is represented by the recent use of ice which has had its breaking strength reduced by super-salting, whereby model ice is produced by means of specific salt concentrations and deliberate freezing methods at low temperatures. However, while the ice thickness is represented in this way true to scale, the strength distribution over the cross-section deviates greatly from that of natural ice. Thus, inter alia, the strength of a weak porous salt ice layer produced by supercooling is increased by additional freezing of a thin fresh ice coating, so that the upper layer takes over a considerable part of the overall breaking strength. The deflection of this model ice is shown by experience to be appreciably higher than that of comparable natural ice. Hence, it is not to be expected here either that the size of the ice sheets existing in the model ice breaking, as well as their movement behaviour, are sufficiently reproducible.

In addition to the model tests for estimating the capacity necessary in the case of ice breaking, a series of other model, large-scale and laboratory tests are also possible, which may be useful for the clarification of further questions arising in the design of an ice-breaking bulk carrier.

2.2.4. *Model tests in the Versuchsanstalt für Wasserbau u. Schiffbau Berlin.*

In the framework of a rather large-scale test programme for various types of an ice-breaking bulk carrier for the AG Weser Bremen, tests were carried out in the Versuchsanstalt für Wasserbau und Schiffbau Berlin, in which the behaviour of the ice-breaker model in case of collision with a fixed cylinder braked with verying degrees of intensity, corresponding somewhat to a hard glacial ice sheet of great thickness, was observed and the horizontal and vertical stresses occurring on the stem were measured. As the cylinder, on which the inclined ice-breaker stem slides, was placed completely rigidly, the test conditions are too unfavourable, as even glacial ice of the greatest hardness permits a certain penetration of the stem, especially as in most cases younger and hence softer ice surrounds the glacial core of old and hard glacier ice. Nevertheless. valuable indications were obtained about the size of the impact components and the behaviour of the ship. Measurement and observation show that the model, at the time of the first impact of the inclined stem on the fixed cylinder, undergoes longitudinal bending vibrations. These vibrations led to numerous lifts and recoils of the model stem against the obstacle, connected with corresponding impact peaks.

Figure 6 shows the horizontal and vertical forces at the first impact of the model against the cylinder. The corresponding forces of the second, third and fourth impacts are of the same order of magnitude, although they are rather more divergent. Within certain limits, the friction when the stem slides up was changed. Owing to the highly elastic bending vibrations of the model on the rigid obstacle and the divergences in measured value linked therewith, this influence could however not be clearly ascertained. Even if the ship's impact on the ice is not so hard as in the model test, it is to be assumed that, as a result of the longitudinal bending vibrations set up, movement and force amplitudes occur which must be taken into account when calculating the strength and the approximate determination of which should be possible in case of reduction of the test results.

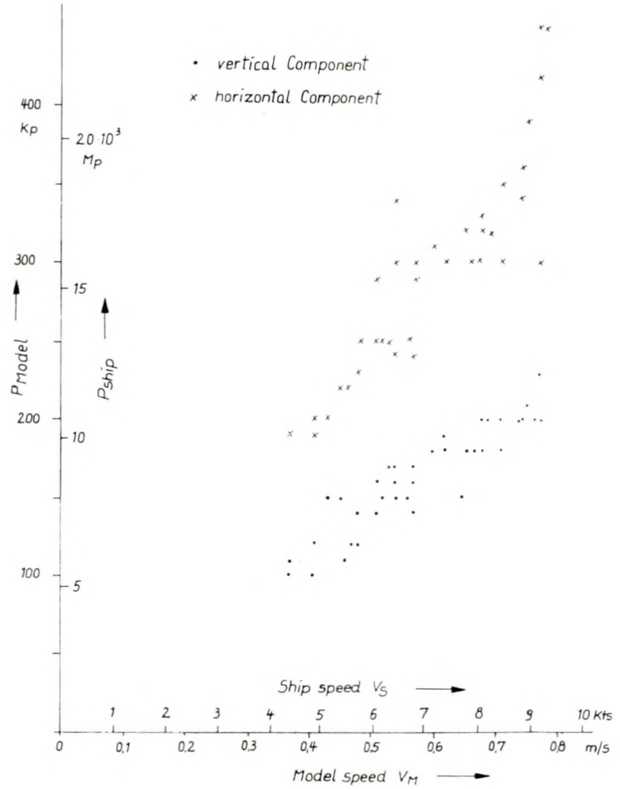

Fig. 6.

Vertical and horizontal forces on the stem at the first impact.

2.2.5. *Conclusion.*

The remarks made in the foregoing show that we are at present still in the early stages of a meaningful model test technique for ice-breaking bulk carriers, but that good initial data are available for getting nearer to a solution of the multifarious problems. Further large-scale, model and laboratory tests as well as theoretical calculations and analyses are increasingly necessary in order to provide good bases for the design of these ships, which in the near future will be utilised as efficient means of transporting the Arctic mineral resources.

2.3 **Behaviour of ferries in ice.**

2.3.1. *General.*

So as to distinguish the ferries considered here from other ships and the multitude of possible types of ferry boat, our comments are confined to the double-end ferries in use on the Kiel Canal, which can sail and manœuvre altogether indifferently in both axial directions, i.e., forwards and backwards.

The ferries, which are built as inland waterway vessels, are driven by chains, rudder propellers or Voith-Schneider propellers (VSP).

The limitation to the Kiel Canal includes all essential boundary conditions, with the exception of the current in streams and watercourses, which would also have to be taken into account in the case of river ferries.

2.3.2. *Date to be taken into consideration on the Kiel Canal.*

In particular, the following partial factors must be taken into account in respect of ferries on the Kiel Canal :

Traffic conditions :

The obligation to maintain ferry traffic requires special technical and operating efforts. The ferry boats must maintain their service even when only very large ships pass through the Kiel Canal, kept open by ice-breakers, while comparable motorised ships have already abandoned the canal.

A special difficulty resides in the fact that the ferries cannot sail in an undisturbed channel which they themselves keep open in the ice by their passage to and fro. Owing to the passage of ships sailing in the canal axis, the surface ice is pushed increasingly into the channel, the ferry bays and in front of the ferry piers. This can occur to such an extent that the ferry bay is crammed with ice as far as the bottom and then the ferry pier has to be kept free by means of grab dredgers. Thus, a movement and retention of the ice occurs constantly, so that the ferry boats are subjected to difficult operating conditions.

Even in colder regions, with consequently greater ice thicknesses and in the case of larger water surfaces, more favourable conditions exist.

Type of waters :

The water in the Kiel Canal consists practically, in the western part influenced by the Elbe and by tributaries, of fresh water, and in the eastern part towards the Baltic increasingly of salt water. Sea water from the Baltic enters through the locks in Holtenau. As the ferries are utilised predominantly in the western part of the Canal, fresh water conditions prevail. In case of persistently low temperatures, surface ice rapidly forms there, which is reinforced by drift ice which enters, downstream in the Elbe, through the locks at Brunsbüttel.

The greatest depth of water amounts to 11 m, and the trapezoid canal cross-section contains approx. 800 sq. metres (in future to be increased to about 1,350 sq. metres) surface (immersed main section of the control ship approx. 200 sq. metres); the heat reservoir of the deeper water levels is therefore relatively small. In addition, there is the fact that the volume of water is greatly churned up by shipping and hence assumes almost uniform temperatures.

Owing to the small amount of heat storage in the depths of the canal, attempts to keep the ferry bays free of ice by means of propeller-form propulsion equipment or by air from perforated compressed air pipes in the direction of the ferry line proved fruitless.

In Sweden, for example, these methods yielded considerable successes, owing to the large quantities of water available.

Ferry boat :

The development of the types of ferry used on the Kiel Canal can be summarised as follows :

	Chain ferries	Ferry with outboard engine	Hinged ferry	45 t VSP ferry	100 t VSP ferry
Displacement loaded (t) . . .	90-115	185	234	165	414
Engine output (h.p.)	2 × 30	2 × 75	2 × 100	2 × 120	4 × 240
Pay load (t)	20	40	45	45	100
Output (h.p.) Displacement (t)	0.63-0.52	0.81	0.85	1.45	2.32

The ferries are classified chronologically according to commissioning in the above list.

The gradual enlargement of the pay load takes into account the increasing traffic demands.

The rise in the capacity is connected with the increased pay load. As however the last columns show, the specific capacity h.p. It has increased more than proportionally. This increase was aimed at not only in order to step up the speed, which remains of secondary importance in the case of short ferry journeys of approx. 150 to 200 m or 500 m in Brunsbüttel, but also to improve the acceleration processes (mooring and casting off, manoeuvring). This increase in the specific capacity is also of immediate benefit to operation under ice conditions.

It is obvious that the chain ferries, which owing to their peculiar drive are no longer suited to modern traffic and also naturally have special difficulties in ice in the ferry bays, despite the chain traction which is favourable for progression, are being gradually replaced by VSP ferries.

Specific ice difficulties are unknown in the case of the shuttle ferries. Some of the experiences set forth below for VSP ferries are also valid analogously for shuttle ferries as well.

It was decided to choose the Voith-Schneider drive because it offers quite generally the advantage for ferries that landing and casting off manoeuvres can be carried out with the greatest precision and smoothly. Furthermore, the Voith-Schneider ferry is able to adjust itself in an optimum way on the ferry course itself to the lengthwise traffic which has priority.

As difficulties in the ice may cancel out these advantages, structural measures were taken from the outset in the VSP ferries, on the basis of experience collected, to increase the ice resistance :

At stem and stern, the ship's frame was equipped with sloping surfaces in the waterline, thereby preventing a piling-up of ice. The two VSP are placed under a protective tunnel, thereby attaining a great immersion depth. Towards the ends of the ship, the « tunnels » are protected by special collars, which will repel the pieces of ice that are forced under the ship's hull in the course of the journey.

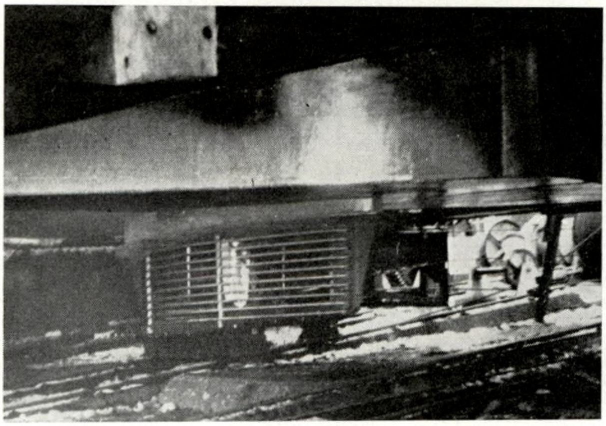

Fig. 7.

Ice basket on a 45 t VSP ferry

After several trials — despite the favourable experiences in Sweden — we abandoned the method of protecting the propeller by ice baskets. In the Kiel Canal, the ice in the mass is pulverised to such an extent as a result of the heavy shipping traffic, etc., that the ice baskets become blocked with ice chips and the necessary inflow and outflow are stopped. The variation of the rod distances, etc., also yielded no satisfactory results so far.

The 100-t ferries have been given a further improved design by comparison with the 45-t ferries and are fitted with additional ice rams which repel massive conglomerations of ice and protect the propeller blades against large ice sheets.

In the exceptionally hard winter of 1962-63, numerous cases of damage to the blades and the driving gear occurred. Subsequently, special ice-resistant blades were fitted, in which furthermore the shaft was moved in the direction of the inlet edge. This reduces the momentums which originate from the impacts due to encounters with obstacles and which are transmitted into the kinematics. Finally, safety

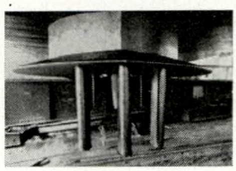

Fig. 8.

Ice rams on a VSP ferry.

valves were built into the control hydraulics, which carry off excess pressures originating from impacts and reduce short-lived overstresses of the kinematics.

These measures were given a practical test in the long and icy winter of 1969-70. The damage which occurred — in overall figures, less than in 1962-63 — consisted mainly of deformations of the blades themselves. This is a considerable improvement, as the blades can be relatively easily removed, repaired and re-fitted. Damage to the kinematics have become a very rare occurrence.

In the case of a ferry under construction, the propellers were placed still deeper. Furthermore — as hitherto the full gradient could not be made use of — the number of revolutions is reduced and placed on full gradient. In this way, with a higher torque, a reduction of the peripheral speed and hence a reduction of the impacts is attained. The peripheral speeds are below those of comparable propeller screws, the outermost edges of which, where the collision with the ice occurs, are correspondingly more greatly endangered.

Ferry landing installations :

The structural set-up of the landing installations has a far from inconsiderable influence on the conditions in which the ferry is berthed.

The landward landing flaps, adjusted to the water level by means of a float or operated hydraulically, have a jib length of 6 m. The landing flaps provide, as a result of the geometric conditions, a transit roadway as free from buckling as possible at different water levels.

In this connection, however, they have additional importance because they can absorb a certain piling-up of ice at the ferry terminus without hindering the landing of the ship. In fact, however, under extremely harsh conditions, the pile of ice is larger than the length of the flaps. In order to give the pile of ice the possibility of expansion, it is endeavoured to have a ferry bay with a large surface. The economic limitation resides in the high cost. In this connection, it must also be borne in mind that under the conditions, already described, of ice movement owing to the shipping traffic through the canal, any ferry bay — regardless of its size — is blocked by piled ice. In order to make possible a free outflow of the ice, it would be necessary to refrain to the fullest possible extent from using any supporting and guiding dolphins.

2.3.3. *Operating ferries in the ice.*

The technical measures referred to in the foregoing are supplemented by operational precautions. The VSP ferries dealt with exhaustively here are adjusted in their design to ice conditions, insofar as this does not — or not essentially — cause prejudice to the smooth-water operation, which is largely preponderant. They are therefore not ice-breaking ferries in the true sense. Hence, the channels of the ferry terminals which are very badly hindered by ice are kept free by high-powered tugs. At the ferry piers which are badly hindered by ice, there are either tugs or substitute ferries with running propellers, which endeavour as far as possible to clear the ferry bays of ice. The good manoeuvring possibilities of the VSP are fully made use of in order, when crossing, to push to one side the impeding masses of ice or to keep the ferry bays free of ice by means of opposite thrust directions of the VSP. The potentialities of the VSP are also fully utilised in the case of free crossing, turning or slowing down when recognisably large pieces of ice are encountered. In these measures or manoeuvres, the experience, reaction capacity and tenacity of purpose of the ship's captain naturally play a decisive role.

2.3.4. *Summary.*

By means of measures in respect of ship design and hydraulics, it is possible to respect to the fullest extent the obligations to maintain the ferry service over the Kiel Canal in icy weather. The expenditure involved is considerable. Even if we do not entirely succeed in preventing damage in icy conditions, it should be borne in mind that the ferries sail for more than 95% of their operating time in calm water conditions, for which they are equipped, and that they still provide a service under extremely icy conditions, when comparable motorised ships cease operation or avoid the passage. An analytical research into the combined effects between ferries and their propulsion systems with the ice is rendered difficult by lack of knowledge of the various magnitudes exerting an influence. At the present time, the latter seem still to be inaccessible to research, as they depend, in the shipping area under consideration, on innumerable boundary conditions.

2.4 Notes on ice control and impediments to shipping by ice on the tidal Elbe.

2.4.1. *General.*

In the tidal Elbe (Fig. 9), closed ice surfaces form only on secondary arms and in the tidal limit region upstream from Hamburg. Downstream, shipping and the great widths prevent the formation of an ice surface.

The drift ice drifts with the flow and ebb current upstream and downstream. In this way, as a result of the successive water levels and current speeds, changing from tide to tide, as well as the marked irregularities of the river bed in some places, there occur temporarily considerable collections of ice, which can seriously upset small-scale shipping, in the case of drift ice cover which is, on the whole, only of average level.

In severe winters, the ice can also cause a hindrance to shipping by reason of changes in the water level. They may occur if ice deposits, fixed drift ice fields and closed ice surfaces in secondary channels change the size and roughness of the river channel and an ice cover, which has formed in the upper non-tidal reach of the river, restricts the supply of water from upstream. In addition to the tidal movement at sea, the upstream water and the size and condition of the river channel are the essential factors influencing the water movement occurring in the tidal reaches of a river.

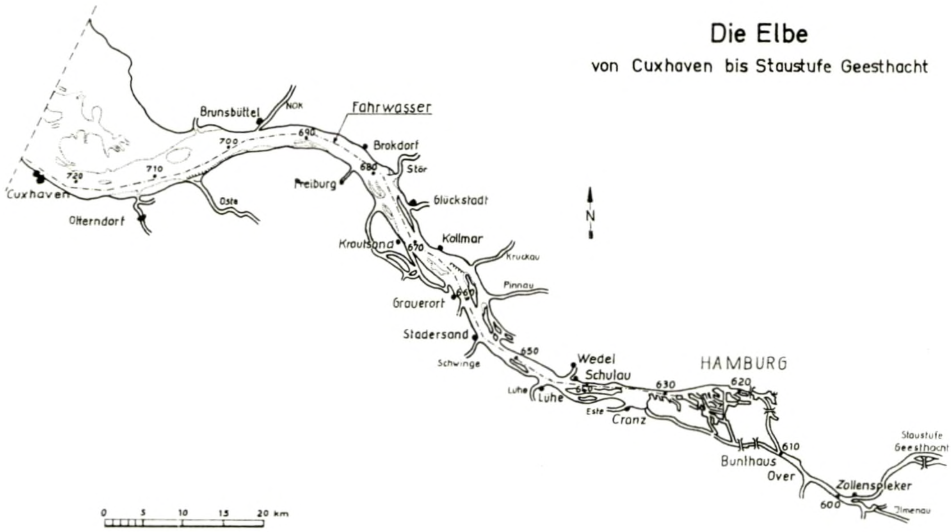

Fig. 9

The Elbe from Cuxhaven to Geesthacht barrage

LEGENDS.

Staustufe	Barrage
Fahrwasser	Fairway

2.4.2. *Notes on the causes of ice accumulations and changes in water level.*

Apart from tidal currents, water levels and the local conditions in the form of projecting banks, structures built in the river, frequent shoals and secondary channels, the wind thrust, which counteracts or reinforces the drift, due to current, of the drift ice is one of the essential causes of the differing ice cover in specific places. In addition to the local conditions, their change from place to place is also of importance, as — with the change of the river bed as well as the greater distance from the sea and the upper tide limit — the duration of the flow and ebb and the distance covered by a molecule of liquid during one tide also change. As furthermore the water movement at a given place on a tidal river is finally determined by the form of the entire tidal area as the oscillation space of the tidal wave, the local situation is not to be judged without taking account of the dimensions and properties of the entire estuary.

The ice deposits in the tidal river occur at the time of the fall of the water levels, if — when the tide goes out — the ice sheets become dry, push against each other and freeze together. The extent of the deposits depends on the slope of the beaches as well as on the existence of sands and shoals which are submerged at higher water levels. In the course of several tides, extensive ice accumulations may occur, especially in cases where the water levels are medium.

The alteration of the river by ice deposits, fixed drift ice fields and closed ice surfaces leads as a rule to an increased abatement of the tidal wave, as a greater roughness and more marked lack of uniformity occur (the change of the shapes and sizes of the cross-section over the longitudinal axis of the river is described as lack of uniformity). In addition, other reflections occur owing to the change in the oscillation space. As a result of the limitation of the upstream water by the ice surface in the tideless upper reach of the river, the raising of the tidal water level by the upstream water also becomes less great. In addition to the change in the heights and entry times of the water levels, a change occurs in the current conditions and in the river flow which exerts an effect on the ice drift and hence on the local ice accumulations. If large accumulations of ice nevertheless continue to form at the same places, then the influence of the local conditions of the river bed is preponderant.

2.4.3. *Ice impediments and changes of water level in the Elbe.*

Figure 9 shows the course of the Elbe between Hamburg and Cuxhaven. Especially in the reach between Hamburg and the mouth of the Stör (just downstream from Glückstadt), the river shows an irregular line. The navigable channel changes sides several times, due to influences exerted on the course of the tidal wave and the currents by curves, junctions of tributaries and different sizes and shapes of cross-sections. Between the banks and the navigable channel there are in places extensive stretches of open water on which ice is deposited. Furthermore, there are several islands, shoals and secondary channels which are piled high with ice sheets or frozen. This reach offers, together with its irregularities, the preconditions for local ice accumulations; they occur mainly at km 645, between km 651 and 654, 661 and 668 and from 673 to 681.

Downstream from the Stör estuary to about Brunsbüttel (km 700), the Elbe shows less marked irregularities. The cross-section parts with shallow water are also smaller here by comparison with the size of the overall cross-section. Downstream from Brunsbüttel, the mouth of the Elbe widens greatly and a stretch of extensive sand banks and mud flats begins. In severe winters, there are also considerable ice accumulations downstream from the Stör estuary, but their occurrence is mainly due to the wind, e.g., an East-South-East wind leads to ice accumulation off Brunsbüttel and an east wind often causes an accumulation off Cuxhaven.

In the reach of the river upstream from Hamburg, the widths are less great and a fixed ice surface is formed, first of all in the region of the flood-tide boundary, as it is there that the drift ice drifting from upstream mainly piles up.

Large-scale shipping is not impeded by drift ice covering the Elbe. Small-scale shipping, however, frequently needs help from ice-breakers. Several ships then follow, mostly in middle line, the ice-breakers performing their routine tasks. The ice may, however, also cause difficulties for medium-sized ships, as it blocks the cooling water pipes.

The abatement of the tidal wave by ice can be seen from Figure 10, which shows the course of the low water and high water marks in the case of an incoming tide with the presence of much ice, as well as the course of the marks which would occur under otherwise identical conditions in a river free of ice. The lines showing the course in an ice-free river are drawn in dashes, assuming that the upstream water occurs in the same quantity as flows away when the tide has come in under the ice cover in the tideless reach. This outflow amounts, depending on the age and smoothness of the ice cover, to about 0.3 to 0.5 times the outflow in an ice-free river. The other dotted lines represent the course that would occur if the tideless reach was also ice-free and if there was no reduced outflow through ice. The comparison of the lines shows that in the case of a river carrying ice, a fall in the high water mark and a rise in the low water mark occur upstream from Glückstadt. The limitation of the upstream water by the ice cover in the tideless Elbe supports the reduction of the high water mark and counteracts the raising of the low water mark. Downstream from Glückstadt, the high water mark rises, and the low water mark falls through the reflection of the tidal wave as a result of the effects of ice upstream.

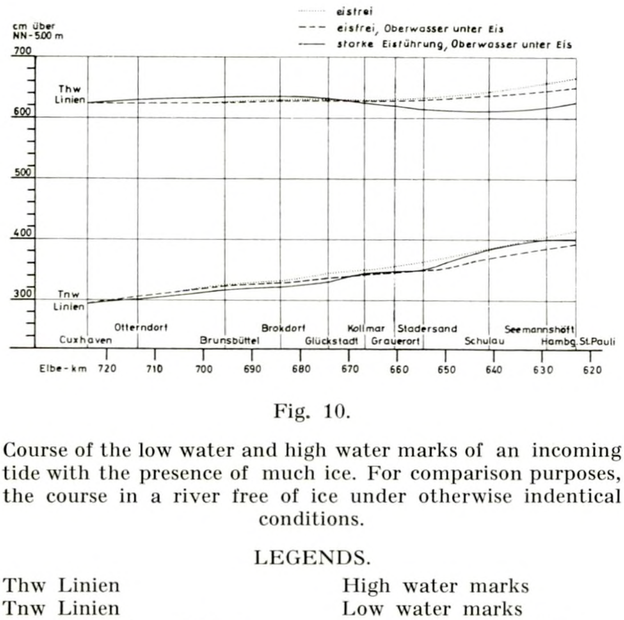

Fig. 10.

Course of the low water and high water marks of an incoming tide with the presence of much ice. For comparison purposes, the course in a river free of ice under otherwise indentical conditions.

LEGENDS.

Thw Linien	High water marks
Tnw Linien	Low water marks
cm über NN — 5.00 m	cm over LL — 5.00 m
eisfrei, Oberwasser unter Eis	ice-free, upper water under ice
starke Eisführung, Oberwasser unter Eis	much ice transported, upper water under ice

Naturally, different changes in low water and high water marks occur from tide to tide and from one icy winter to another. The reduction of the high water mark by ice, which upsets shipping, is aggravated by the fact that in winter easterly winds are frequent, which cause the water level in the Elbe to fall. Furthermore, the reduction by ice occurs in the fresh water reach of the river, in which the depth of immersion of the ships is greater. If account is taken of the effects of ice on the water levels by a greater keel clearance of the ships, then in the case of a ship with 14 m draught and a fall in the high water mark through ice of approx. 0.30m, the keel clearance related to the draught is increased by about 2%.

2.4.4. *Summary.*

Small-scale shipping may, on large tidal rivers such as the Elbe, on which — owing to the shipping traffic and the large widths — no closed ice surfaces form in winter, be especially impeded by the fact that the ice accumulates and piles up in certain places. In addition to the changing course of the tides, the effects of wind and local irregularities in the course of the river are causes of the accumulations of ice. Furthermore, the river bed is changed by ice deposits on beaches and shoals, fixed drift ice fields and ice surfaces on secondary channels and this may lead to a fall in the high water mark, whereby the traffic of large ships, with deep draught and utilising the time range of the high water mark, is handicapped. In addition, there is a reduction of the water levels as the result of the decreased flow owing to an ice cover in the upper tideless reach of the river. The hydraulic engineer must take account of the effects of ice on shipping when engaging in works on the river. A reduction of the impeding effects of ice is to be attained if the irregularities in the course of the river are decreased. By means of this smoothing of the line, it is possible at the same time to improve the discharge capacity of the ice-free river as well, which in the case of narrowly dimensioned water depths has a greater importance for shipping than the impeding effects of ice.

3. MEANS OF COMBATING ICE

3.1 General.

The ice-breaker is still at the present time the preponderant medium for combating ice. On the ocean-going shipping lanes, it serves for maintaining the traffic. On the inland rivers, its use is necessary for the conservation of the incoming tide, while at the same time it ensures the timely resumption of shipping traffic.

On the inland navigation canals which are used by barges, the traffic can only be maintained by ice-breaker if, in the case of an ice thickness of about 12-15 cm still to be coped with by shipping, no substantial new ice formation occurs. If under these conditions the daily average air temperatures fall to —5° C, then traffic comes to a standstill within one day, despite the ice-breaker, as the water is constantly churned up by shipping as far as the bottom, so that the small heat reserve in the water is rapidly consumed, despite the ice cover available, and the formation of new ice starts immediately. Furthermore, the sheet-ice cannot sufficiently be pushed to the side by the vessels passing through, owing to lack of space in the narrow canals. Shortly before the cessation of shipping, there exists therefore only a narrow « navigable channel » of the width of one ship in the middle of the fairway, in which overtaking is impossible and meetings with an oncoming ship often result in the fact that the vessel with the weaker engine comes to a stop on the side in the sheet-ice. If the sheet-ice is further crushed by shipping or ice-breakers, there exists a tough ice slurry, which can no longer be coped with by the barges which usually have engines of 200 to 600 h.p. The breaking-up of the ice on the artificial inland waterways therefore occurs mainly for the purpose of curtailing the periods when traffic is suspended. With the onset of a definite thaw, the ice is broken up there so as to curtail the duration of the traffic suspension as well as to release the ships which have come to a halt in the fairway.

The air-bubbles method, which requires a rather large heat reserve in great depth of water in order to prevent ice formation, cannot be taken into consideration either for the maintenance of traffic on inland waterways with relatively small water depths, as owing to the pronounced mixing of the water by shipping and currents, sufficient heat is not available on the bottom. On the other hand, the injection of air in order to keep the lock gates free of ice in the Hanover area has been successfully used for the past three years. Here, however, it was a question of keeping sheets of ice away from the critical gate areas so as to ensure a danger-free movement of the falling and mitreing gates. By means of the air which rises in places very strongly from the bottom to the water surface, a « water mountain » is formed on the surface which, with uninterrupted operation in frosty weather, keeps a relatively large area in front of the lock gates free from ice.

The following equipment is used : compressor with hourly capacity of 4.1 cu.m; operating pressure 2.5 atm. over; air piping for outlet pipes ⌀ 3/4 in.; pipes ⌀ 3 to 5 mm; distance between pipes 0.5 to 1.0 m; in 3 m water depth. In the case of the Uelzen lock (Elbe-Seitenkanal), a compressor with 56 cu.m/h is provided.

The irksome and often dangerous operation of freeing the gates of ice can be dispensed with, as the lochs remain ready for operation for the passage of the icebreakers.

The supply of heated cooling water from power stations and industries represents another possibility for combating ice. Navigable rivers and canalised rivers are being used to an increasing extent for cooling purposes. The heated cooling water can be used in quite large reaches for thawing purposes. We report below on this use of the introduction of cooling water.

3.2 **Combating ice by introduction of heat.**

A prerequisite for an efficient use of introduction of cooling water for combating ice is a knowledge of the processes in the cooling or heating of the water. Some details about the physical data and research results in the following section give an idea of these processes. Subsequently, by means of three examples, we report on practical application considerations and on tests.

3.2.1. *Comments on heat exchange in ice formation.*

In constant weather conditions, the temperature of a river within a few days is balanced out at a certain value. At this temperature, the heat increase resulting from overall radiation is exactly offset by the loss of heat caused by evaporation and convection. The water temperature indeed rises in the course of the day and falls in the course of the night, but in each case after 24 hours it again passes through the same values. This temperature (with daily recurrence) is known as the equilibrium temperature. In winter, this equilibrium temperature may be roughly equated with the air temperature.

In the case of an inflow of cold air, the equilibrium temperature is abruptly lowered. The speed with which the water tries to adjust itself to the new air temperature is proportional to the difference between the transient water temperature and the new equilibrium temperature, and it further depends on the depth of the water and the wind velocity. In the following tables, some values are given for the loss of heat (thermal units per sq.m and degree of difference in temperature) for various wind velocities :

Wind velocity	0 m/s	3 m/s	8 m/s
open water at 0° . . .	15 therms/sq.m., degree	25 therms/sq.m., degree	35 therms/sq.m., degree
Core ice of 3-5 cm in thickness	10 therms/sq.m., degree	16 therms/sq.m., degree	

As long as the water surface is warmer than the air, the heat losses per degree of difference in temperature are to be placed 3% higher.

Owing to the heat loss from the surface, the head of water underneath is cooled. The deeper the river, the more slowly its temperature falls. With continuing cooling, the temperature falls to below 0° and then, when ice formation starts, rises to 0°.

As soon as ice appears on the surface, the heat loss also changes. Measurements of the surface temperatures have shown that, e.g., with an air temperature of —15° and slight wind, the water surfaces still open have a temperature of —1°, in the same way as small drift ice structures and the inner surfaces of drift ice sheets that are still damp. The collars of drift ice sheets have temperatures which, with a clear sky, are somewhat below the air temperature. If in the further course of ice formation, the inner surfaces of the drift ice sheets freeze, their temperature falls until they reach with some dm thickness the temperature of the collar. As the difference between equilibrium temperature and surface temperature is then $\sim$ 0, the heat loss is also $\sim$ 0, i.e., the drift ice sheets act as heat insulator. However, this does not mean that the heat loss of the river is thereby reduced in proportion, which is still open surfaces to total surface. On the one hand, the drift ice sheets with their high collars reduce the wind velocity in the vicinity of the water surface. On the other hand, vertical air movements are provoked by the very great differences in temperature between water surface and the collars of the drift ice sheets, which can lead, especially with low wind speeds, to a considerably higher heat loss. Over a river containing drift ice, when the wind is light, the air can be seen to flicker as over a dry stretch of ground in the summer sun. Quantitatively speaking, the alteration of the heat exchange is very hard to trace, because the quantity of drift ice formed is almost impossible to determine.

If a closed ice surface has formed, then those effects which are due to the relatively warm water surfaces between the ice sheets no longer exist. With increasing thickness of the ice cover, its heat insulating capacity also increases. If finally only as much heat reaches the atmosphere from the water through the ice as is supplied at the same time to the water from underground and from the fall energy, then the increase in thickness comes to a halt.

The heat insulation capacity of thin core ice sheets can be determined, without taking into consideration the sources of energy just referred to, from the speed of growth in certain atmospheric conditions. For the first 3-5 cm of ice thickness, the heat losses entered in the foregoing table are calculated. The heat insulation capacity of clear core ice is not extremely great, which also manifests itself in relatively high surface temperatures. Ice surfaces resulting from drift ice sheets that have been pushed together bear on a plate similar to core ice a crust of loose material of a high insulation capacity originating from the collar of the drift ice sheet.

3.2.2. *Utilisation of the waste heat from power stations.*

The planned Krümmel power station will be taken as the first example. This power station is to be built on the Elbe, about 6 km upstream from the Geesthacht dam. It will produce 1,200 MW of electricity and will convey waste heat of 2,600 MW = 620 Mcal/s into the river. In this way, with a required melting heat of 80 Mcal/t, 7.75 t/h ice can be melted. As the discharge is checked upstream of the introduction by an ice cover, minor current speeds prevail, so that the hot water that is introduced can be distributed over the cross-section. Light to medium drift ice will be melted on the way to the dam (the flow times amount to between 3 and 5 hours). It is questionable whether the large drift ice sheets of 3-6 m ⌀ and up to 0.4 m thickness will already be melted within this stretch, because in the quite calm current the water underneath the sheet which is cooled by the melting process is only gradually replaced by fresh hot water. If considerably more than 7.75 t/h ice drift past the power station, then an ice situation may occur, as before. This ice cover would be thawed from beneath by the waste heat introduced. The river surface as far as the dam amounts to 1.4 million sq.m, and the mass of the ice cover to about 280,000 t. With a melting capacity of 7.75 t/h, some 10 hours would be necessary to melt the sheet again as far as the dam.

In case of an inrush of cold air, a current phenomenon in this region, with air temperatures of about —12° and wind speed of 5 m/s, some 400 W/sq.m of heat are removed from the water surface. The 2,600 MW of the power station are sufficient to replace the heat removed from 6.5 million sq.m of river surface. It is enough to keep a reach of the river of about 20-25 km in length downstream from the power station free of ice. As, with an increasing open surface, a larger share of the waste heat is released in the atmosphere and less and less heat is left over for melting the available ice cover, this reach will be open only after a long lapse of time.

If ice-breakers operate upstream from the power station, ice sheets of 5-20 m ⌀ and approx. 0.3 m thickness drift past the power station. The Geesthacht dam is subjected to very great stresses by these hard lumps at the overfall. Based on the results of laboratory tests by Sokolov (4), melting speeds of the ice sheets on the way between power station and dam were calculated at about 0.3-1 cm/h. During the flow time as far as the dam, a layer of 0.9-5.0 cm thickness is then melted from the underneath of the sheets. In this way, the thickness of the ice sheets is reduced by the introduction of hot water. As however the temperature in the ice is determined by the air temperature, the hardness of the ice is not decreased by the introduction of cooling water. However, the use of ice-breakers as a rule occurs only when the thaw sets in and with relatively higher air temperatures.

As second example, the combating of ice by waste heat in the canals of the Federal Republic of Germany will be discussed. The Main-Danube Canal, the Elbe-Seitenkanal and the Mittellandkanal after widening each have about 50 m surface width and about 170 sq.m cross-section. The inrush of cold air with —12° C and 5 m/s is again taken as basis, whereby 400 W/sq.m of heat are removed from the water surface.

If 20 cu.m/h of cooling water at +5° C are pumped into the canal, this means that 420 MW of waste heat are introduced. This quantity of heat is sufficient to replenish the heat loss of approx. 10^6 sq.m of water surface. With a width of 50 m, this makes 20 km of canal length. If the water temperature before the power station was 0° C, and after it +5° C, then it is again 0° C after 20 km. The current speed amounts to about 12 cm/s, and the flow time just over 2 days. In order to keep the canal free from ice continuously, such a waste heat inlet would need to be installed every 20 km.

The difference between transient temperature (+2° C) and equilibrium temperature (—13° C) under the conditions referred to amounts to about 15° C. If a thaw now sets in, the equilibrium temperature rises, e.g., to 0° C and this interval is reduced on an average to 3.5° C. In this way, the cooling speed also decreases to about 1/4 of the original value. If a chain of power stations are installed along a canal, which in case of danger of ice introduce 420 MW of waste heat every 20 km, these power stations must, in case of a thaw, cut their input to 100 MW of waste heat each, so as not to overheat the canal. Except in periods of frost, they therefore have to discharge their waste heat mostly via cooling towers or in some other way. This double installation makes the process very expensive.

The third example concerns the effects of a hot water input in constant operation near Hanover in the Mittelland-Kanal with a water volume of approx. 0.5 cu.m/s and a temperature of 12°-16° C in winter. In the winter of 1969-70, measurements and observations were carried out here concerning the extent and dimensions of the influence of the hot water input on the increase and decrease of ice formation in the canal.

The most important results of the investigations were : Without hot water supply, the ice thickness constantly increased, with falling air temperatures, to a steady condition between 25 and 30 cm. Once this condition was reached, the ice thickness was no longer changed significantly by subsequent waves of heat and cold, as the thick ice covering largely prevented the heat exchange between air and water.

In the indirect sphere of influence of the hot water input (distance of 6-20 km), the ice formation under the effects of cold air increased only hesitantly. Any increase in the air temperatures, still below freezing point, led to a halt in ice formation. If the air temperatures rose above freezing point, then an immediate decrease in the ice thickness was observable.

In the direct sphere of influence, either no ice covering occurred, or in extreme cases an ice covering (5 cm to 10 cm) which impeded shipping only slightly. These reaches were in a short time again ice-free in the case of any moderation of the frost below freezing point.

In the sphere of influence of the hot water inputs, the water temperatures, in the case of pronounced frost attacks, reached freezing point later than in the other reaches. Owing to the stored heat reserve in the water, the ice formation also started later, so that the traffic could be maintained over short periods of frost, whereas a few kilometres further it was often impossible for 8 to 10 days owing to severe icing.

On the canal reaches widened from 30 m to 47 m, a 20% to 25% greater ice thickness was measured. The reason for this could not yet be established.

On the basis of these results of the investigations, a test was carried out in Minden in January 1972, at the beginning of the first frost period, whereby 2,962,000 cu.m of water (approx. 13 cu.m/s) were pumped via the main pumping station there from the Weser into the Mittellandkanal in 72 hours (3 days).

Owing to the Veltheim and Kirchlengern power stations, located on the Weser about 20 km above Minden, the water temperature in the Weser at the beginning of the test was still +5.3° C, but it fell during the test to +0.6° C. In the same period, the average daytime air temperatures fell from —3° C to —11° C, the water temperatures of the Mittellandkanal at the beginning of the test were +2.2° C in Minden and +0.5° C 18 km to the east.

It was planned to convey the entire pumped volume of water from Minden through the canal cross-section of 81 sq.m in the easterly direction via an outlet near Hanover into the Leine. However, with the East wind which increased from 3 m/s to 10.7 m/s in the test period, 37% of the pumped volume of water was transported westward from Minden. Owing to the water cooled to +0.6° C from the Weser and owing to the piling-up of the water by the wind, which was dangerous for shipping (bridge passages too low) in the west, the test had to be abandoned prematurely. At that time, the Mittellandkanal was still free from ice over a reach of 18 km to west and 13.5 to the east of the Minden pumping station, whereas the average ice thickness outside this ice-free reach 31.5 km long already amounted to 9 cm. The longer ice-free reach to the west of Minden, into which only 37% of the total pumped volume of water flowed, was conditioned by the air temperatures which in the first 1 1/2 days of the test were about 3° C higher on a daily average than to the east of Minden.

As a last example, considerations about combating ice in the lock installations of the Kiel Canal at Brunsbüttel are described.

The Kiel Canal is equipped with two pairs of locks at the access to the Elbe, the so-called Old Locks and the New Locks, constructed at a later date. The locks serve for shipping traffic, drainage and at the same time are protective embankments.

The Old Locks are fitted with mitreing gates — with ebb and flood tide gates.

When the water surfaces of the lock chambers and especially of the mitreing gate shaft of the Old Locks are iced over, locking through the Old Locks becomes impossible.

The New Locks are fitted with rolling gates. Through icing, an ice plating forms in the finely-linked framework structure on the ballast tanks, etc. The ice plating causes great strains on the rolling gates at low water and pronounced lift at high water. A constant change of the ballasting of the gates is necessary. The New Locks thus remain operational, but the gate movements are rendered difficult and slowed down.

By the introduction of hot water into the Brunsbüttel estuary port, the water surface of the Kiel Canal in the Brunsbüttel area including the ferry bays located there could be kept free from ice. The ice sheets drifting from the Elbe into the estuary port would be gradually thawed. Heated water would penetrate into the locks and bring about a decrease of ice in the lock chambers and gate shafts. Especially with the water levels, which are lower in the Elbe than in the Kiel Canal, the heated water would flow, by the locking process, from the estuary port through the locks into the outer harbours and thus keep at least the lock chambers and gate shafts free from ice.

According to estimates, with an excess temperature of 8° C (prescribed maximum value) and an introduction in the immediate vicinity of the locks with a cooling water requirement of approx. 7 cu.m/s to 10 cu.m/s, a canal reach of approx. 2,000 m in length can be kept free from ice. If the hot water zone is extended as far as the Ostermoor ferry, which lies at about 2,500 m from the locks, the required heated cooling water would be about 15 cu.m/s. This requirement can easily be met by the cooling water discharges from the Brunsbüttel nuclear power station (approx. 45 cu.m/s) and the heavy industry which is still settling there.

However, the nuclear power station lies on the Elbe at a distance of approx. 5 km from the locks of the Kiel Canal. As the nuclear power station would have to supply the greater part of the heated water, it must still be investigated whether the cost of an introduction is in due proportion to the utility.

The fact that severe icy winters occur only seldom in the Brunsbüttel area is an argument against the introduction. In the case of permanent input, damage occurs for the aquatic resources and fish, as account must then be taken in summer of water temperatures in the region of 30° C and even in winter with temporary local temperature increases to about 15° C. In this way, the operation of a branch piping, to be opened differently in accordance with requirements, must be taken into consideration.

To sum up, it results from these examples that the cooling water from power stations and industrial plants is a suitable medium for combating ice. Efficient use of it, however, is accompanied by the precondition that it should be a permanent component of the considerations about the location and operation of plants working with cooling water. This should be attained in the light of the major benefits for the national economy resulting from a thorough reduction of the ice obstacle on shipping lanes.

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RÉSUMÉ

La glace occasionne des dégâts aux ouvrages des voies navigables et gêne la navigation et le fonctionnement des installations de réglage du trafic établies le long de ces voies. Le rapport ci-dessous fait état des essais, des observations et des expériences réalisées à propos de l'action des glaces.

Peu de données existent sur la poussée exercée par les glaces sur les ouvrages. Les mesurages effectués lors de la construction du barrage de l'Eider ont permis de constater des efforts de compression atteignant au maximum 20 kgs/cm^e. L'effort de choc des blocs de glace charriés n'a pas pu être mesuré directement, mais on a pu le déduire, approximativement seulement, de la déformation subie par certains ouvrages. L'effort est comparable à un choc d'accostage. Les ouvrages, situés dans les cours d'eau menacés par les glaces ou le long de ceux-ci, devraient être conçus, quant à leur emplacement et à leur configuration, de manière à pouvoir esquiver, dans la mesure du possible, l'attaque des glaçons.

De même, les efforts ne sont pas exactement connus en cas d'attaque des bateaux par les glaçons. Des brise-glaces et des cargos briseurs de glace ont été étudiés sur modèle. De tels essais sont très difficiles à réaliser pour le motif que les vitesses-étalon doivent être calculées d'après des lois différentes (bris, transport et frottement de glissement des glaçons). Lors d'un essai, on remplaça un glaçon par un rouleau fixe à soumettre à un freinage variable. Lorsque le brise-glace modèle à étrave inclinée toucha le rouleau, le bateau présenta des vibrations de flexion longitudinales.

Le fait que la navigation est gênée par la glace sur les voies d'eau porte directement préjudice au trafic terrestre lorsque ce dernier traverse les voies d'eau en empruntant les bacs. Aux fins de maintenir le plus longtemps possible le service des passages d'eau, on a résolu d'utiliser, sur le canal dit « Nord-Ostsee-Kanal » (reliant la mer du Nord à la Baltique), des bacs munis d'hélices Voith-Schneider, placées à la coque sous tuyères, afin d'augmenter la profondeur d'immersion. Il en résulta une amélioration de l'exploitation en période de glaces. Mais la mise en service des bacs pendant cette période ne pouvant pas entraver sensiblement la navigation en eaux dégagées des glaces, il importe de rechercher d'autres moyens de réduire le volume des glaçons s'accumulant aux abords du débarcadère et dans le chenal de navigation, lorsque le charriage est important.

Dans les rivières à marée, dans lesquelles la navigation et les grandes largeurs empêchent la formation d'une couche de glace ferme, les glaçons charriés s'accumulent souvent en certains endroits, sous l'action des mouvements variables de la marée, sous l'action du vent et des caractéristiques locales de la rivière. Ils entravent spécialement la petite navigation. C'est notamment le cas sur l'Elbe. Les dépôts de glace sur les rives, les champs de glace flottante immobilisés et le blocage par la glace des chenaux latéraux, qui entraînent des modifications du chenal de navigation, influent sur les niveaux de la rivière. Les fluctuations rendent difficile la navigation des bateaux à grand tirant d'eau qui profitent de l'amplitude de la marée. De même, une réduction du débit provenant de la zone d'amont de la rivière, non soumise à marée, réduction résultant de la formation à cet endroit d'une couche de glace, contribue à modifier le niveau des eaux. Pendant les hivers rigoureux, on a constaté sur l'Elbe des chutes des niveaux Th-w de l'ordre de 0,30 m.

On peut empêcher les fortes accumulations de glaces en utilisant des brise-glaces et en procédant à des travaux d'aménagement (ouvrages). Sur les voies d'eau intérieures, la mise en service de brise-glace n'est pas toujours efficace pour le motif que la glace brisée ne peut être évacuée en volume suffisant. Sur ces voies d'eau, il faut essayer d'empêcher la formation de glaces par des apports d'eau chaude de réfrigération provenant des centrales électriques ou en fondant les champs de glace. Des études ont été effectuées sur l'échange de chaleur qui s'opère lors de la formation de la glace. Elles ont permis de constater notamment que la glace flottante peut contrarier un refroidissement de l'eau lorsque la vitesse du vent croît, mais qu'elle favorise le refroidissement, aux bords, lorsque la vitesse du vent est faible, de par la création de mouvements d'air verticaux. C'est précisément pourquoi il est difficile de déterminer l'ampleur de la chaleur émise par l'eau en cas de glace flottante.

Une analyse théorique de l'effet que produirait l'introduction d'eau de réfrigération provenant de la centrale nucléaire, dont la construction est projetée à Geesthacht-Krümmel sur l'Elbe, a permis d'établir que, si la température et la vitesse du vent sont normales, une section de rivière de 20 à 25 km pouvait être maintenue exempte de glaces, selon le débit.

Les mêmes considérations — portant sur l'introduction de 20 m^3/s d'eau de réfrigération à + 5° dans les canaux d'environ 50 m de largeur de plan d'eau et de 170 m^2 de surface de profil en travers, c'est le cas du canal Main-Danube, du canal latéral de l'Elbe et du « Mittellandkanal » ont permis d'établir que la section exempte de glace peut être de 20 km de longueur.

Les observations et les mesures effectuées lors d'une introduction d'eau chaude dans le « Mittellandkanal » à proximité d'Hanovre — environ 0,5 m^3/s d'eau à température constante de 12°-16°C fut introduit — ont permis de constater une diminution sensible des épaisseurs de glace dans une zone d'influence de 6 à 20 km.

Les introductions d'eau chaude peuvent également se faire dans une voie d'eau dans le but de tenir dégagée les installations éclusières et autres. On envisage l'application d'un tel procédé sur le canal reliant la Mer du Nord à la Baltique. On utiliserait l'eau de réfrigération d'une centrale nucléaire en voie de construction près de Brunsbüttel.

S. II - 4

PAPER

by

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ICE COVER FORMATION AND EFFECTS OF ICE ON STRUCTURES AND ON NAVIGATION IN THE LOWER PART OF THE RIVER RHINE

The presence of ice in the rivers of the Netherlands is not a very common occurrence. In the central area of the country, where the main rivers Rhine and Meuse find their way towards the sea, on an average only about 10 days per year the maximum day temperature remains below zero. As a result, in the lower reach of the rivers navigation is hampered on an average for small craft only during 8-10 days per year and for more powerful ships this happens during 4-7 days per year. The winters being rather mild, on an average during one out of five winters the ice cover in the rivers becomes land-fast. Then backwater effects due to the ice cover formation are occurring and the flow distribution over the various tributaries is changed considerably.

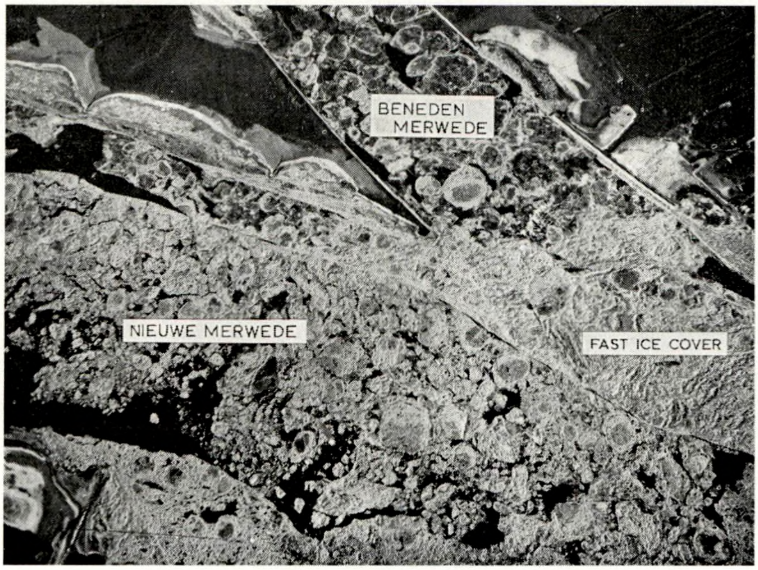
When ice is expected on the river, the marker buoys are removed from the river at the last possible moment. The ice may force them out of position so that they no longer provide a proper indication of the navigable channels in the river.

They are returned to their positions as soon as the ice situation allows.

On the wider rivers that use these buoys, such as the Nieuwe Merwede, the Hollandsch Diep and the Haringvliet, the removal of some or all of the buoys creates problems for vessels which have not yet been brought to a standstill by the ice, and increases their chances of running aground.

This is a risk which cannot reasonably be taken, especially when there is ice on the river.

In general, shipping on the wide waterways mentioned above comes to a halt when an ice sheet more or less completely covers the water surface (see photo).



Ice sheet near Werkendam.

On some of the other waterways in the area, the formation of a sheet of fast ice is delayed or completely prevented by, amongst other things, the intensity of shipping traffic.

While the mass of ice is kept moving, the navigability of the river will depend to a great extent on the engine capacity of individual ships. It has been observed during consecutive ice winters that, thanks to increased engine capacity, shipping is able to cope with ever greater masses of ice. Furthermore, the ships mainly travel in convoys, sometimes assisted by unattached tugs which are able to serve as ice-breakers.

Only when fast ice stretches over the full width of the river do the larger motor vessels have to cease navigation.

The rivers are bordered by districts which lie below the waterlevels prevailing in the rivers. These districts are protected against inundations by dikes along the rivers.

Especially at the entrance of the tidal region conditions are favourable for the start of the formation of a landfast ice cover. This solid mass of ice may grow very thick indeed and usually several ice-dams are formed. When thaw sets in rapidly, or thaw starts in the (more southern) upper reaches of the Rhine and Meuse these dams may cause a dangerous rise in the water level, threatening the dikes and the land behind.

In history numerous dike breaches due to these backwater effects have caused serious inundations.

To reduce the danger of the floods and to open up the river for shipping as soon as possible ice-breakers start to break up the fast ice cover from the down stream and before thaw sets in. In the winter of 1860-61 an ice-breaker was used for the first time, but not until 1890 were ice-breakers used on a larger scale. To carry out the ice-breaking programme on the river Rhine and its branches during the winter 1962-63, 24 ice-breakers were in action.

Since 1850 important regulation works were carried out in the delta of the Rhine and Meuse. It is due to these regulation works and to the ice-breaking programme that no dike breaches, resulting from ice dams, have occurred since 1861.

In the course of time there have also been changes in the methods of dealing with ice, the main change being that the ice-breaking programme is now initiated at an earlier stage.

In the earliest days (1860-61) a start was made on breaking up the ice only at the onset of a thaw. Now, a century later, a start is made as soon as ice begins to form on the river in order to prevent it as far as possible from becoming landfast.

So the discharge of ice starts immediately, which reduces the extent of any sheet ice and ice-dams which may form later.

This is one reason why little or no damage is caused to river works, such as groynes, breakwaters, bank revetments bridge piers, etc., which are designed partly with a view to facilitating ice discharge along the river. Usually the only indication that there has been any ice is a bent or broken beacon at the end of a groyne.

A layer of fast ice may also change the flow pattern of a river and thus also effect the configuration of the river bed.

This is certainly true when an ice-dam is formed, in which case scouring of the river bed may be expected on the spot or further upstream, the transported sediment being deposited in the slow water downstream of the ice-dam.

If these sand deposits are not carried away by the heavy flow of water produced when the thaw sets in, it will be necessary to dredge the river bed in order to restore the requisite profile.

When the delta project, which is under construction now, will come into operation it has to be expected that the discharge of drift ice will meet more obstructions. This project provides for the closure of three large sea-arms situated between the Western Scheldt and the Rotterdam Waterway. Furthermore the waters of the tidal delta will be devided into two separate basins by means of the Volkerakdam. The southern basin will be entirely cut off from the sea and become an almost stagnant fresh water lake. The northern basin which comprises the mouth of the Rhine and Meuse, will continue to be in communication with the sea.

In the mouth of the Haringvliet estuary a discharge sluice has been built. Through 17 gates of 56,5 $\times$ 5,5 m^2 surplus water of the Rhine and the Meuse will be discharged into the sea. The Rotterdam Waterway connecting Rotterdam with the North Sea will remain open for shipping. Consequently tidal waves will still be able to penetrate inland via this inlet. This scheme will upset completely the ice formation and its discharge. This is the reason that, in recent years, whenever ice conditions occurred studies have been made about the ice phenomena in the Rhine delta especially with regard to the changes in the future.

Fig. 1.

Soon after entering Dutch territory the river Rhine is splitting up into various branches (see fig. 1). The southernmost tributary, called Waal, is the main carrier of water and, if available, of ice. On a part of the northern branches called Nederrijn-Lek and IJssel a fast ice cover is formed in most cases already during early stages of a severe winter period. The IJssel debouches into the almost stagnant fresh water basin « the IJssel Lake » which freezes early even during moderate winters (average about 25 days per year). During such circumstances the ice discharge of the river Waal is of the order of 2.10^6 m^3 or 6.10^6 m^2 per day.

This quantity of ice is formed downstream of Cologne because upstream of this city nearly no ice is observed due to the narrows at the Lorelei. It is to be expected that the ice production of the Rhine and especially in the German part of the river will decrease due to the discharge of considerable quantities of warm cooling and waste water coming from the German industrial area bordering the river and its tributaries.

An investigation has been made on the ice production on the Netherlands part of the river. Fig. 2 and fig. 3 give the increase of the ice discharge coefficient (C) over a stretch of 100 km as a function of the air temperature for two branches of the Rhine, namely the Waal and Nederrijn-Lek. The ice discharge coefficient has been defined by Santema and Valken [1] as the ratio of the ice discharge in m^2/sec and the discharge of water in m^3/sec.

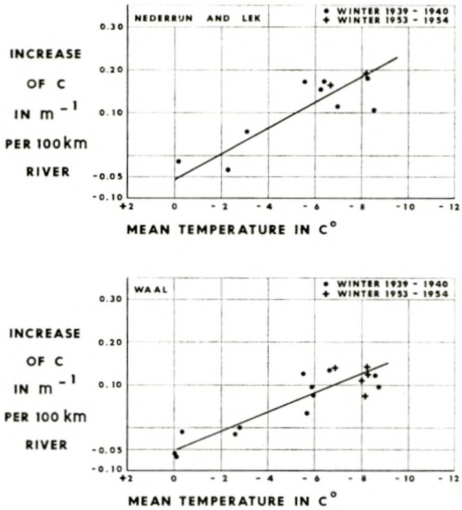


Fig. 2 — Fig. 3.

Ice production.

The graphs are based on numerous, but rather rough, estimations of the ice cover coefficient during the winters of 1939-40 and 1953-54. Obviously the Nederrijn-Lek has a greater ice production than the Waal. The slope of the waterlevels is nearly the same for both rivers while the ratio of the depths was 1 : 1,3 and that of the discharge 1 : 3. Over the whole depth the temperature of the water during the period of floating ice was zero centigrade or a little lower.

The ice formed in the stretch downstream of Cologne is discharged to the tidal zone of the delta. As can be seen on fig. 1 the branch Waal continues in some wide estuaries called Beneden Merwede, Hollandsch Diep and Haringvliet. The river Meuse is also debouching in the Hollandsch Diep. The rivers and estuaries mentioned above contain predominantly fresh water, but there is a considerable tidal movement. The tidal range varies from about 1,75 m at the seaface to about 1,1 m at Werkendam. In this tidal area huge quantities of ice are formed. The total area of the water surface of Nieuwe Merwede, Hollandsch Diep and Haringvliet is about 130 km^2. As a comparision it can be mentioned that the Rhine between Werkendam and Cologne has an area of water of about 80 km^2.

The ice production per unit area in the fresh water tidal zone is even bigger than in the river itself. In the estuaries there are extensive shallow zones which are covered during long periods of the tidal cycle with only a thin layer of almost stagnant water. At HW the ice produced here is moved by the tidal currents and wind to the main channels and the southern (predominant down-wind) shore. Therefore on part of the shallows, especially those along the northern shore of the estuaries, every tide new ice is being formed.

This is the reason why in general on the Haringvliet-Hollandsch Diep stretch ice is observed one or two days before drift ice is occurring on the river Rhine itself. The ice formed in this area together with the ice originating from the river is moved to and fro by the tidal currents and drifted away by the, during severe winter conditions predominant, northern or northeasterly winds. Studies have been made about the ice drift in the tidal areas and the discharge of this ice to the North Sea. Ice floes in the Hollandsch Diep and Haringvliet have been marked from helicopters with dyes. The marked floes were traced back by air reconnaissance. The result of this investigation is shown on fig. 4.

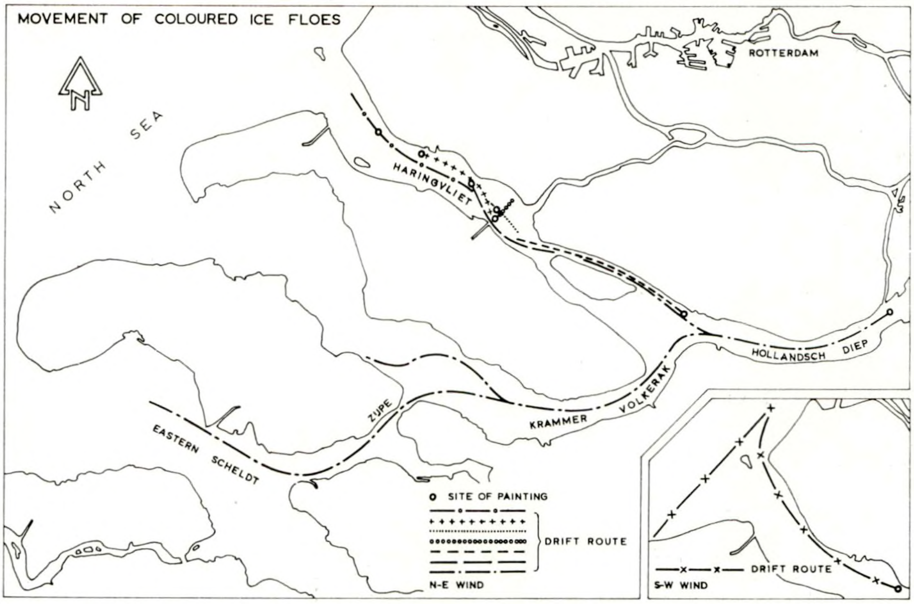


Fig. 4.

It appears that the majority of the floes marked in the Hollandsch Diep were observed to follow the Volkerak-Krammer-Zijpe-Eastern-Scheldt route to the sea. Only a few floes were found in the eastern part of the Haringvliet and not one floe was observed to find its way to the sea through this estuary. The average ice drift per tidal cycle on the Hollandsch Diep varied between 1 and 6 km. In the Volkerak-Krammer stretch this drift was about 13-23 km per tidal cycle. In the eastern part of the Haringvliet the drift was observed to be 1-3 km per tidal cycle and in the western N.W. orientated part hardly any drift at all was found during severe winter conditions. However when weather changed and with thaw S.W. winds occurred, within one tidal cycle, the marked floes

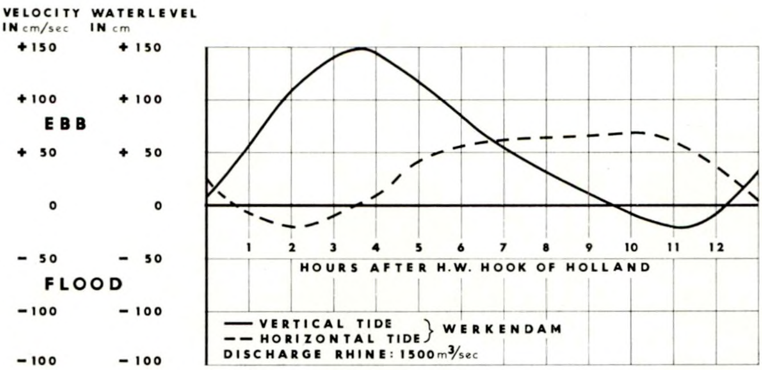


Fig. 5.

Horizontal and vertical tide Nieuwe Merwede at Werkendam.

of the western Haringvliet were observed scattered along the adjoining Northsea shores. From this investigation it followed clearly that in addition to the water movement the wind force and direction are the main factors influencing the drift of ice in the wide tidal estuaries.

In the transition zone between the tidal area with twodirectional flow and the river with a constant unidirectional flow there is a river section in which during a relatively long period of the tidal cycle the flow velocities are very low. A typical example of a velocity curve in the Nieuwe Merwede-Werkendam area is given in fig. 5. During the flood period of the tidal cycle the velocities are low and they tend to pack the ice together in the relatively narrow river section, thus increasing the ice cover coefficient. This weak flood period is followed after HW by a long period of slack water during which, if the conditions are favourable, the ice may freeze together to a solid sheet.

From a number of observations in the area concerned it appeared that the following combination of conditions is critical for the formation of a landfast ice cover in the upper reaches of the tidal zone of the delta (also in the Nederrijn-Lek area) :

1. The ice cover coefficient has a value of 1 (or somewhat greater due to packing) during a period of 5 or 8 hours.
2. The average temperature during that period is lower than —9° C.
3. The water velocity during the period concerned is not more than 50 cm/sec.

In fig. 6 an example is given of the associated effects leading to the formation of a landfast ice cover near Werkendam and in the Lek during the 1954 winter.

Once a fast ice cover is formed in the Werkendam-Nieuwe Merwede region the fast cover grows upstream due to juxtaposition of floes on an average at a rate of about 25 km per day on the Waal. On the river Meuse an average upstream movement of the edge of the fast ice cover of about 18 km per day is observed.

As soon as the ice become landfast ice-breakers start to proceed from the downstream edge of the ice cover, in order to remove ice-dams and to clear the river for the free discharge of water. Ice-breaking is only done during the ebb tide since during flood the danger exists that the ice-breakers will become trapped. If a progress is made of 3 1/2 km per tidal cycle 300.000 m³ (about 1.000.000 m²) free ice is produced.

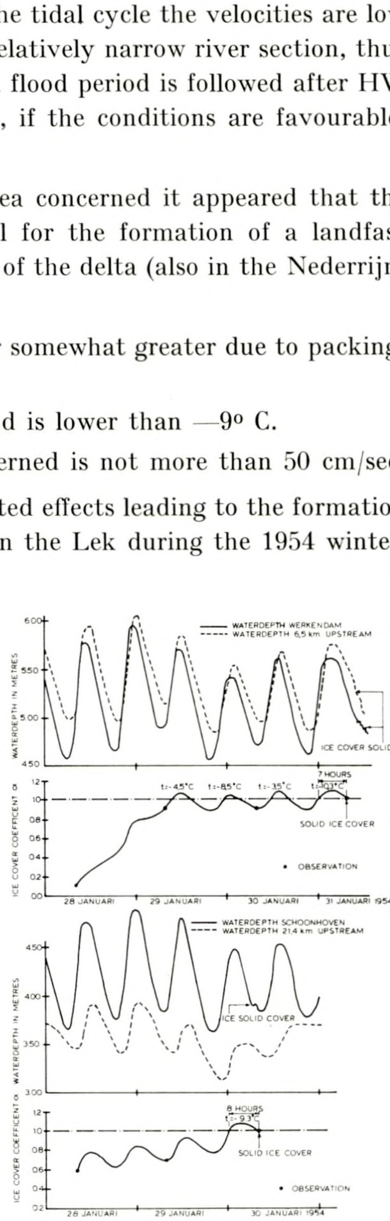


Fig. 6.

Whereas ice control at the beginning of the century was mainly concerned with clearing away the ice when the thaw came, the prevention or restriction of ice formation on rivers is an important aspect of ice control today.

One way of restricting ice formation is to eliminate irregularities in the flow pattern of the river. The river regulation work carried out in the lower reaches of the Dutch rivers has been an important step in the right direction. Thanks to the elimination of stretches of slow water and obstacles in the river bed, drifting ice is kept on the move and conditions favourable to ice formation are combated.

In rivers, current turbulence causes a considerable exchange of heat between the various layers of water. The effects of this natural phenomenon inhibiting ice formation can be intensified by keeping the surface water moving. For this reason reduction of shipping intensity due to other factors should be kept to a minimum. If shipping is too light to keep as much ice as possible moving downstream in the earliest stages of ice formation, then the time has come to enlist powerful tugs to combat the ice.

The occurrence of river ice has almost certainly been influenced in the last few decades by a slight rise in the water temperature caused by warm industrial effluent and coolant from electric power stations.

If ice formation proceeds to the point where, despite constant agitation of the surface water, fast ice begins to form, ice-breakers must be brought in to break up the sheet of ice as quickly as possible, with subsequent discharge downstream of the ice as it becomes disengaged.

The craft employed as ice-breakers are tugs designed with an eye to being used against ice; they have specially reinforced bows and a specially adapted body. The best results are obtained by using tugs of varying power to complement one another's efforts.

Tugs of 160 hp, 325 hp and 375 hp combine well in this respect.

There are various methods of breaking up ice.

One of the heavier vessels (375 hp) stays in the centre of the channel, flanked on both sides by one or two motor tugs (325 hp) depending on the compactness of the ice field to be broken up and the width to be broken. They can proceed with the vessels taking it in turns to lead until the ice layer becomes too thick or hard.

The leading vessel creates a channel and makes cracks in the ice sheet running from the bows in all directions but mainly diagonally backwards. The accompanying vessels can then break up the ice field more easily as it will now be open on one side (see fig. 7).

If the above formation is employed, it is necessary to have one or two vessels (depending on the amount of work) immediately downstream from the ice-breakers to break up the ice still further until the individual pieces of ice are too small to get stuck in shallows or along the banks.

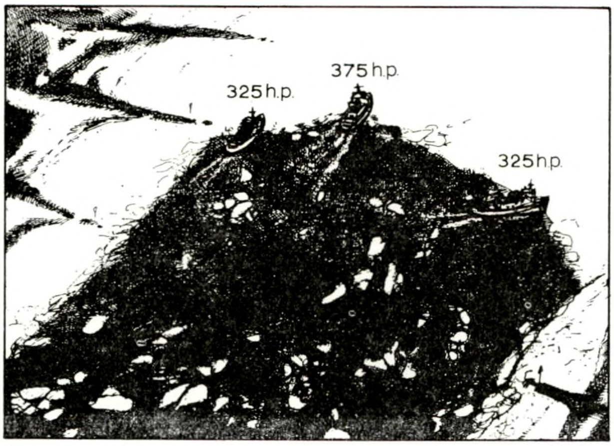


FIG. 7

Fig. 7.

Ice-breakers on the river.

Where only two vessels are available for the actual ice-breaking, good results can still be obtained if they each break off strips of ice perpendicular to the current from the downstream end of the sheet of fast ice. This method can only be employed with highly manœuvrable boats with a small turning circle.

On parts of the river where the ice does not extend from one side to the other, the ice-breakers can best sail, one behind the other and longitudinally to the river axis, along the edge of the fast ice. In such circumstances, if the ice is up to some 10 cm thick, the most effective method is to have the ice-breaker sail at full steam along the edge of the ice. The waves thus generated have a greater breaking force than the impact of the vessel itself.

In the tidal area the same method as above should be used, for breaking very large floating sheets of ice or fast ice. In this case, however, the ice-breakers more usually operate quite independently, as the most important task is to keep the masses of ice moving by breaking them up as much as possible.

The ice conditions and the changes taking place from day to day are observed from a number of set points, such as locks, bridges and harbours. Anyone using the information thus obtained will have to be acquainted with local conditions and also know precisely where the observations have been made.

As the observations are made from the bank or shore, the observer cannot be expected, in the case of wide waterways, to be able to give an entirely accurate and complete picture of the ice situation. The observation point is usually too low for this and the observations made are inadequate for a detailed study of ice formation and movement.

Reconnaissance is therefore carried out by an aircraft, which photographs the ice conditions on the rivers at various times. A detailed survey of the ice situation can thus be gained very quickly.

In addition to the consequences of a landfast ice cover the formation of ice-dams and its associated effects on the water movement has been a subject of special interest.

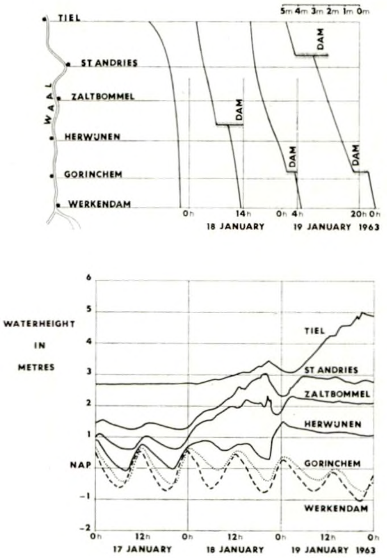


Fig. 8.

History of formation of ice dams in 1963.

The investigations concerning ice dams are concentrated especially to the tidal area since, due to the delta project, the conditions are changing considerably in that area. The aim of the investigations is to determine the hydraulic conditions under which ice dams are being formed and to find out which river sections will be vulnerable in the future for the formation of these dams.

On fig. 8 an example is given of the history of the formation of some ice dams during the 1962-1963 winter. In the lower part of this figure the recorded waterlevels at the gauges along the Nieuwe Merwede-Waal section are given while in the upper part are shown the locations or the gauges and, at four instants, the longitudinal profiles of the waterlevel with the location of the ice dams.

On January 17th the tidal movements was not yet disturbed by the presence of a fast ice cover. After the midnight H.W. on the 17th a landfast ice cover was formed in the Werkendam area, which resulted in a general divergency of the waterlevels as compared to the normal tidal movement in the entire river section. At about 7 a.m. on the 18th an ice dam was formed between Herwijnen and Zaltbommel causing a deviation of the waterlevels up and downstream of this dam. The maximum differential head between the Herwijnen and Zaltbommel gauges was about 2 m at about 21 hour on the 18th. Then is was LW at the downstream side.

Apparently the dam could not withstand this head and it collapsed. This resulted in a sudden rise of the downstream waterlevels and a fall upstream. Due to the high velocities in the downstream section and probably the ample supply of ice a new dam was formed, around H.W., a few hours later in the section between Herwijnen and Gorinchen. This dam damped out almost all tidal movement upstream.

At about noon of January 19th another dam was formed between St. Andries and Tiel.

For a number of years the history of the formation of ice dams has been reconstructed. Using the gauge readings and the reconstruction of the discharge distribution it was possible to determine the hydrodynamic conditions occurring during the formation of the ice dams. Using the work of Kivisild published at the eighth I.A.H.R. Congress held in 1959 in Montreal [2], [3] the Froude number was chosen to describe the hydrodynamic situation. The results of this investigation are shown on figure 9. A good agreement is found with the findings of Kivisild. Also for the river-Waal an average critical Froude number of

$$F_r = \frac{V}{\sqrt{g\,h}} = 0.08$$

is found for the formation of an ice dam. The single observations vary mainly between $F_r = 0.06$ and $F_r = 0.09$.

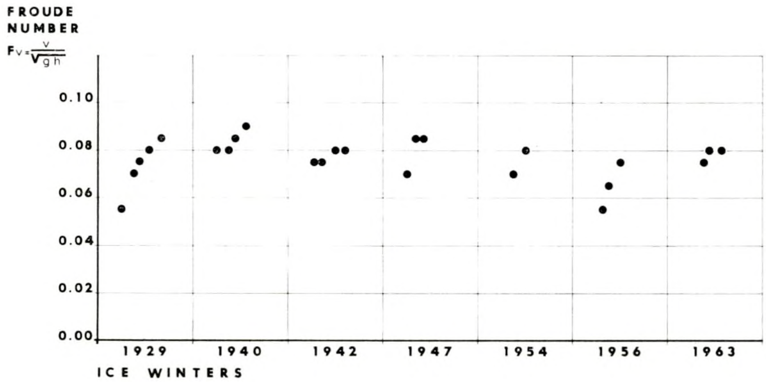


Fig. 9.

Froude number during formation of ice dam.

As of the 1956 winter good detailed information was available about the hydrodynamic situation the formation of ice dams during that winter was reproduced in an analogue computer. This computer is specially built for the computation of the tidal movement of the Delta area. An ice dam could be inserted as a special section with a variable resistance. It appeared that the methods used for the determination of the hydrodynamic situation in the other winters were giving reliable results.

With the aid of the analogue computer a study was made of the hydrodynamic conditions occuring in the riversections concerned after the completion of the Delta project.

During low upland discharges, which prevail during ice conditions, the discharge sluices in the Haringvliet estuary will be closed and the Froude number in the Werkendam-Zaltbommel area will be lower than the critical value. During higher upland discharges the Froude number will rise, but, within certain limits, it can be controlled with the aid of the Haringvlietsluices and other means in the river system. The investigations on this subject are not yet completed.

From the studies described in this paper the following general conclusions could be drawn :

— The discharge route of the ice to the sea through the southern Delta will be blocked due to the construction of a dam in the Volkerak.

— The possibility of discharging ice through the Haringvliet and the discharge sluice in the mouth of this estuary is highly problematic during continuing freezing periods with prevailing NE to E winds.

— If in the Haringvliet and Hollandsch Diep the ice cover should be removed in a systematic way the ice production of these wide estuaries should be considerably bigger than the production of the rivers.

— The formation of ice-dams is related to the hydrodynamic situation in the river section concerned ($0{,}06 < Fr < 0{,}09$).

From these conclusions it was possible to determine a general operational procedure which can be followed during ice periods after the completion of the Delta project. The main points are :

— During the freezing period no efforts should be made to break and discharge the ice in the Hollandsch Diep and Haringvliet, unless shipping interests would make this necessary.

— Ice-breaking activities for safeguarding the free discharge of upland water should be confined to the narrow (and deep) rivers of the Oude Maas, Beneden Merwede — Waal route.

— The hydrodynamic situation should be followed carefully and all possible means should be used to avoid a critical situation for the formation of ice-dams.

— During break-up and S or S.W. winds as soon as possible the ice of Hollandsch Diep and Haringvliet should be discharged to the North Sea.

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RÉSUMÉ

Des études ont été entreprises aux Pays-Bas sur les phénomènes qui se déroulent lors de la formation de la couche de glace sur les différents bras du Rhin. Ces études ont été orientées vers la situation future qui se présentera lorsqu'après l'achèvement du Projet du Delta, le mouvement de l'eau dans la région prise en considération, sera considérablement modifié.

Afin d'étudier les possibilités d'évacuation des glaces vers la mer, le mouvement des glaces flottantes dans les estuaires a été observé par marquage des glaçons au moyen d'un colorant.

Pour déterminer l'influence de la couche de glace solide sur la répartition des débits et des plans d'eau, on procèda à l'observation des niveaux aux échelles et à la mesure des débits. Ceci a permis de tirer des conclusions quant à la rugosité du fleuve avec une couche de glace solide.

La formation d'embâcle dans la région des cours d'eau à marée a été examinée et mise en rapport avec les conditions de l'écoulement.

Ces investigations ont permis d'établir la procédure d'exploitation à suivre après l'achèvement du Projet du Delta.

Les dégâts causés par la glace aux ouvrages le long des rives, ponts, quais et digues sont généralement peu importants. La navigation est pratiquement arrêtée lorsque les rivières sont entièrement gelées.

Pour favoriser le dégagement des glaces et prévenir autant que possible les embâcles, on utilise notamment des brise-glaces.

S. II - 4

PAPER

by

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METHODS OF PREVENTING ICE PROPAGATION IN CONFINED WATERS

1. INTRODUCTION

In the sea and river ports of the colder climatic zones, where port waters and approaches are ice-bound during winter seasons, considerable difficulties are experienced, ice preventing safe navigation and normal port operating, due to the propagation of broken ice floes, driven by wind, waves or current.

In a number of countries investigations are being carried out in order to find most adequate means of protection from drift-ice. This paper is concerned with discussing an attempt to apply an underwater pneumatic barrier to this effect.

Two systems are comprised in the complete pneumatic barrier assembly, viz,

— an air supply installation, consisting of a compressor, a piping system and valves, and of a perforated pipe horizontally disposed at the required depth in a water basin;

— air bubbles that rise from the perforated pipe towards the water surface, its interaction with the surrounding water medium and the effects of this interaction.

The first system of component parts decides on the possibility of adequate supply of air volume, the second one determines the character of action of the pneumatic barrier and its efficacy.

The principle of action of the pneumatic barrier, consisting in forming a discontinuity area within the water medium and horizontal currents at its surface, has been known for quite a long time. The water-and-air mixture moving upwards from the perforated pipe towards the surface gives rise to a vertical current, which changes into a horizontal surface flow, passing away in two opposite directions from the barrier.

As early as 1907 Ph. Brasher, an American, took his patent rights for the principle of action of an underwater pneumatic barrier for the attenuation of water waves. In the years to follow, owing to the importance of this discovery, this problem was further explored in a number of tests, but the results were far from satisfactory. Their main objective was to investigate the wave attenuation effects, while only non-numerous tests were concerned with other possible applications of an underwater pneumatic barrier.

These pneumatic barriers, the eventual assessment of their parameters and possible end-uses of these solutions in hydraulic engineering have been the object of interest of the Maritime Hydraulics Division, Institute of Hydro-Engineering, of the Polish Academy of Sciences, Gdansk. Within the last few years tests were run and investigations conducted in order to establish the relationships existing between the pneumatic barrier parameters and the effect of joint action of air bubbles with the water medium, attempting, among others, to assess the effects of such interaction on controling the movement of drifting ice masses in confined water areas.

2. ASSESSMENT OF CURRENT MAGNITUDE ON WATER SURFACE

While recognising the surface current to be the most important parameter of a pneumatic barrier acting on the ice drift, it was attempted to determine its nature and extent, both theoretically and by experiment.

In order to find the system of values on which the effects of air bubbles interaction with water medium depend, the dimensionless values were entered into the descriptive equations, striving to obtain the criterial number whereon it depends.

A detailed analysis of this phenomenon has shown that the horizontal velocities of water current will depend on the shear stress on the surface of division between the air and water media, τ. Consequently, the value sought for is the dependence of τ on the barrier parameters, while assuming :

— the stream of gaseous medium (air) flowing through a channel forming inside the surrounding liquid to represent the model of the phenomenon (Fig. 1);

— the axially-symmetrical stream of bubbles passing from one single hole in the submerged pipe to be an element representative for the entire pneumatic barrier of the tested type (the barrier to be continuous at the water surface level);

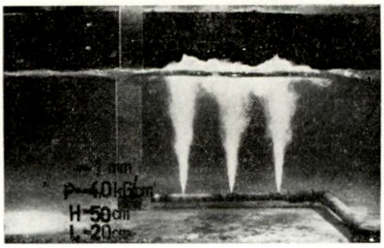

Fig. 1.

Air streams passing through water medium.

— the flow to be adiabatic and irreversible;
— the resistance factor, ξ, to be constant for the given problem, in view of the nature of the phenomenon at the division surface of phases, also owing to the drops being carried away, the considerable roughness and turbulent flow;
— water evaporation and transport of drops are disregarded;
— the barrier to be operated in stagnant water;
— the air outlet holes to be cylindrical in shape.

It should be explained that the adoption of a flow model as representing an axially-symmetrical stream, conical in shape, was not intended to provide an exact mathematical description of the phenomenon and of the flow-connected values distribution, but rather to summarize a set of parameters that may be of importance in this type of phenomenon.

By making use of the energy balance equation, the first law of thermodynamics equation, and the shear stress relationship on the surface of division of the air and water media (1), the shear stress relationship was found to be

$$\tau = f\,/N_a,\ N_b\,/$$

where Na and Nb are the adopted criterial numbers, according to formulae

$$N_a = \frac{Q}{H^2\sqrt{gH}}\ \frac{\rho'}{\rho} \quad \text{and} \quad N_b = \frac{H}{D}$$

Q — volume of air discharged, m^3/s.
H — depth of air outlet holes, m.
D — hole diameter, m.
ρ' — water density, kg/m^3.
ρ — mean density of gas in the stream, kg/m^3.
g — acceleration of gravity.

The mean density of air, ρ, was found from a relationship derived from Poisson' s adiabatic equation.

$$\frac{1}{\rho} = \frac{1}{\rho_0}\ \frac{P_0}{g\rho' H}\left[1 - \left(1 - \frac{g\rho' H}{P_0}\right)^{\frac{x-1}{x}}\right]\frac{x}{x-1}$$

ρ_0 — gas density at the outlet hole.
P_0 — outer pressure at the hole level.
x — Poisson's adiabatic exponent (for air = 1.4).

As previously explained, velocity u, is the function of stress τ, wherefore it was attempted to find the velocity rates as depending on the experimental values, in form of :

$$\frac{u}{\sqrt{gH}} = f\left(N_a,\ N_b\right)$$

Measurements were carried out of the velocities of water currents formed by the pneumatic barrier, the installation parameters being as follows : cylindrical hole diameters 1.0 to 4.0 mm, air pressure in the perforated pipe 0.0 to 5.0×10^5 N/m^2 and 30, 50 and 80 cm water depths, corresponding to N_a numbers within the interval of 0.05 to 35 and N_b numbers of 75 to 800.

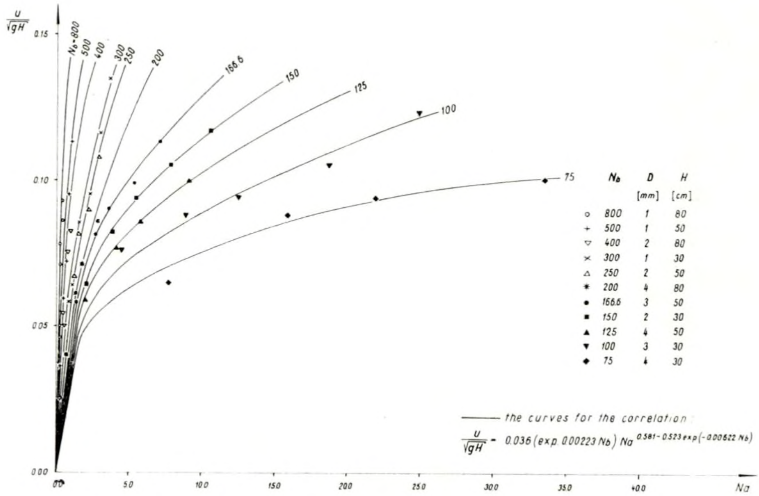

Fig. 2.

Relationship $\frac{u}{\sqrt{gH}} = f\ (N_a,\ N_b)$ for tests in the flume.

The results are presented in Figure 2. The family of curves is described by the relationship

$$\frac{u}{\sqrt{gH}} = 0{,}036\ .\ /\exp 0{,}00223\ N_b/\ .\ N_a^{\ 0{,}581-0{,}528\ .\ \exp /-0{,}00622\ N_b/}$$

To check the correctness of the obtained dependencies for other conditions, an additional tests series was run for greater depths of submergence, down to 9.0 m deep and hole diameters of 3.9 and 4.5 mm respectively (2).

The obtained results showed good coincidence with the defined correlation (Fig. 3).

From the performed tests and theory considerations it follows that water current velocities increase with volume of air supply, Q, and with the depth of installation level, H, while the dimensionless number N_a and N_b constitute the criterion of similitude for the tested type of barrier.

Before the commencement of practical solutions, work was carried out to determine the conditions of air flowing out through the cylindrical holes placed in the water medium, and a method was elaborated to assess the air output capacity per single hole.

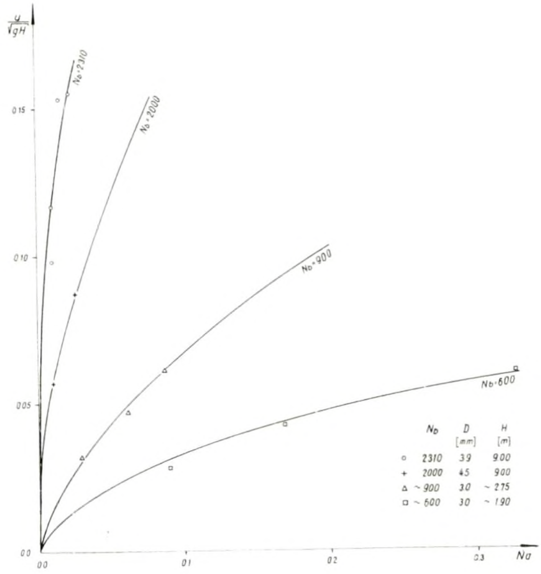

Fig. 3.

Composition of coincidence for the correlation obtained from the flume tests with the test results in another condition.

The objects for research were the conditions of air flowing out through the cylindrical holes. The adoption of a cylindrical shape for the perforations was dictated by the ease with which they are drilled in the pipe walls; they consequently represent what usually might be expected of similar solutions in practice. Tests have determined the air discharge volume, depending on the hole diameter, hole length, the diameter of the pipe in which holes were drilled, water pressure above the hole outlet and the degree of air compression. The purpose of those tests was to explain the effect of the mentioned factors on the discharge character of compressed air passing into the water medium and also to lay down the relationship enabling to calculate exactly the volume of air discharging from the perforated pipe.

To determine the air outflow into air medium through the holes, formula (3), for the determination of outflow velocity, is applied :

$$W = \sqrt{2 \frac{x}{x - 1} p_r v_r \left[1 - \left(\frac{p_o}{p_r} \right)^{\frac{x - 1}{x}} \right]}$$

W — gas outflow velocity, m/s.

x — Poisson's adiabatic exponent.

p_r — absolute pressure inside the pipeline, N/m^2.

v_r — specific gas volume, under measurement conditions, m^3/kg.

p_o — absolute pressure outside the holes, N/m^2.

Assuming air temperature inside the perforated pipe to be practically constant,

$$p_r \, v_r = RT_r \text{ or } p_r \, v_r = \text{idem.}$$

R = gas constant of air.

T_r — gas temperature under measurement conditions, Kelvin degrees.

The outflow velocity, w, is function of p_o/p_r ratio;

$$w = f \; / \; \frac{p_o}{p_r} \; /$$

Tests were run in order to determine the values for outflow ratio, $\alpha = \frac{W_{real}}{W_{teor}}$

and β_{kr} below which — under the given conditions — velocity ceases to increase. That type of measurement was necessary as we are unaware of the relationship that might exist between the respective outflow velocities of air-to-air and air-to-water discharges.

The evaluation of results from the tests carried out demonstrates that neither the hole diameter, the perforated pipe dia. nor the hole thickness-to-diameter ratio, nor even the depth at which the hole is placed under water have any essential effect on the outflow velocity, w.

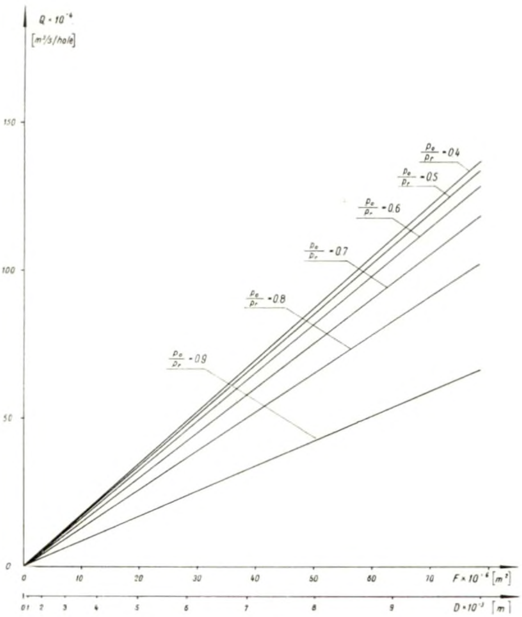

Fig. 4.

Diagram of determination of

$$Q = f \left[F\ (D);\ \frac{p_o}{p_r} \right],\ (\text{for } f_r = 286.5^{\circ}\ K)$$

The critical pressure ratio under which there is no increase in actual velocities of discharge under the test conditions, was found to be 0.4 (4). The diagram in Figure 4 was constructed from the experimentally established gas outflow and from the theoretical relationship to determine the outflow velocity; it serves for the determination of the volume of discharged air, Q, in the system of

$$Q = f \left[F\ (D);\ \frac{p_o}{p_r} \right]$$

for the hole diameters ranging from 1.0 to 10.0 mm and 0.4 to 0.9 pressure ratios, where :

Q — discharged air volume, m^3/s.

F — hole sectional area, m^2.

D — hole diameter, m.

3. ATTEMPTS TO APPLY UNDERWATER PNEUMATIC BARRIERS TO PREVENT ICE PROPAGATION

The action of surface currents generated by the underwater pneumatic barrier on drift ice was observed on various hydraulic structures and under different ice conditions. Site investigations were carried out on floating docks, on ferry landing berths and entrances to the port.

A Pneumatic Barrier for Floating Docks.

During the winter season, when the port and yard basins are ice-bound, ice blocks fill the spot when immersing a graving dock in water, rendering docking and undocking of vessels very difficult or impossible. To prevent ice inflow into the dock a pneumatic underwater barrier was applied.

First attempts were carried out about middle of the sixties. Perforated pipes, of 80 mm tube dia., and 8 mm holes spaced at 25 cm intervals from each other were installed on the dock. Perforated pipes were laid on both ends of the dock, between the dock side walls (Fig. 5).

Fig. 5.

General view of the air barrier installed in a dock and of the ice field in front of it.

Air volume at disposal amounted to about 5.0 N m^3/s, under 3×10^5 N/m^2 pressure acting on a barrier about 45 m long. The course of experiment was as follows : Before the dock immersion, compressed air supply was connected to the piping system. At the moment when the perforated pipe was flush with water level and scarcely covered with water (5-10 cm), ice props began to form, since the temperature drop due to decompression caused freezing in of water. Those props fell off as soon as the dock became filled with water 20-30 cm deep. When the immersion depth of about 50 cm was reached, ice floes only locally penetrated past the barrier and into the dock. With further immersion the barrier effect gradually became apparent. At 60-70 cm depths the inflow of ice was stopped altogether and a totally ice-free water strip emerged, over 20 m wide, extending in front of the dock (Fig. 6). Ships passing into the dock above the barrier dragged no ice floes with them.

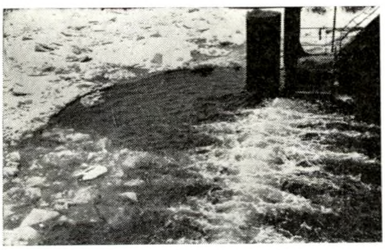

Fig. 6.

Ice field and ice-free zone in front of the dock, when dock drawing is 70 cm deep.

The successive experiment aimed at a reduction in air volume necessary for the barrier action; to achieve this the hole diameter was left unaltered, 8 mm wide, but the spacing of holes was increased, up to 1 m. The barrier was put to operate only after its immersion depth was well in excess of 10 cm, thus preventing the formation of ice props. Air supply was reduced after the immersion in water several metres deep, when the barrier effect was found sufficient to prevent ice drifting into the dock. Now this type of barrier proved to be less effective, as with the wide spacing of holes in lesser depths the particular air streams failed to operate in conjunction, and smaller floes sometimes penetrated into the dock site. It was only after several metres' depth above the dock floor and above the pipe outlet hole was achieved, that the air streams contacted with each other on water surface and successfully prevented ice from drifting into the dock.

After those practical experiences a different mode of solution was proposed for the piping system, to stop ice, even at the first moment of dock immersion. To do so, the pipe installation (the perforated pipe) was suspended around the dock apron. 1.5 m deep. With this solution the adopted spacing of holes was 30 cm and 3 mm hole dia. Somewhat earlier it was found that a pipeline with holes of 2 mm dia., immersed in water 2 m deep, originated a surface current of about 0.5 m/s current velocity (the air volume discharged being $Q = 0.3$ Nm³/min per hole at 6×10^5 N/m² pressure). This barrier effectively kept ice floes away but in practical operation it proved of little avail. The holes continuously submerged in water were soon stuck with impurities and the suspended pipeline installation was often damaged by the approaching tugboats. Ultimately it was decided to use a pneumatic barrier of the given parameters but laid on the dock floor and around its apron, permitting the passage of some ice above the dock area in the initial phase of dock immersion.

Similar ice-protecting barrier was used at the dry dock gate in one of the Polish shipbuilding yards. The barrier there is put to operate after filling the dock well and before opening its gate. After the gate is hauled away, the pneumatic barrier is provided at the dock entrance, preventing ice penetrating inside and being no obstacle for vessels to enter the dock.

A practical question now arises on how to match the parameters for a pneumatic barrier. Authors are of opinion that — to start with — one should take into consideration the practically available volume of compressed air, and to draft the barrier design in a manner enabling a full utilisation of all the air available at the moment when the dock is first being immersed. Next moment during immersion the output capacity of air can be reduced — provided however that the flow velocity induced by the barrier (which can be calculated from the formula given in the earlier part of this paper) must be in excess of the speed of water flowing into the dock. The latter is dependent on the speed with which the dock is being immersed and can be determined by a separate calculation. Least quantities of air are consumed while the dock is well immersed. Air consumption will also depend on some special circumstances of dock location (e.g., ice drift directed towards the dock by winds or currents). The barrier should be disconnected when the dock is refloated.

Several years of pneumatic barrier operation on docks of various types fully confirmed the efficient action of that type of barrier.

Pneumatic Barriers for Ferry Landing Berths.

In winter seasons drift-ice is the obstacle to prevent free manœuvring of vessels when berthing, this being particulary difficult in the case of ferry communication. Pneumatic underwater barriers were applied to make the water surface in such berths ice-free and to keep ice at a certain distance from the quay wall, leaving sufficient open-water track for unhindered navigation.

The action of two types of barriers was observed. The first one was laid at the berth of a motor boat. A perforated pipe, of 60 mm dia., with holes 3 mm dia., spaced every 0.5 m, was installed there. The pipeline length was 20 m. The total air volume necessary for the running of the barrier was 0.2 N m^3/s at 3×10^5 N/m^2 pressure. The perforated pipe was laid at the bottom of the basin, closely adjacent to the wall, and the extruding air moved upwards along the quay wall, generating a strong ice-repellent current. The barrier of the above parameters was found to operate with success.

Adequate matching of parameters for a pneumatic barrier as a rule will depend on local conditions, i.e., on the prevailing winds or currents that may shift the ice blocks towards the barrier.

Another barrier was installed at the landing place of a road communication ferry. The landing stage for this ferry was located in a recess inside the quayside wall, and both the river current and the wind tended to drive ice floes into that recess. When berthing, the ferry piled up and broke the floes, often resulting in damage to the facilities installed at the landing place. The ferry landing recess in question was about 15 m deep. Its width at the entrance was about 10 m, and at the movable mooring stage — 8 m. To free the landing place from the drift ice, sections of perforated pipe were installed in the water : one at the mooring stage inside the recess, another in its middle length and the third one at the entrance section.

On calculations, performated pipes of 50 mm dia. with holes of 3 mm dia., disposed every 0,5 m, were adopted for the purpose. The general demand for compressed air to keep the pneumatic appliance workable in all its sections was 0.56 Nm^3/s at 3×10^5 N/m^2 pressure.

The following operating cycle was adopted for the barrier servicing :

1. starting to operate section at the movable stage;
2. starting to operate mid-length section, at the moment when ice was displaced from the recess by action of the first section operating;
3. starting to operate the entrance section 1, after ice was displaced past the landing place area (and past the area of action of the second pipe section operating).

From that moment onward only one section of the perforated pipe might be left operating, being the third one, or the entrance section, keeping ice away from the landing place of the ferry. During the small and medium-icing periods, whenever broken ice floes were the only obstacle to navigation, the performance of the barrier was highly satisfactory and only isolated ice floes occasionally might be dragged with the ferry into the berthing area. However, with fast ice cover during severe winter seasons, the crushed ice sheets, though kept at some distance by the barrier, had no place to be drifted to and so the barrier was less efficient. Still, the ferry could land in the recess, which was entirely impossible prior to the barrier installation.

Both examples of the pneumatic barrier application demonstrate its positive effects when used to free berths and landings from ice. The choice of parameters for the barrier will invariably depend on the local conditions prevailing at the spot in which it was designed to operate.

Pneumatic Barrier at a Port Entrance.

It may happen sometimes that broken ice floes are floating in port approaches in the vicinity of the entrance to the port and are drifting there, pushed by wind or local currents, rendering safe navigation a risky affair, especially for smaller craft.

It was attempted to install underwater pneumatic barriers to keep drift-ice away from the port outskirts.

At the site where investigations were run the port entrance was 38 m wide and the pipeline was laid 9 m deep. Holes in the perforated pipe were spaced every 30 cm and outlet nozzles of 6 mm dia., were installed directed seawards and at a dip angle of 45° down from the horizontal. The air volume available for experiments was 60 Nm^3/min, at about 1.5×10^5 N/m^2 pressure in the pipeline. Under the test conditions the surface current thus induced attained maximum velocities of 1.5 m/s.

The thickness of ice cover during observations was 20 to 25 cm. The ice field stretched over a 200 to 250 m area from the spot where the pneumatic barrier was placed. The air temperature was + 1°C, water temperature + 2°C, wind force 5 to 6 m/s, wind direction — at right angles to the barrier, pushing the ice floes into the port (Fig. 7). During the experiments the barrier was started to operate many times, until ice propagation was stopped in the protected zone. It was then disconnected and the experiment repeated.

It was found that, under the given conditions, already after some five minutes (Fig. 8) ice was stopped and then further shifted away, indicating full efficacy of the equipment.

Fig. 7.

Ice pattern before the start of barrier action.

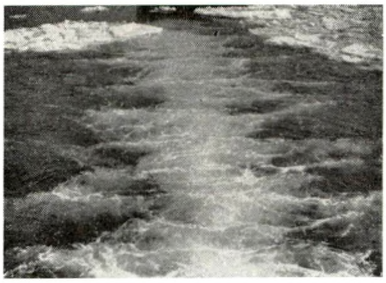

Fig. 8.

Transition situation 5 minutes past start of the air barrier action.

The rather easy effect on ice stopping makes us infer that the compressed air supplies might be handled in lesser quantities and therefore with more economy. Probably even here, as in the previous instances of the barrier application, its parameters have to be matched, depending on the local conditions.

4. CONCLUDING REMARKS

The conducted researches point to considerable efficacy of the pneumatic barrier action, when used for the purpose of preventing ice propagation in the vicinity of maritime structures and facilities. Particularly efficient are the underwater barriers installed at the ferry landing places and on the floating docks.

For the latter case also economic effects were calculated (4), which even under the Polish conditions, where winters are not very long-lasting, proved to be quite substantial.

The additional attraction of the pneumatic barriers is in their simple manufacturing and operating. They can be used wherever compressed air is available or installation of portable air compressors possible.

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RÉSUMÉ

Dans les ports maritimes et fluviaux d'une zone climatique froide où les hivers sont accompagnés de la formation d'une couverture de glace sur les étendues d'eaux portuaires ainsi que les accès au port, d'importantes difficultés se révèlent dans le domaine de l'exploitation des ports, causées par la dérive et le déplacement des débris de glaces flottantes sous l'effet du vent, de la houle et des courants. Dans ce rapport les auteurs présentent l'application d'un écran pneumatique immergé servant à la maîtrise des déplacements des glaces flottantes.

Le dispositif de maîtrise se compose : d'une conduite d'amenée d'air comprimé, d'un tuyau perforé-distributeur d'air comprimé dont les jets forment des bulles d'air remontant à la surface, formant l'écran pneumatique. Le dispositif d'amenée sert à l'approvisionnement du tuyau en air en quantité et sous pression convenables. Le tuyau contribue à la formation de l'écran pneumatique et à son fonctionnement efficace. Le principe de fonctionnement des écrans pneumatiques, les méthodes de calcul de leurs paramètres ainsi que leur application pratique font l'objet d'études de l'Institut Hydrotechnique de l'Académie Polonaise des Sciences à Gdansk, Pologne.

Les travaux de recherches concernant les écrans pneumatiques avaient en vue la détermination des interdépendances des paramètres de l'écran, l'interaction du jet d'air et de l'eau ambiante ainsi que l'efficacité de leur fonctionnement, entre autres dans le domaine de la maîtrise du déplacement des glaces flottantes.

Le paramètre le plus important étant le courant de surface généré par l'écran pneumatique, il a été étudié théoriquement et expérimentalement.

Les interdépendances suivantes ont été déterminées :

$$\frac{U}{\sqrt{gH}} = 0.036 \;.\; /\exp \;.\; 0.00223\ N_b/ \;.\; N_a^{\,0.581-0.528\ .\ \exp/-0.00622\ N_b}$$

représentent une famille de courbes reliant les vitesses de surface à des nombres de critère N_a et N_b, caractérisant les conditions de fonctionnement de l'écran. Les détails et les désignations sont présentés dans le rapport en langue anglaise.

Des travaux préliminaires ont été effectués avant les essais pratiques du dispositif, ayant en vue la détermination des conditions de l'écoulement de l'air comprimé par des ouvertures cylindriques submergées dans l'eau. Une méthode de mesure du débit d'air par une ouverture cylindrique a été mise au point. Dans le présent rapport, les résultats obtenus ont été présentés sous forme de dépendance du débit d'air et de l'aire de l'ouverture ainsi que du rapport entre les pressions dans la conduite à air comprimé et celle du milieu ambiant.

Des essais d'application pratique des écrans pneumatiques ont été effectués, notamment pour la protection des docks flottants et des cales sèches, pour des accostages des ferry-boats ainsi que pour la protection des entrées portuaires contre l'intrusion des glaces flottantes.

Après une série d'essais faits à l'échelle naturelle, on a constaté que, pour la protection des docks flottants, l'écran généré sur le périmètre de la coque donne les meilleurs résultats. Les auteurs recommandent de choisir les paramètres de l'écran de façon à obtenir le maximum d'efficacité du dispositif pour le volume d'air comprimé disponible au moment du début de son immersion. Pendant l'immersion même du dock flottant on peut réduire le débit d'air comprimé de manière que le courant de surface généré par l'écran (valeur à déterminer par la formule donnée au début du rapport) soit plus fort que le courant d'eau affluante au dock appelée par son immersion. La consommation minimum d'air comprimé a lieu soit au moment où le dock est complètement immergé, soit au moment où la quantité d'air comprimé dépend de la force du courant, soit de celle du vent causant la dérive des glaces vers le dock. L'efficacité des écrans pneumatiques s'est révélée excellente après plusieurs années de leur fonctionnement. Un écran pneumatique a été installé dans le but d'éloigner les glaces flottantes et de les maintenir à une certaine distance du quai ce qui permettait les manœuvres et l'approche d'un ferry-boat à quai. Dans ce cas le tuyau-distributeur d'air comprimé a été placé directement au pied du mur du quai, de sorte que les bulles d'air longeaient la paroi du quai, en formant à la surface un fort courant dérivant les glaçons au large. Pour protéger un quai d'accostage se trouvant dans une darse étroite, en retrait du quai, trois écrans ont été installés dont le fonctionnement successif servait à écarter progressivement les glaces flottantes et à les pousser au large de la darse. Pour arrêter l'intrusion des glaces flottantes à l'intérieur d'un port, le dispositif a été placé à son entrée, sur le fond marin.

Le choix des paramètres de l'écran pneumatique est intimement lié aux conditions locales : la force et la direction des vents et courants susceptibles de dériver un banc de glaces flottantes en direction de l'objectif protégé.

L'efficacité du fonctionnement des écrans pneumatiques s'est montrée particulièrement importante dans le domaine de la maîtrise des déplacements des glaces flottantes au voisinage des constructions et des dispositifs hydrotechniques. L'application des écrans pneumatiques à la protection des quais d'accostage des ferry-boats et des docks flottants a donné des résultats particulièrement spectaculaires, dont les effets économiques ont été très appréciables même dans les conditions des ports polonais de la Baltique, où l'hiver est de relativement courte durée.

En ce qui concerne l'installation et l'exploitation des écrans pneumatiques, elles sont très simples à condition de disposer soit d'une source adéquate d'air comprimé fixe, soit, de compresseurs transportables à débit et pression convenables.

S. II - 4

PAPER

by

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NAVIGATION OF ICE-COVERED WATERS. SOME NEW INITIATIVES BY THE UNITED STATES OF AMERICA

I. INTRODUCTION

Maintenance of navigation and navigational aids for the ice-infested waters of the United States of America is varied, complex, and subject to important new technical initiatives underway on the part of both private industry and the Federal Government. During winter and early spring, ice cover hinders or prohibits navigation on the East Coast of the United States as far south as Chesapeake Bay, throughout all the Great Lakes, the Upper Mississippi River and its principal tributaries — the Ohio, Illinois, and Missouri Rivers, and in the Cook Inlet and the Bering Sea of Alaska. North of the Bering Strait, year-round ice cover extends throughout the polar basin.

Until less than a decade ago, Federal policy was not to make a major effort to extend the shipping season in any of these waters. Ice navigation technology and practices employed during this period for inland waterways are well described in the paper published in 1957 by Aune, Beaudin and Borrowman (1). However, the mid-western United States found itself experiencing an increasing handicap in both domestic and foreign markets because of this seasonal shipping pattern. Accordingly, the U. S. Congress has taken two initiatives. The first, in 1966, called for the Board of Engineers for Rivers and Harbors, U. S. Army Corps of Engineers, to determine whether modifications could be made in navigational project plans with regard to the practicability, means, and economic justification for providing year-round navigation on the Upper Mississippi River. The study is currently scheduled for completion in 1976. The second initiative, as expressed

(1) AUNE, C.A., BEAUDIN, L.A., and BORROWMAN, J.K., « Effects of ice on Inland Navigation », Communication 3. Section I. XIX Permanent International Navigation Congress, London, England, 1957.

in Section 107 (b) of the River and Harbor Act (Public Law 91-611) approved on 31 December 1970, calls for :

> « ... a program to demonstrate the practicability of extending the navigation season on the Great Lakes and St. Lawrence Seaway. Such a program shall include, but not be limited to, ship voyages extending beyond the normal navigation season; observation and surveillance of ice conditions and ice forces, environmental and ecological investigations; collection of technical data related to improved vessel design; ice control facilities, and aids to navigation; physical model studies; and coordination of the collection and dissemination of information to shippers on weather and ice conditions. The Secretary of the Army, acting through the Chief of Engineers, shall submit a report describing the results of the program to Congress not later than July 30, 1974. »

In addition to this legislative attention, discovery in 1968 of the largest oil field in North America at Prudhoe Bay on the shores of the Arctic Ocean focused political attention on the need to improve the nation's polar transportation capabilities. On 23 August 1968, Secretary Alan Boyd issued the following Department of Transportation (DOT) order :

> « DOT will investigate the feasibility of extending the shipping season so as to permit development of ocean transportation to and from Arctic Alaska... »

As a result of the economic considerations and political interest cited above, the goal of cost-effective commercial navigation through ice-covered waters is being pursued at an increasing rate within the United States. These efforts are primarily three fold : improved knowledge of the controlling physical environment; the design, construction and testing of ice-reinforced vessels and barges with their associated waterways and navigational facilities, and the acquisition of continued operational experience leading to reliable scheduling, marked cost reduction, and improved operational safety. This paper cites examples for the following geographic regions : Great Lakes and the St. Lawrence Seaway, the Mississippi River System, the New England coastal region, and Alaskan waters.

II. EXTENDED NAVIGATION SEASON DEMONSTRATION PROGRAM FOR THE GREAT LAKES AND THE SAINT LAWRENCE SEAWAY

1. Organization and funding :

This three-year demonstration program is directed by the Winter Navigation Board, a special multi-agency organization chaired by the U. S. Army Corps of Engineers. «Lead Agencies» responsible for carrying out the «Winter Navigation Program» are :

Ice Information, Lake Survey Center; Ice Navigation, Coast Guard; Ice Engineering, Corps of Engineers; Ice Control, St. Lawrence Seaway Development

Corporation; Ice Management in Channels, Locks and Harbors, Corps of Engineers; Economic Evaluation, Corps of Engineers; and Environmental Evaluation, Environmental Protection Agency.

Funding of these efforts is from the $6.5 million authorized to be expended under the enabling Act for the three-year demonstration. Additional funds are expended by each participating agency as part of their regular governmental activities which lend support to those of the Demonstration program. A distribution of the Demonstration's funding by functional category and by agency is shown in Table I. Because funding did not become available until late in calendar year 1971, many of the planned technical efforts did not reach full-scale during the 1971-72 winter.

TABLE I

Demonstration program of extension of the navigation season on the Great Lakes — St. Lawrence Seaway

A. **Funding by study item and year(*)**

(Thousands of Dollars)

Fiscal Year (end 30 June)

Study Item	1972	1973	1974	Total
Ice information	275	295	754	1,324
Ice navigation	170	340	780	1,290
Ice engineering	60	150	825	1,035
Ice control	100	250	350	700
Ice management in Harbors, locks and canals	30	207	898	135
Environmental evaluation	40	85	68	360
Economic evaluation	5	20	100	185
Program management	60	153	258	471
Total	740	1,500	4,260	6,500

B. **Funding by participating agency(*)**

(Thousands of Dollars)

Agency	1972	1973	1974	Total
Army corps of engineers	345	1,450	1,786	3,581
St. Lawrence Seaway Development Corp	100	579	293	972
U. U. Coast Guard	162	532	339	1,033
Maritime administration	50	207	55	312
National weather ser.	33	70	90	193
Lake survey center	32	85	47	164
Environmental protection agency	2	26	56	84
U. S. Bureau of sports fishery and wildlife	6	66	39	111
U. S. Bureau of outdoor recreation	10	20	20	50
Total	740	1 500	4,260	6,500

(*) Subject to funds actually appropriated by the Congress.

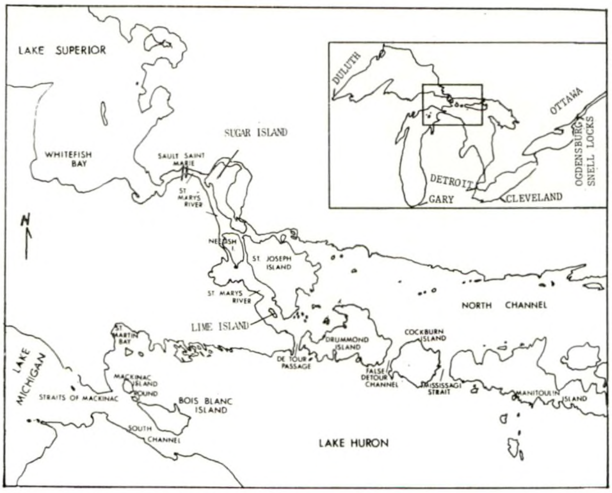

Fig. 1.

Locator map for the Great Lakes-St. Lawrence Seaway area.

Plan général de la région des Grands Lacs et du Canal Maritime du Saint-Laurent.

2. **Ice information :**

This effort monitors, observes, analyses, predicts and disseminates ice data to the various user groups and program elements in the Great Lakes - St. Lawrence Seaway area. The program centers about an « Ice Navigation Center » operated by the Rescue Coordination Center, Ninth Coast Guard District Headquarters, in Cleveland, Ohio in conjunction with the National Weather Service and the Lake Survey. Techniques of surveillance include aerial photography of restricted channels, ground surveys of ice characteristics, measurements of ice thickness, snow cover and extent of ice coverage at 25 Lake Survey and 33 Coast Guard stations, aerial reconnaissance flights using trained ice observers, and monitoring of water levels at key coastal points. The ice data from the various shore units and the aerial reconnaissance are transmitted by radio twice a week to the Ice Navigation Center and also to the National Weather Service in Detroit, Michigan. The Ice Navigation Center is also connected by Bell Dataphone facsimile to the Canadian Ice Forecasting Center in Ottawa, Ontario. The Ice Navigation Center then issues approximately five times a week by teletype and by radio broadcast an ice summary message to all major commands in the District for further dissemination to the shipping industry. An ice forecast provided by the National Weather Service is also included in the message. The message is mailed to over 70 users, mainly shipping interests, and is also available for personal pickup at the Sault Ste Marie Locks and at 46 Coast Guard stations on the Great Lakes.

In addition to the effort directed towards establishing the regional synoptic ice picture, the Corps of Engineers has a localized observation program established for the The St. Mary's River providing time lapse photography and comprehensive measurements of water flow rate. Aerial mapping of the ice-covered U. S. portion of the St. Lawrence Seaway has been contracted for by the St. Lawrence Seaway Development Corportation, thereby providing 15 to 20 mapping flights during December and January and 10 to 15 mapping flights during March and April, from Cornwall Island to eastern Lake Ontario. Regular observations of surface ice characteristics, supplemented by air/water temperature and solar radiation readings, are being used by the Corporation to compile ice formation and decay profiles. It is also extending and improving existing freezing degree-day tables relative to the ice cover of the St. Lawrence River.

The National Weather Service at Detroit, Michigan is also using available ice surveillance data, including that from satellites, to prepare an ice forecasting manual and to determine the improvements needed in the forecasts themselves. Potential improvements include use of the thermocline depth, the heat budget, heat coupling values, satellite-derived temperature data, infra-red imagery and ice climatology in actual preparation of ice forecasts. Also included in the forecasting manual will be methods for using the concepts of ice dynamics to predict ice fracture, wind-driven ice, and packing of ice against shorelines and in harbors.

3. **Ice navigation :**

This effort involves three areas of activity : icebreaking and channel clearing; improved aids to navigation system, and commercial vessel operations. In past years, the Coast Guard has had only the cutter MACKINAW (3,000 tons and 10,000 shaft horsepower) assigned to heavy duty icebreaking service in the Great Lakes. Designed specifically for Great Lakes icebreaking and equipped with a bow propeller, the MACKINAW can, because of her relatively shallow draft of 19 feet (5.7 m), work in all the major channels of the Great Lakes. However, the vessel must cover five major lakes; accordingly, the ocean-going WIND-class icebreaker EDISTO (displacement of 6,515 tons and 10,000 shaft horsepower) has had her home port shifted from Boston, Massachusetts to Milwaukee, Wisconsin as part of the winter navigation program. The deeper draft of the EDISTO (29 feet or 8.7 m) has mean she can enter only about six Great Lakes ports when in normal ballast. Because of this draft problem, the EDISTO was assigned the Straits of Mackinac region while the MACKINAW assisted ore carriers through Whitefish Bay and the shallow St. Mary's River. Icebreaking tugs 110 feet (33 m) in length with 1,000 shaft-horsepower have been found to be very useful in breaking out ore carriers pinched in shore and floe ice.

During this first winter, the Coast Guard has been investigating the possibility of introducing new concepts of icebreaking technology applicable to existing tugs and to any future lake icebreakers. One of these experiments installed an air/water bubbler system near the keel of the CGC RARITAN, a 110 foot (33 m) tug. Connected by valves to the release ports were a 225 horsepower, 3,500 gallon (12,265 liter) per minute water pump and a 900 cubic foot (25 m^3) per minute air compressor providing 100 pounds per square inch (7 kg/cm^2) pressure which, when operating, were capable of reducing hull friction by bubbling air or water along the hull. Conducted in sheet ice of Green Bay during February 1972, results of these tests will supplement findings of a similar technique utilized by shipbuilders at Wartsila, Finland.

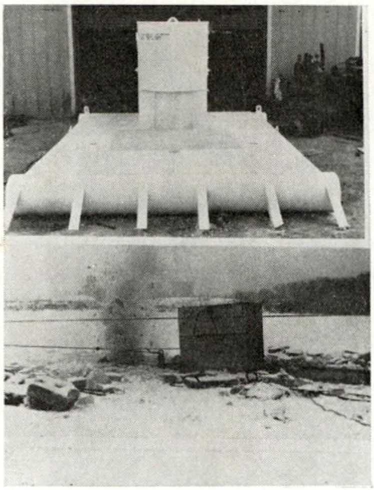

Fig. 2.

Experimental icebreaking barge using underwater repetitive explosions off Muskegon, Michigan during February 1972. Top : Barge as built by the Southwest Research Institute; explosive gases escape through port in center picture. Bottom : Barge under actual field test.

Un chaland brise-glaces utilisant des explosions répétitives sous l'eau près de Muskegon (Etat de Michigan) en février 1972. Au dessus : Le chaland, construit par Southwest Research Institute; les gaz explosifs s'échappent par la cavité au centre de la figure. En dessous : Le chaland en service actuel.

An ice clearance method using the « Repetitive Explosive Device for Soil Displacement (REDSOD) » concept patented by the Southwest Research Institute also underwent field experimentation at Muskegon, Michigan during February 1972. This experiment used a 2-cubic foot 57 (liter) firing chamber to detonate a propane-air mixture and release the resulting gases rapidly from a ram bow extending under the ice cover (Figure 2). Each explosion, which can take place at six second intervals, broke an area of about 200 square feet (18.6 m^2) of 18 inch (46 cm) hard blue ice. However, the experiment suffered from not having solved the problem of how to dispose of the broken ice; it is still not known whether it is better for the broken ice to be lifted upwards and left on top of the shorefast ice or whether it is better for the broken ice to be showed under the fixed ice cover. Either way would give a temporarily clear channel, something not obtained with today's icebreaking techniques.

A second unconventional icebreaking experiment in March 1972 used an experimental 22-foot (6.6 m) long ice cutter barge built by Consultec, Inc. Field tests in a Pensylvania lake compared the practicability and efficiency of using vertically mounted routers (cutters) versus « chain saws » in ice about two to four inches (5 to 10 cm) thick; initial results indicated that the « chain saw » approach was better and merited further exploratory development.

Great Lakes shipping operators continue to emphasize that winter navigation will be hazardous until an adequate all-weather aids to navigation system is available, particularly for constricted, winding, dredged channels such as that of the St. Mary's River. During the winter of 1971-72, the Coast Guard has tested in Whitefish Bay, at Sault Ste. Marie in St. Mary's River, in the Mackinac Straits, and in Western Lake Erie 5×18 foot (1.5×5.5 m) ice buoys with a modified lighting system, structural strengthening, and a grillage over the lantern for protection when the buoy is submerged under the ice. One of the test sites, the Detroit East Outer Entrance Light, is the same position where the Swedish « push-down, pop-up » buoy failed during the previous winter. The goal of the ultimate configuration, of course, is a buoy which remains above the ice, upright, free from surface ice, and with moorings capable of keeping the buoy on station until the area is so ice-covered that it is no longer traversible by ships. Six X-band radar transponder beacons (RACONS) were also tested, as were nine expendable, inexpensive ice structures placed on shore fast ice once ice had formed. These latter structures consisted of three foam-filled, 55 gallon (209 liter) oil drums, interlocked, and equipped with guys for ice anchoring.

Two experimental navigational approaches utilizing laser beams are also being tested. During the 1971-72 winter, the Maritime Administration initiated testing of a Precise Laser Navigation System (PLANS) designed ultimately to provide attitude and cross track information as well as distance and rate of closure to strategically placed shoreside reflectors. The Coast Guard plans to experiment with a laser beam oriented along a standard range for providing a «wire in the sky effect» (l'effet d'un «cable dans le ciel») during night and periods of limited visibility such as light snow, rain and slet. With this new technique, if the laser beam passes a few hundred feet over the vessel, the distance off the center of the beam should be readily discernible.

The Coast Guard is also experimenting with two different concepts of electronic navigation for ice-covered channels. The first of these to be tested was the Coast Guard Loran Assistance Device (COGLAD), a device which prints on an X-Y recorder a ship's track derived from Loran-C signals. The first demonstration of this device in the Great Lakes area took place during October 1971 aboard the CGC ACACIA in the St. Clair River; the test indicated accuracies of the order of $\pm$ 50 feet ($\pm$ 15 m).

The second concept is the Wire Guidance Aid to Navigation System (WIGANS). Although the « follow the-wire » concept was initially tested over 50 years ago (1), the technique has been simplified and made much more portable. In the Coast Guard experiment (2), a 3/8 inch (1 cm), direct burial cable with two =//=12 (American Wire Gauge) electrical conductors was laid for about five miles (8 km) along the Muskegon Channel between Lake Michigan and Lake Muskegon in early 1972. The cable was energized by a 400 Hz motorgenerator set, the circuit completed by ground return, and the resulting magnetic field monitored by two sensing coils mounted on each side of the CGC WOODBINE as the vessel sailed along the ice-covered channel.

Resulting voltages induced in each coil are related to the transverse or crosstrack position of the ship to the channel cable. The resulting signal was displayed by an inexpensive oscilloscope in such a way that the helmsman can interpret the signal so as to know whether « the ship must come left (or right) to be directly over the cable (Figure 3). In the Muskegon Channel, where water depths were

(1) Crossley, A., « Piloting vessels by electrically energized cables », *Proc. Inst. Radio Engineers*, Vol. 9, number 4, March 1921.

(2) McIntosh, J.A., « Follow-the-wire » marine aid to navigation system: Report on initial demonstration installation, *Final Report*, Proj. 726450, USCG, May, 1972.

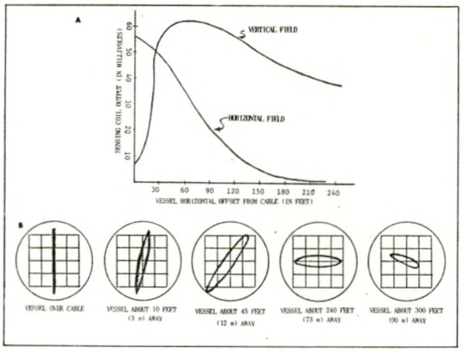

Fig. 3.

« Follow-the-Wire » technique utilized experimentally in Muskegon, Michigan navigational channel during January 1972. A : Measured horizontal and vertical fields (in millivolts) generated at different distances from the leader cable. B : Typical signal displays on oscilloscope for different vessel distances (horizontal) from the cable.

La technique « follow-the-wire » (suivre le câble métallique) soumise aux essais dans le canal de navigation à Muskegon (Etat de Michigan) en janvier 1972. A : Force électromagnétique horizontale et verticale mesurée (en millivolts) produite à différentes distances du câble central. B : Signal typique sur l'oscilloscope pour différentes distances horizontales entre le navire et le câble.

of the order of 30 to 50 feet (9 to 15 m), usable signals were received at distances of up to 300 to 350 feet (90 to 105 m) from the cable. The tests found the CGC WOODBINE to be able to easily, accurately and repeatedly navigate the track designated by the cable, irrespective of visibility and ice conditions. The system, however, still needs testing by commercial users to determine the effect of metallic cargo, the behavior of the signal when a ship does a wide swing in a marked turn, and the effects of burying the cable in the channel to avoid having the cable shifted by currents of natural and vessel origin.

With respect to commercial vessel design, the Maritime Administration has work underway to determine the optimum bow configuration for an ore ship in an ice model tank at Wartsila, Finland, as well as experimentation in a United States ice model tank with various devices to reduce ice resistance. Once the results of the models tests are known, the Maritime Administration and the Coast Guard plan to sponsor a full-scale test using a regular commercial Great Lakes vessel. Early indications of these studies suggest that today's ore carriers have too blunt a bow and too little power if they are to engage successfully in year-round navigation.

4. **Ice engineering :**

At the present time, a general lack of information exists relative to the forces created by a vessel pushing strong winter ice against a shore structure such as a piling, a pier, wharf or dam. Hence, a comprehensive observational program is now underway by the U. S. Army Cold Regions Research and Engineering Laboratory at Hanover, New Hampshire. Here, after up to eight inches (20 cm) of ice have been grown in four feet (120 cm) of water that fills a 22 × 22 foot cold room (6.7 × 6.7 m), a piling is pushed horizontally into the floating ice sheet. Circular and flat piles from 1.6 to 36 inches (3.8 to 90 cm) wide have also been tested at various speeds as have wedge shaped piles of 45° and 90°. Plans call for testing sloping piles as well. Various types of ice failure have been noted and theories are now being developed to explain each mode of failure.

5. **Ice control :**

Ice problems are particularly severe at the end and beginning of the navigation season in the St. Lawrence Seaway. Hence, both U. S. and Canadian navigation and power entities have had continuing programs of ice control since the seaway opened in 1959. These ice control structures vary from relatively simple ice anchoring cables to multimillion dollar movable gate dams and diversion works. Typical experimentation during the winter of 1971-72 replaced the previous year's ice anchorage cable system in the Wiley-Dondero Canal immediately upstream from the Snell Lock, near Ogdensburg, New York, with an ice boom made of logs cut from a local forest and held in place by concrete anchors embedded in the bottom (Figure 4). The St. Lawrence Seaway Corporation has

Fig. 4.

Ice boom in operation on January 16, 1960, between Ogdensburg, New York and Prescott, Ontario to keep broken ice out of ferry route and away from intakes of the Moses - Saunders power dam on the St. Lawrence Seaway. (Photograph courtesy of Power Authority of the State of New York).

Défenses flottantes utilisées le 16 janvier 1972 entre Ogdensburg (Etat de New York) et Prescott (province d'Ontario) pour retenir la glace hors de la route du bac et loin des prises d'eau du barrage hydroélectrique Moses-Saunders sur le Canal Maritime du Saint-Laurent. (Photo Ministère de l'énergie de l'Etat de New York).

also let three basic conceptual design studies for ice-stabilizing structures to leading engineering firms that would provide better methods for facilitating winter navigation while avoiding interference with the flow of the river. In addition, the St. Lawrence Seaway Development Corporation has placed blankets made from 1-3/8 inch by 24 inch (3.5 × 60 cm) closed cell polyethylene foam plank on the surface of water and on the relatively thin ice along the downstream guide wall at the Snell Lock and under the bridges of the guide wall extension. An appraisal is now underway of the effects these planks had on differing widths and depths of water relative to inhibition of buildup of ice around hydraulic structures exposed to below freezing temperatures.

6. **Ice management in channels, locks and harbors :**

Difficult ice management problems in channels, in harbors and lock entrances, in berthing areas, and operating shore facilities continue to exist during severe winter weather. Shipping channels are particularly susceptible to ice jamming when frequently broken tracks permit the resulting ice floes to pack into the narrow channels under the effect of strong currents. A major problem of the extended navigation season is the breaking of the natural ice bridges which normally form across channels once navigation ceases during the winter months. To overcome problems of this type, the Army Corps of Engineers installed and tested several ice control devices and techniques in St. Mary's River below the Soo Locks during the winter of 1971-72. Two major projects were undertaken in particular. The first was directed towards providing a continuing ferry service between the mainland and Sugar Island, and the second was to improve the ability to steer ore carriers around the 70° bend near Lime Island (See Figure 1).

In the case of the Sugar Island ferry, the Corps of Engineers installed an air-bubbler « flush » system at the mainland ferry slip. A gentle, continual current of air under water at the ferry slip kept the water from freezing. As the ferry approached, should broken ice have accumulated in the slip, a large blast of air was released from the bubbler which forced the ice from the slip. This flushing action was remotely controlled from the ferry operator as he approached. As a secondary measure to assure operation of the ferry, a barge was moored upstream of the mainland ferry slip to hold shore-fast ice in place, thereby keeping the ice from breaking off into the navigation channel and eventually hindering ferry operations. A Navy « mule », which is nothing more than a surplus propulsion unit used originally to power landing craft, was attached to the barge to further aid the ferry operations. The « mule » in this case provided additional flushing action as needed at the slip and for a distance out into the channel. The barge and « mule » were removed, however, for the additional turbulance caused by this unit made docking of the ferry difficult. In practice, the shoreside system worked very well. Nevertheless, the broken ice at mid-channel eventually became so heavy that the ferry could not operate on a reliable schedule and a Coast Guard 110 foot (33 m) tug was subtituted on an emergency basis as needed during January 1972.

In the case of the Lime Island turn, the Army Corps of Engineers concluded as early as 1969 that a 10-mile air bubbler system between De Tour Passage and Lime Island was the most feasible way for keeping the channel open. The seriousness of the ice problem for this stretch of river was described by Mr. C. Beukema, Vice President of United States Steel Corporation, at the Department of Transportation's Season Extension Seminar in May 1971, as follows :

« ... Probably because of little current, the ice formation is early and heavy in this area. On January 12 (1971), the ice here was 8 to 10 inches (20.32 to 25.4 cm) thick and became thicker principally as the ships rafted it to the side into thicker ledges. Turns in such conditions are difficult for the « long ships » that could use a « sideways » hinge in the middle for this maneuver. Substantial go-ahead power is diverted to side thrust against the ice in these turns ... ».

In the winter of 1970-71 encouraging results had already been achieved by the Corps of Engineers using a bubbler system in Duluth Harbor adjacent to the Seaway Port Authority Dock. Here polyethylene pipe 1.5 inches (3.75 cm) in diameter had been laid as a near rectangle 1,600 feet (480 m) long parallel to the dock, 950 feet (285 m) wide at the northern end and 900 feet wide (270 m) wide at the southern end, with metal orifices installed at 15 foot (4.5 m) intervals on the 1,600 foot (480 m) sides. The pipe was installed at a depth of 27 feet (8 m), and ice thicknesses over the pipe generally varied from 20 to 24 inches 50 to 60 cm). Operation of the installation began on 8 March 1971, and bubbling terminated on the easterly line on 24 March 1971. The bubbler system created open areas of water over the pipe about 25 feet (8 m) in width, while reduced ice thicknesses extended back from the open areas. When the Coast Guard 180-foot (54 m) cutter WOODRUSH got underway on 25 March 1971, she found the harbor ice outside the bubbler system area to have a thickness of up to 23 inches (57 cm) that required alternate ramming and backing movements in order to proceed. As soon as the WOODRUSH entered the bubbler test area, the ice cover cracked in the direction of travel for the entire 1,600 foot (480 meter) length of the test area, and the buoy-tender proceeded non-stop through the area without difficulty.

With the Duluth bubbler experiment as background, the Winter Navigation Board selected the Lime Island site for the 1971-72 winter bubbler experiment rather than other areas of the Great Lakes or the St. Lawrence Seaway in the belief that activities should take place where the vessels were running.

The Lime Island site was ideally located since there was a joint effort between industry and the Coast Guard known as « Operation Taconite » to ship ore from Minnesota to the Gary, Indiana area past the normal closing date for the run, i.e., to operate from 17 December 1971 to 31 January 1972.

Design of the bubbler system was completed on 24 November 1971, and all materials were purchased and fabrication of the line completed by 11 December 1971. The actual bubbler line consisted of plastic pipe of 2 inch (5 cm) inside diameter with 5/64th inch (2 cm) holes spaced at 15 foot (4.5 m) intervals. Compressed air was forced into the line from onshore air compressor at between 25 and 30 pounds per square inch (1.8 and 2.1 kg/cm^2). Air escaped from holes in the plastic pipe at a rate of approximately 0.8 CFM (225 1/min), and rose to the surface in a divergent, inverted cone pattern. The rising air bubbles induced a current of the warmer (sometimes as little as 0.6° warmer) bottom water to the surface, thereby melting the ice cover. Towed to the Lime Island site on 12 December 1971 by a Corps of Engineers vessel, the assembled bubbler was installed by 21 December 1971. The bubbler extended approximately 3,000 feet (910 m) along the channel and had a feeder pipe of 5,000 feet (1,520 m). The air-filled pipe was anchored near the bottom by lines attached to concrete weights. The bubbler was put into operation on 20 December 1971 for eight hours a day; on 3 January 1972, 24 hours per day operation was commenced. By 5 January 1972, shippers had already reported that the bubbler was keeping the track above it open and free of ice. In the immediate area of the bubbler, the ice also appeared to be thinner than at some distance away. Although the open area eventually froze during a spell of extremely cold weather, the channel ice stayed thinner over the bubbler line throughout the remainder of the shipping season which actually closed on 1 February 1972.

7. **Environmental and economic evaluation :**

These two aspects of the « Winter Navigation Program » were just getting underway during 1972. They include development of plant, wildlife, and fishery baselines, as well as compiling both the adverse and beneficial impacts caused by icebreaking operations and to commercial vessels associated with the extended shipping season.

8. **Summary of accomplishments to Date :**

The first year of the Great Lakes Shipping Season Extension Program made definite progress towards better defining the technical and socio-economic problems that must be overcome to guarantee more than a 250-day shipping season in initiating the research and development necessary to overcome these problems, and in developing actual field expertise with an extended shipping season. For example, because of a shipping strike on the eastern coast of the United States, 135 ocean-bound vessels were still on the Great Lakes as late as 4 December 1971 even though the previously announced official St. Lawrence Seaway closing date was 12 December 1971; yet all of these vessels were able to reach the sea by keeping the Seaway open until 20 December 1971. Similarly, in « Operation TACONITE », the seven ore carriers of the United States Steel Corporation carried cargoes of non-freezing iron ore pellets through the Soo Locks as late as 1 February 1972. As a result, an additional 1,976,000 tons of cargo moved through the locks after their normal closing date of 15 December.

III. WINTER NAVIGATION DIFFICULTIES ALONG UPPER MISSISSIPPI RIVER SYSTEM

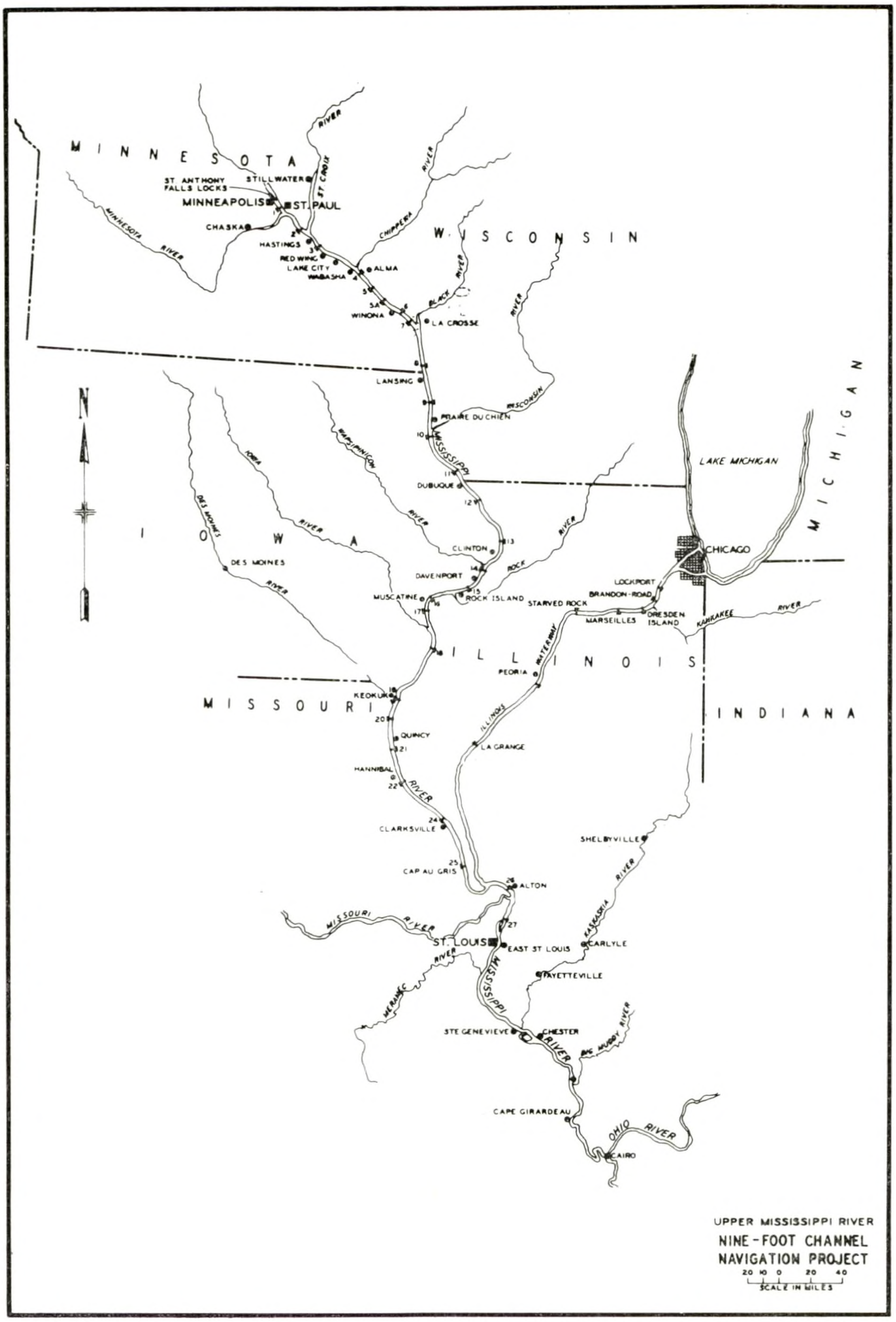

Fig. 5.

Locator map for the Upper Mississippi River.

Plan général de la région du haut Mississippi.

TABLE II

Difficulties involved in year-round navigation on the upper Mississippi River system

Problem	General Remarks	Possible Solutions
I. *Lock and Dam Sites.*		
a) Broken Ice in Lock Chamber.	Down-bound tows push much ice into the lock that must be locked through first.	Ice excavation techniques being explored by Coast Guard may give clean channels.
b) Icing of Recesses in Lock Miter Gates.	With three exceptions, all locks are mitertype gates; broken ice drifts or is pushed by tows into gate recesses. Resulting less than full lock width delays traffic and exposes gates to tow damage.	Bubbler system; introduction of ground water flow; flush system using pumps or small tug boats; insulating foam; heating system; replacement of miter gates with different gate styles; ice sluice on down stream gates.
c) Ice Buildup on Lock Walls and Gates.	Ice accumulates on lock walls each time lockage is made; eventually ice shelf as much as 3 feet (1 m) wide forms at upper pool elevation.	Use of heating system or unique coatings that are non-adhesive to ice.
d) Freezing of Lock Valves.	Ice freezing on and adjacent to lock valves causes valve sticking followed by harmful sudden closure.	Heating systems.
e) Maintenance of Locks and Swing Span Bridges.	Maintenance scheduled for closed navigation season.	Additional work crews to reduce down time.
f) Passing Ice at Navigation Dam.	Unusual warm spells cause movement of ice cover in navigation pools and tributary streams, thereby creating situation when large quantities of broken ice must be passed over the dams into the downstream channel. Tows and barges caught in resulting ice gorge must be extracted by powerful towboats before being pushed against next downstream dam.	Use of auxiliary locks; place bubbler systems in front of dams.
II. *Navigation of River Reaches Between Locks.*		
a) Ice Cover.	Few tows manage to navigate as far north as Quad Cities (Lock 14) during February without incurring damage to the towboat or the barges.	Introduce a new Coast Guard class of efficient, economical ice breaker or icebreaking barge especially designed for river use. Study use of thermal discharges from thermal power plants — such plants can effect ice cover two to four miles (3.2 to 6.4 km) downstream.

Continuation page 16.

TABLE II *(Continued)*

Problem	General Remarks	Possible Solutions
b) Ice Fields.	Fields of broken ice may extend to channel bottom, thereby making tows practically immobile.	Develop improved methods of anchoring river ice.
c) Ice Gorges.	Extremely difficult and generally impossible to navigate through an ice gorge.	Develop improved methods of anchoring and storing river ice utilize blasting with « ANFO » and dusting with heat absorbing materials such as glassy coal slag.
d) Difficulty in Navigating River Bedns.	Towboats and barges turn in ice cover by a series of gradual steps involving alternate forward and backward movements.	Utilize Coast Guard icebreaking equipment to keep open channels at turns.
III. *Associated Problems.*		
a) Difficult Access to Docks and Wharves.	Ice will be thicker in approaches to shore than in main channel.	Utilize Coast Guard icebreaking services.
b) Ice Buildup on Bottom of Tows.	When tow moves through ice fields, ice adheres to the bottoms and sides; bottom buildup may be so much that barge cannot cross lock sill.	Place bubbler system off sill entrance to wash ice buildup off barge.
c) Flood Periods.	Barge navigation and lockage hampered.	Improve control of river levels.
d) Lack of Navigational Aids.	Existing buoys not designed for staying on station on ice-covered waters and hence are removed.	Introduce improved Coast Guard ice buoys and electronic « River and Harbor Navigation System ».
e) Extremely Cold Weather.	Periods of extreme cold slow all types of outdoor labor and create ice fogs over open water.	Improved working clothes.
f) Ice Action on Bridge Piers and Shore Structures.	Effects of plowing channel on nearby bridge piers and shore structures not understood.	Accelerate model and field studies by the U.S. Army Cold Regions Research and Engineering Laboratory.
g) Operation of Movable Railroad Bridges.	Many swing span bridges use grease as lubricant and may not swing in belowzero weather unless expensive modifications are made.	Exercise bridge facilities at frequent intervals or develop improved grease.
h) Traffic Management.	No « voice of control » when tows queue for entrance to a lock or ice-restricted channel.	Appropriate government official should take charge in view of channel being Federal waterway.
i) Detrimental Effect on Winter Recreation.	Open channels may be hazard to fishermen and snowmobiles.	Educational program showing yearround navigation to be overall economic benefit to region.

As has been pointed out in the earlier paper by Aune *et al* (1), the existing nine-foot (2.1 m) channel navigation project of the Upper Mississippi River extends from Alton, Illinois to Minneapolis, Minnesota (Figure 5) and is maintained at that depth by the use of 34 locks, 28 dams and dredging. Towboats operate into early winter throughout the Upper Mississippi River as long as ice conditions do not present serious risks, wile navigation up the Illinois River to Chicago takes place throughout the entire winter. Generally ice begins forming in December and reaches its greatest thickness of about 18 inches (45 cm) in February. Upstream from Lock 19 at Keokuk, Iowa, the navigation season closes about 15 December and opens about mid-March. During the open season when ice is not a problem, tows are usually made of three barges in width (105 feet; 31.5 meters) and are up to 1,200 feet (365 m) in length. Tows moving through ice are handled by towboats averaging about four to five hundred horsepower per barge, providing there is minimum power of about 3,200 horsepower to start with. Most of the new towboats are powered with « Kort Nozzles », making the vessels not as efficient in ice as if they had open propellers. Such tows do not have trouble if « blue » sheet ice does not exceed four inches (10 cm) in thickness; however, barge operations cease when the ice cover begins to exceed six inches (15 cm).

If year-round navigation on the Upper Mississippi River is to be achieved, the major problems that must be overcome fall into these categories; (a) operation of locks and dams, (b) navigation of the river reaches between locks and (c) associated problems. Solutions to these problems are not yet adequately researched, the state of the art is well described in several Army Corps of Engineers reports (2), (3), and (4).

Table II provides a paraphrased condensation of these key issues.

IV. ICE NAVIGATION IN NEW ENGLAND WATERS DURING WINTER MONTHS :

The principal areas with winter ice problems for waterborne commerce in the New England region are the Buzzards Bay and Nantucket Sound areas (Figure 6). Here the lack of an offshore warm current combined with extremely cold temperatures causes ice broken by the rise and fall of the tide to be driven about by strong wind and currents. The major problem is Buzzards Bay where

(1) Aune, C.A., Beaudin, L.A., Borrowman, J.K., « Influence of ice on navigable waterways on sea and inland ports », Section I, Communication 3, XIX International Navigation Congress, London, 1957.

(2) « After action report, Ice conditions, winter of 1965-66 », U. S. Engineer District, Rock Island, Illinois, August 1967.

(3) « Mississippi River year-round navigation — Record of conference of 23-24 July, 1968 », U. S. Army Engineers District, Rock Island, Illinois.

(4) « Mississippi River year-round navigation — Plan of survey for overall study », U.S. Army Engineer North Central Division, Chicago, Illinois, November 1970.

long restricted and dredged channels with many obstructions on the sea bottom require precise navigation by shipping using the Cape Cod Canal. Reliability of the aids to navigation become particularly uncertain in this area when moving ice is present. Experience indicates that three inches or more of sheet ice moving with the tide or current will disrupt an 8 × 26 foot (2.4 × 7.8 m) lighted buoy even with an 8,500 pound (3,800 kg) sinker used as the anchor. Ice 12 inches (30 cm) or more thick moving with the tide will completely submerge buoys as large as 9 × 38 foot (2.7 × 11.5 m) thereby destroying the lanterns and associatet components.

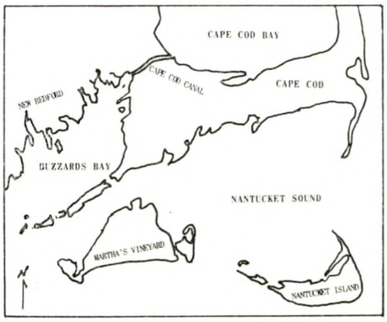

Fig. 6.

Locator map for the Buzzards Bay-Nantucket Sound region of New England.

Plan général de la région de Buzzards Bay - Nantucket Sound dans la Nouvelle-Angleterre.

During the winters of 1966-67 through 1970-71, ice conditions in Buzzards Bay were extremely heavy; buoys were unreliable from 14 January at the earliest to 15 March at the latest and moved off station as much as 12,400 feet (4,000 m) in only a few days time. Hence, most of the regular lighted buoys were removed or replaced by ice buoys or inexpensive unlighted buoys; even so, ice damage to buoys in the First Coast Guard District during the winter of 1970-71 amounted to 55,000 dollars direct replacement damage, 45,000 dollars of which was experienced in Buzzards Bay. In addition to buoy damage, four fixed structures were also destroyed during the winter of 1970-71 in the Hog Island Channel of Buzzards Bay. Two of these structures were prestressed concrete, single pile construction approximately four year old. The other two structures were five pile clusters of 12-inch (30 cm) I-beams less than five months old. Both types of structures are being replaced with five pile wooden clusters.

In the New England area, buoy icing starts when freezing spray builds into a heavy ice accumulation on the buoy cage. This accumulation will eventually capsize the buoy or, at the least, cause it to tilt excessively and thereby reduce its visibility. A common occurrence is that the freezing spray blocks the buoy's ventilation system causing a light outage to occur as the zinc air batteries become inoperable. Once a buoy and its anchor chain becomes submerged, they become hazards to navigation and, in fact, many buoys show signs of having been struck by passing vessels. Deicing buoys is still a difficult business. During the severe winter of 1970-71, the CGC HORNBEAM found the only satisfactory way to deice buoys was to take them aboard and knock off the ice with fire axes and crow bars. Hooking and lifting a heavily iced buoy on board is also difficult. One method used to free the hoisting bails when the buoy was not too heavily iced was to blast the bail with one or two shots of 12-gauge number six shot from a shotgun.

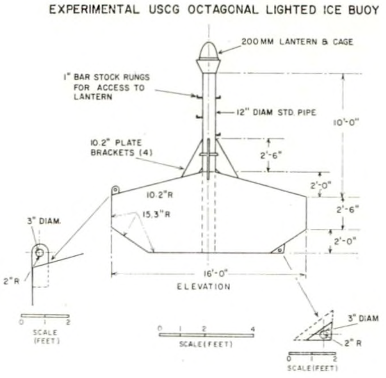

Fig. 7.

Schematic layout of experimental ice-buoy to be tested by U. S. Coast Guard during the winter of 1972-73.

Plan schématique du nouveau type de bouée des glaces devant être soumis aux essais pendant l'hiver de 1972-73.

Coast Guard improvements in ice buoy design are now underway. One new design of interest (Figure 7) uses an eight-sided 5 × 18 foot (1.5 × 5.4 m) buoy weighing about 15,200 pounds (6,840 kg) or half the weight of the « converted C-pinch gas buoy » which had been used successfully as an ice buoy in previous years. This new buoy will have sufficient reserve buoyancy to carry 44,000 pounds (20,000 kg) of ice or a 53-inch (132 cm) covering of ice before submerging.

V. ICE NAVIGATION IN ALASKAN WATERS

Prior to 1964, scheduled navigation ceased between November and April because of ice cover in Cook Inlet, a 165 mile (265 km) long indentation which experiences tidal ranges of as much as 35 feet (10.4 m) near its head. Starting in 1964, however, the advent of extensive off-shore oil and natural gas operations in Cook Inlet, plus a related growth of population and commerce in the Anchorage, Alaska metropolitan area near the upper end of the inlet, established a requirement for year-round marine traffic. This need was met by Sea Land Service, Inc., initiating regular weekly sailings throughout the year between Seattle and Anchorage with two 20-knot (37 km/hr) containerized ships capable of carrying 375 35-foot (10.5 m) containers. At present, the ports of the Cook Inlet complex experience approximately 64 arrivals and departures of ocean going vessels monthly. This traffic consists of general cargo ships, container vessels, tankers carrying crude or refined products, and ships of novel design carrying liquified natural gas and ammonia by products of the natural gas industry. The annual volume of this traffic is estimated as follows : (a) petroleum : 14,144,000 tons, (b) liquid natural gas : 106,000 tons; (c) anhydrous ammonia : 170,000 tons and (d) dangerous petroleum derived cargo : 1,000,000 tons.

Fig. 8.

Locator map for Alaskan region.

Plan général de la région de l'Alaska.

The common method of navigating Cook Inlet during periods of ice-infestation is to follow the path of least resistance; give the ship its head and let her feel her own way through the broken floes at a dead slow speed. With the exception of the two Sea-Land containerships, which are of heavier construction in the bow even though not truly ice-reinforced, vessels transiting Cook Inlet during winter are of customary ocean-going construction. However, during the winter of 1971-72, eight cases of ice damage to vessels were reported, all being cracks in the bow area at the water line. Fortunately, it is a common practice to run Cook Inlet ballasted by the stern and with unladen forward tanks to reduce the pollution potential. During the ice season, buoys are removed from the inlet, and no sepcial aids to navigation are erected to replace them. Position fixing in Cook Inlet is then primarily by radar and visual means.

The biggest ice navigation problem in Cook Inlet is breaking of moorings and fittings caused by the immense pressure of large ice floes of as much as 24 inches (60 cm) thickness being pushed about by gale winds and 4 to 8 knot (123 to 246 m/minute) tidal currents. For these reasons the ground tackle of most commercial vessels is not strong enough to permit anchoring in the open roadstead. Even when tied up alongside a dock, moorings are a major problem. For example, under pressure from moving ice on 9 March 1971, the CGC GLACIER, when moored to the Anchorage petroleum dock, broke three tripled nylon lines of 4-inch (10 cm) and three tripled nylon lines of 5.5 inch (14 cm) diameter and then moved forward at two knots until making contact with the container ship SS PHILADELPHIA.

Coast Guard experimentation with several types of icebreakers in heavy Cook Inlet ice has found that a small icebreaker the size of the CGC STORIS (displacement 1,925 tons and 1,800 horsepower) cannot effectively operate in moderate or heavier ice. On the other hand, the WIND-Class icebreaker (displacement 6,515 tons and 10,000 horsepower) is definitely limited by size and draft in the confined, shallow waters off Anchorage. What appears to be needed for this region is a medium size, 200 to 250 feet (60 to 75 meters) shallow draft icebreaker of about 6,000 shaft horsepower. Such a vessel could work effectively in Cook Inlet, in the shoal waters of northern Alaska, in the Great Lakes, and in bays and rivers of the U.S. east coast.

To develop the offshore oil fields in the upper half of Cook Inlet, 14 large offshore structures have been built in water depths at mean low tide of as much as 102 feet (31 m). Ice forces against these structures have been measured during four different winter seasons by Blenkarn (1) by use of a specially instrumented test pile and by strain gauges operated on several of the platforms. His conclusions are that effective structural ice loading in Cook Inlet is less than 125 pounds per square inch (8.8 kg/cm^2), including allowance for the dynamic response of the involved structure, forces imposed by pressure ridges are two to three times the forces imposed by uniform floes, and that the maximum measured intensity of

(1) Blenkarn, K.A., « Measurement and analysis of Ice forces on Cook Inlet structures », *Offshore Technology Conference*, Preprint 1261, II-365 to II-378, 1970, Houston, Texas.

pressure ridge loading is in the range of 60,000 to 70,000 pounds (27,000 to 31,500 kg) per foot (0.3 m) of leg diameter.

North of the Aleutian Islands, little coastal shipping was needed prior to 1968 except for the summer resupply of about 75,000 tons for such small scattered towns and villages of Arctic Alaska as Nome, Kotzebue, and Point Barrow. This traffic was generally handled by Liberty and Victory-class freight vessels of World War II vintage. In 1968, however, the discovery of the Prudhoe Bay oil field created a major requirement for marine operations in this area. At the present time, the combined military and civilian annual requirements of the North Slope facilities currently approximate 200,000 tons per year. Most of this tonnage is moved by tug-barge combinations that avoid heavy ice concentrations by moving along close to the shore. In some years, this movement is easy when the polar ice pack moves far offshore between mid-July and early October; in other years, the ice remains close in and coastal barging is very much a touch-and-go operation and there is considerable damage. Along this low lying coast with its numerous offshore shoals, conventional navigation aids are not maintained because of cost effectiveness considerations. Vessel positioning is accordingly accomplished by a combination of radar, celestial and navigational satellite fixes, and by use of OMEGA and LORAN-C receivers. Radar transponders operating in the X-band with a 90 second sweep are also installed at key coastal points; in the summer of 1972, for example, 11 of these transponders were operational.

For the time being, oil companies plan to avoid major ice navigation problems by sending the North Slope oil south through a 780 mile (1,250 km) pipeline to the ice-free port of Valdez, Alaska. However, the Coast Guard continues to be interested in the feasibility of achieving year-round navigation as far north as the Arctic Ocean. For example, the Seward Peninsula at the Bering Strait is very mineralized and the area needs an economic method of transporting the minerals from the area on a year-round basis. In addition, the extensive continental shelf to the north and south of the Bering Strait, with a water depth of about 120 feet (36 m), has sedimentary formations and geologic structures that may ultimately contain commercial deposits of coal, oil, and natural gas. During the period 21-26 April 1969, the WIND-Class icebreaker, BURTON ISLAND, evaluated the extent of penetration, the general ice conditions, and the feasibility of escorting large commercial shipping vessels to such points in this region as Nome, Port Clarence, and Kotzebue. After passing through a consolidated heavy ridged ice belt near St. Lawrence Island with ice from 20 to 40 inches (50 to 100 cm) in thickness between 62° 30'N and 64°N latitude, the BURTON ISLAND found relatively easy going by using leads and polynas through the Bering Straits as far north as 67° 15'N. Latitude, 166° 30'W. Longitude, at which time she had to turn back because of sailing orders. Similar experimentation was done by her sister icebreaker, USCGC NORTHWIND, during February-April 1970. On the basis of these cruises, the following conclusions have been drawn concerning the possibility of providing year-round shipping service to this region using ice-strengthened vessels :

a. **Nome :** Year-round service to Nome appears feasible, provided one to two days of delay due to adverse ice and weather conditions can be tolerated. The period between February and April would require the longest time for transiting between open water and Nome and would average about five to eight days, with other periods being proportionately less. Single vessels on a relatively continuous schedule with an icebreaker stationed along the track might be able to provide a more stable time of transit.

b. **Port Clarence :** Time of transit from open water to Port Clarence would be more variable than to Nome because of increased ice pressure and heavier ridging north of 64° 30'N. In general, ice transit times would be from nine to twelve days during the worst time of the year.

c. **Kotzebue :** Floe ice comes under extensive pressure and ridging in the Bering Straits; hence, there would be no guaranteed time period for the run to Kotzebue at the height of winter when only WIND class icebreakers were used as escorts.

During these winter operations, the icebreakers found it necessary on some occasions to reduce topside ice adhesion. Techniques for doing this included using canvas covers, grease, and commercial deicers. The USCGC BURTON ISLAND found the trade product, SANTOMELT 990-CR, to be very effective in keeping its flight deck, turnbuckles, shackles and lines clear of ice.

Because the wide-shallow continental shelf east of Point Barrow is also likely to contain what may eventually be commercial deposits of oil and natural gas, industrial studies have been made to determine the feasibility of constructing fixed offshore structures capable of direct exposure to polar pack ice. Garwick and Lloyd's study (1) indicated that reinforced concrete caissons with a conical shaped section exposed to the ice zone offered major advantages of practicability and economy for the construction of loading terminals, ice barriers, and drilling and production platforms. While none of these facilities are currently known to be under construction, the Imperial Oil Company of Canada is already planning one or more experimental sand islands off the McKenzie River Delta in about 12 feet (3.6 m) of water in the near future.

During the summer of 1969 and the spring of 1970, the Humble Oil and Refining Company, with assistance from the Atlantic Richfield Oil Company and the British Petroleum Company, also conducted a $40 million ice navigation experiment utilizing the SS MANHATTAN, the largest commercial vessel ever built in the United States. Conversion of this tanker of 115,000 deadweight

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(1) Gorwick, B.C., and Lloyd, R.R. « Design and construction procedures for proposed Arctic offshore structures », Offshore Technology Conference Preprint 1260, pp. II-351 to II-364, Houston, Texas, 1970.

tons into an icebreaking ship within a period of nine months and her sailing on a round-trip through the Northwest Passage between the east coast of the United States and Prudhoe Bay, Alaska during the summer of 1969 is a saga of modern industrial enterprise. This experiment has been described in general terms by a number of papers, two of the best being those of Goettel and Super (1) and Mookhoek and Bielstein (2). Spring and late summer voyages, especially designed to obtain a vast amount of engineering and operational data, demonstrated that even these cruises by the MANHATTAN should be considered essentially as being half scale model tests in the natural environment. While detailed technical results have not been released, a press release by Humble Oil and Refining Company on 21 October 1970 did state :

> « The use of icebreaking tankers to transport crude oil from Alaska's North Slope to U. S. Markets is commercially feasible... but pipeline transportation appears to have an economic edge at present ... The Company said its Arctic marine studies indicate that icebreaking tankers could move North Slope oil through the Bering Strait to the West Coast. Preliminary design studies for icebreaking tankers... were based on a 1,250 foot (375 m) ship of 300,000 deadweight tons. Such a vessel would be capable of year-round operations without icebreaker assistance... Use of the giant icebreaking ships would require construction of an offshore loading terminal in the Arctic waters of the Beaufort Sea. Feasibility and basic design studies on the terminal facility have been completed... »

Mookhoek and Bielstein of Humble in their above cited paper outlined a first-generation design for such an arctic tanker and noted it would have the following differences from the conventional tankers :

(a) Special shape at bow and stern, as well as multiple screws and rudders.

(b) Strengthened ice belt over the entire length of the vessel.

(c) Navigation bridge located far forward to improve visibility.

(d) Clean ballast tanks capability of acting as heeling tanks and as « safety tanks » for receiving contents of any ruptured cargo tanks.

(e) Extensive covered areas to protect deck machinery and topside personnel from inclement weather.

If built it is surmised that such an artic tanker would have an 80-foot (24 m) draft, a 170 to 200 foot (51 to 60 m) beam, and engines capable of generating 80,000 to 200,000 shaft horsepower, much of which would be available for backing down.

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(1) Goettel, F.A. and Super, A.D., « The Manhattan Tanker Test », Marine Technical Soc., *Journal*, Vol. 4, N° 5, pp. 60-68, 1970.

(2) Mookhoek, A.D. and Bielstein, W.J., « Problems Associated with the design of an Artic marine transp. sys. », Offshore Tech. Conf. *Preprint*, 1426, II : 123-146, 1971, Houston, Texas.

Other methods have also been studied on paper for transporting Arctic Basin oil south to the United States on a year-round basis. The submarine tanker approach has been described by Jacobsen (1), while the approach using a large icebreaker to tow a controllable, submerged barge of 250,000 ton capacity has been described by Sudbury (2).

Also in the realm of advanced icebreaking technology for polar regions is the new « POLAR » class of U. S. Coast Guard icebreakers. Designed to replace the WIND-class icebreaker, the keel of the POLAR STAR was laid on 15 May 1972 by Lockheed Shipbuilding Corporation at Seattle, Washington. Funds for a sister ship have also been approved by the Congress. This icebreaker will be the most powerful afloat, with an engineering plant rated at about 60,000 shaft horsepower when powered by three Pratt Whitney gas turbines. When not requiring full power, the vessel will use 6 diesel engines of 3,500 shaft horsepower each that will drive the ship at 17 knots. Based partially on studies by Commander R. M. White, USCG, the unique bow configuration uses a double entry angle of 15° and 30° to improve the icebreaking characteristics. Model basin tests of four different hull shapes have also led to an optimum hull designed to reduce the 60 to 70 per cent of hull resistance which is now encountered when breaking ice as a result of simply pushing broken ice aside. When operational, the POLAR-Class icebreaker should be able to transit sheet ice of 6 feet (1.8 m) in thickness by ramming. These capabilities compare with the ability of the World War II WIND-Class icebreaker to maintain way in 3 feet (0.9 m) of sheet ice and to ram successfully pressure ridges 11 feet (3.3. m) in thickness.

VI. ENVIRONMENTAL RESEARCH PERTINENT TO ICE NAVIGATION

The U. S. Coast Guard maintains a continuing program of environmental research relevant to the development of improved ice navigation (3). To date, this work has resulted in use of narrow-beam underwater sonar lowered from the surface for the prupose of determining underwater dimensions of pressure ridges, development of an air-dropped penetrometer capable of remotely measuring the thickness of sea ice (4), and use of side-looking radar to present an all-weather picture of the ice cover (5).

The ice penetrometer developed by the Sandia Corporation for the Coast Guard is a device weighing about 50 pounds (22.5 kg) dropped from an altitude

(1) Jacobsen, L.R., « Subsea transport of Artic oil. — A technical and economic evaluation» Offshore Technology Conference *Preprint*, 1425, pp. II : 95-122, 1971, Houston, Texas.

(2) Sudbury, J.D., « Controlled Depth Submerged Barge », *Proceedings*, Inter-society Conference on Transportation, Washington, D.C., 31 May-2 June 1972, pp. 141-146.

(3) Breslau, L,R., Johnson, J.D., McIntosh, J.A. and Farmer, L.D., « Environmental research relevant to the development of Arctic sea transportation », Mar. Tech. Soc., *Journal*, Vol. 4, n° 5, pp. 19-43, 1970.

(4) Young, C.W. and Keck, L.J., « An air dropped sea ice penetrometer », *Sandia Laboratories development report*, SC-DR-71-0729, 101, pp. 1972.

(5) Johnson, J.D. and Farmer, L.D., « The use of side-looking airborne for sea ice identification, *Journal of Geophysical Research*, Vol. 76, N° 9, pp. 2138-2155, 1971.

of 8,000 feet (2,400 m). The resulting impact velocity of about 500 fps (152.4 m/s) is sufficient to penetrate 10 feet (3 m) of sheet ice. Upon hitting the ice, a whip antenna and radio transmitter (frequency band between 402 and 405 MHz) detaches from the projectile and transmits back the deceleration history which takes place in about 25 milliseconds. By double integrating the deceleration time curve, a determination of ice thickness is made with an accuracy of about 3 inches (7.6 cm) if the ice is at least 1 foot (0.3 m) thick. Throw-away devices of this type could be built in quantities of a thousand for $120 each.

Since 1969, the Coast Guard has been overflying differing kinds of ice with an AN/DPD-2 side looking radar (SLAR) originally developed by Philco-Ford as an Army drone radar. The operating frequency of the radar is Kuband (16.5 GHz) with an antenna beamwidth of 0.4 azimuth ($CSC^{o}\Theta COS\frac{1}{2}\Theta$) elevation. When flown at an altitude of about 8,000 feet (2,400 m), a 10-mile (16 Km) swath is observed on each side of the aircraft, and imagery is recorded on a 5-inch (12.5 cm) wide film at a scale of about 1 : 350,000.

During February-March 1971, this radar and a photographic mapping camera were mounted in a Coast Guard C-130 « Hercules » aircraft and flown over the general confluence area of Lakes Superior, Huron, and Michigan. The purpose was to develop signatures for interpretation of Great Lakes ice cover and for investigating the effect of snow cover on these signatures. The camera used was a standard T-11 mapping frame camera with a 6-inch focal length that gave a scale of about 1 : 15,000 at flight altitude. Analysis of the flights in the North American Arctic leads to the conclusion that SLAR is probably the most useful tool available today for periodic, all weather, day/night coverage of ice (1). Slush, frazil and grease ice sometimes could not be differentiated on the Great Lakes, or, on certain occasions, even detected in open water. Young ice, although readily detectable, could not generally be separated into dark gray and gray-white types. Winter ice could be interpreted with relative ease, including crack and ridge systems. Snow cover on lake ice tends to complicate the identification of ice types; additional field research needs to be done under controlled, well-monitored conditions.

VII. **CONCLUSION**

Because of economic pressures building up for safe, economic and efficient methods of waterborne commerce through ice-covered waters, the United States of America has begun many new initiatives for achieving a much improved capability for navigating through the ice. While too early to tell whether major break-throughs in technology and transportation capability will result, early results appear promising.

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(1) Analysis of SLAR Imagery for Arctic and lake ice, *Raytheon Company Report*, DOT-CG-14486A, Raytheon Company, Wayland, Mass., 168 pages, March, 1972.

VIII. ACKNOWLEDGEMENTS

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RÉSUMÉ

La navigation dans les eaux couvertes par les glaces : quelques nouvelles initiatives aux Etats-Unis

Le maintien de la navigation et des aides à la navigation aux Etats-Unis dans les eaux couvertes de glace est varié, complexe, et soumis à d'importantes nouvelles initiatives techniques entreprises par l'industrie privée et le gouvernement fédéral. Au milieu de la décade de 1960-70, le Mid-West américain éprouvait un désavantage commercial croissant par rapport aux marchés intérieurs et extérieurs du fait que ses voies navigables étaient limitées à une saison de navigation longue de huit à neuf mois. Par conséquent, le Congrès des Etats-Unis a ordonné deux initiatives à prendre pour surmonter ce problème de navigation saisonnière, les résultats devant se faire sentir dès 1974. La première initiative était de déterminer les conditions pratiques, les moyens, et la justification économique sous lesquels la navigation pourraît être assurée pendant toute l'année sur le haut Mississippi; la seconde initiative était un « Programme de démonstration d'une saison de navigation prolongée pour les Grands Lacs et la route maritime du Saint Laurent ». En outre, la découverte, près de l'océan Arctique, en 1968, du champ pétrolifère de Prudhoe Bay, le plus grand de l'Amérique du Nord, provoqua l'intérêt du Ministère des Transports et de l'industrie privée par rapport aux conditions pratiques dans lesquelles la saison de navigation pourrait être prolongée et le transport maritime régulier assuré vers l'Alaska Arctique.

Le « Programme de navigation hivernale » de trois ans pour les Grands Lacs et le St. Lawrence Seaway est dirigé par un comité présidé par le Corps des Ingénieurs de l'Armée américaine, et comporte la représentation des ministères fédéraux, d'agences d'Etats, et de groupes privés. Les principaux ministères entreprennent les études sur les lieux et le travail administratif sous sept catégories fonctionnelles comme suit :

Renseignements sur la glace (Service national météorologique); navigation dans la glace (Service des Garde-Côtes); le Génie Civil appliqué à la glace (Corps des Ingénieurs); le maniement de la glace (St. Lawrence Seaway Development Corporation); le maniement de la glace dans les canaux, écluses et ports (Corps des Ingénieurs); évaluation économique (Corps des Ingénieurs); et évaluation écologique (Ministère de la Protection des Lieux).

A partir de l'hiver de 1971-72, on s'est occupé de développer les renseignements concernant la glace et les techniques de navigation dans la glace. Egalement prévus étaient : L'opération d'un « Centre de navigation dans la glace »; la conduite de surveillance terrestre et aérienne extensive relative aux conditions de la glace, aux mouvements de la glace, et à ses effets sur les niveaux d'eau et sur la propriété le long des rives; et la direction d'essais de certains systèmes de navigation, incluant un système consistant à suivre un cable submergé; un mécanisme intégrateur de position activé par le Loran-C; des bouées spécialement éclairées et construites pour le service dans les eaux couvertes de glace; un indicateur de distance laser; et un radar asservi

par impulsions sur la gamme 5.200-11.000 MHz. On a aussi soumis aux essais un modèle réduit, long de 6,6 mètres, d'un chaland brise-glace; un système employant des bulles pour réduire la friction sur la coque du navire RARITAN; un mécanisme pour briser la glace monté sur un chaland et utilisant des explosions répétées d'un mélange air/propane; un tuyau flexible, long de 910 mètres, laissant échapper des bulles d'air au long du tournant de 70° près de Lime Island dans la rivière St. Mary du Michigan supérieur; et un radeau fait de bûches permettant d'ancrer la glace au-dessus des prises d'eau d'une centrale électrique près des écluses Snell du canal du Saint Laurent.

Les chalands toués sur le haut Mississippi cessent de naviguer lorsque la glace atteint une épaisseur d'à peu près quinze centimètres, alors qu'en février l'épaisseur peut atteindre 45 centimètres. Si la navigation doit être assurée au cours de l'année entière, des solutions techniques doivent être développées pour les problèmes suivants : la glace brisée dans les écluses; la congélation des embrasures des portes d'écluse à onglet; l'amoncellement de glace sur les murs des écluses et contre les parois du fond des chalands; la congélation des valves des écluses; la navigation le long des contours de rivière couverts de glace; les champs de glace et les gorges de glace; l'enlèvement des aides à la navigation flottantes; l'action de la glace sur les butées de pont et sur les structures le long des rives; et la direction du trafic.

Dans la Nouvelle-Angleterre, le plus grand problème associé à la navigation hivernale se présente dans la région de Buzzards Bay-Nantucket Sound. Ici, de forts vents et courants déplacent les champs de glace brisée à tel point que les aides flottantes à la navigation dérivent loin de leurs stations; de plus, un grand nombre de bouées se recouvrent de glace si épaisse qu'elles se submergent et constituent un danger pour la navigation. Un nouveau type de bouée capable de porter une couche de glace épaisse de 132 centimètres est en voie d'être développé pour combattre cette situation.

Dès 1964, la navigation a pu se faire d'une façon continue toute l'année dans la partie supérieure de Cook Inlet en Alaska. Des cargaisons équivalent à un million de tonnes par mois sillonnent actuellement les bancs de glace épais de 60 centimètres en suivant prudemment la route de moindre résistance. Quatorze plate-formes pétrolifères en pleine mer ont aussi été construites dans cette région, capables de résister à la pression de la glace et aux courants de la marée mus de vitesses de 246 mètres à la minute.

En utilisant vers le fin des saisons d'hiver de 1968-69 et 1969-70, les brise-glace du type « WIND », le Service des Gardes-Côtes a réussi à assurer un service de navigation durant toute l'année au moyen de vaisseaux renforcés contre la glace sur la route de Nome et Port Clarence, en Alaska, juste au sud du détroit de Bering. Ce service n'était pas possible au nord du détroit. Il en résulte que les 200.000 tonnes de matériel nécessaires annuellement aujourd'hui au ravitaillement de l'Alaska arctique sont transportées par les chalands à remorque au long de la côte libre de glace chaque été.

Pourtant, l'emploi du vapeur MANHATTAN, transformé en tanker brise-glace en 1969, a démontré les possibilités techniques de ce mode de transport pour l'huile brute provenant de l'Arctique à destination des marchés américains. Cependant, pour l'instant, le transport par pipe-line s'avère plus économique. Le Service des Garde-Côtes fait construire actuellement un brise-glace du type « POLAR » qui sera le plus puissant du monde et qui sera capable de maintenir la marche avant dans un champ de glace d'épaisseur jusqu'à 1,8 mètres. Pour faciliter les opérations dans l'Arctique, le Service des Garde-Côtes a développé l'emploi du radar à transmission latérale comme mécanisme de surveillance de la glace en tous temps, augmenté par des pénétromètres lancés d'avion qui renvoient par télémétrie des renseignements sur l'épaisseur de la glace.

S. II - 4

PAPER

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EFFECT OF ICE ON SHIPS AND STRUCTURES AND MAINTENANCE OF THEIR OPERATION AT SUB-ZERO AIR TEMPERATURES

1. INTRODUCTION

For up to half the year, and sometimes more, the coastal waters of most seas surrounding the USSR, as well as a larger part of inland waterways are bound with ice which, besides disruption of normal ship movements, causes many problems in water transport operations. Those problems arise in ship repair, maintenance of existing and construction of new hydroengineering facilities, organization of safe wintering of ships in rivers affected by ice dam formation, etc. Shipping is endangered by underwater hull fouling with frazil ice (or sludge).

At the same time, the 1971-1975 plan of the USSR national economy development involves a large-scale economic development of northern and eastern regions of the country. Quite naturally, this necessitates improvement in transportation, especially in shipping, as for many districts waterways are the main channels for delivery of bulk and heavy-weight cargoes.

This is why such a great attention is paid in the USSR to the development of ways and means insuring uninterrupted operation of ships at sub-zero air temperatures.

The question of ice influence on inland waterways, sea and river ports and of ways to neutralize the harmful effects of ice was already discussed at the

XIXth Congress of the PIANC in 1957. A comprehensive report was submitted to the Congress by the USSR, so that the present report will be limited to discussion of developments of the last 15 years and prospects of future work bound up with maintaining ice navigation and ensuring the operation of ship-raising facilities, locks and ferry crossings during the periods of sub-zero temperatures. The ice loadings have a considerable influence on the stability, strength and durability of the hydrotechnical structures.

2. PRINCIPAL TYPES OF ICE PROBLEMS ENCOUNTERED IN OPERATION OF SHIPS AND WATERWAY STRUCTURES DURING SUB-ZERO TEMPERATURE PERIODS

For development of effective means to combat harmful impact of ice on waterway structures and shipping it is necessary, first of all, to identify the principal types of ice problems affecting a given object. Therefore, we shall start with a discussion of shipping in ice conditions and problems encountered in maintenance of navigation routes and channels, berthing facilities of ports, ferry crossings, ship-raising facilities and other installations during freeze-up and sub-zero periods.

2.1. Shipping and Ice Conditions Studies.

Due to constant increase in freight turn-over and addition of new ice class ships and icebreakers to the USSR sea and river fleet, the navigation period on Soviet freezing waterways is becoming extended.

On most inland waterways where the navigation period, at present, begins and ends at sub-zero air temperatures, with ice formed or persisting, the main problems consist not only in breaking through the ice, but in operation in the presence of sludge — an ice formation type characteristic for rivers. After erection of a succession of hydroengineering complexes on a river the sludge formation in the deeper part of the storage basin is eliminated, but the same process is intensified down stream. From the point of view of shipping (2) two grades of sludge formation intensity should be distinguished : a sludge layer less than the ship's draught (when the rudders and propellers could operate with relative efficiency) and a sludge layer exceeding the ship's draught (when even a powerful ship is practically immobilized).

Inland vessels can be divided into two categories : those with heated compartments covering up to 80% of the hull length and those with the heated zone not exceeding 30% of the length. Vessels of the first category can move satisfactorily in frazil of the first grade while the second category ships are quite helpless even in such conditions.

Hydrometeorological service bodies in this country supply the river fleet with long- and short-term forecasts of ice phenomena which have a satisfactory degree of realization.

2.2. **Ship Icing.**

Icing of a ship's underwater hull in sludge substantially depends on the ship skin surface temperature. The research described in Rib. 2 proves that : in compartments not heated over all the ship's depth the temperature of side and bottom plating can drop below 0 °C (—1.7 °C was actually measured at ambient air temperature of —12 °C and wind speed up to 11 m/sec.); in compartments located underneath heated compartments skin temperature in bilge and bottom areas does not decrease below 0 °C; the same is true for the plating of the heated compartments themselves; the skin temperature in the area of non-heated compartments immediately above the in-motion waterline can drop easily below zero (down to —7.6 °C, as measured in the above conditions) and even in the area of heated compartments the skin temperature immediately above this waterline can go below zero if the negative temperature of the ambient air exceeds, in numerical value, the positive temperatures inside the compartments. Using the above notes for guidance, one can identify hull areas where the sludge can adhere to the ship's skin.

2.3. **Operation of Canals and Locks on Inland Waterways in Extended Navigation Periods.**

Both in canals with or without locks the ship's route is strictly limited by the canal cross-section. As a result of multiple passage of ships along the same route and subsequent hummocking and regelation of ice cakes scattered by the ships, the thickness of the ice cover is growing rapidly and becoming more and more difficult to break. The situation is somewhat easier at a very intensive traffic, when time intervals between ships passing in the same or opposite direction is too short for ice cakes to adfreeze. The depth of the canal usually restricts the possibility of pushing the broken ice under the edges of solid ice cover and away from ships' route, owing to which fact navigation becomes difficult or quite impossible.

Factors complicating operation of the locks include : formation of ice cover inside the chamber; icing of the chamber walls, upper and lower head gates, culvert sluice slots, mooring floats with rings, shields and upper head damper beams at alternative filling and emptying of the chamber (Fig. 1 *a*); formation of ice caps on mooring and guiding fixtures in the approach channel, especially in the lower one, at peak loads of power station operation and in the upper one at water storage level drop by 10 m or more; frosting of the upper gate on the head race side due to high heat-conductivity of the metal; formation of ice in the gate recesses supplemented by ingress of broken ice from the chamber, and the resulting inability to operate the lower mitred gate; freezing of sealing elements to the sill boards and formation of a mound owing to seepage of water through the seals; failures in automatic controls due to icing of terminal switches, gelation of lubricants, formation of ice in the float shafts; interruptions and failures in operation of mechanisms located in non-heated rooms (especially when using hydraulic drives); icing and loss of flexibility in cables and chains due to repetitive

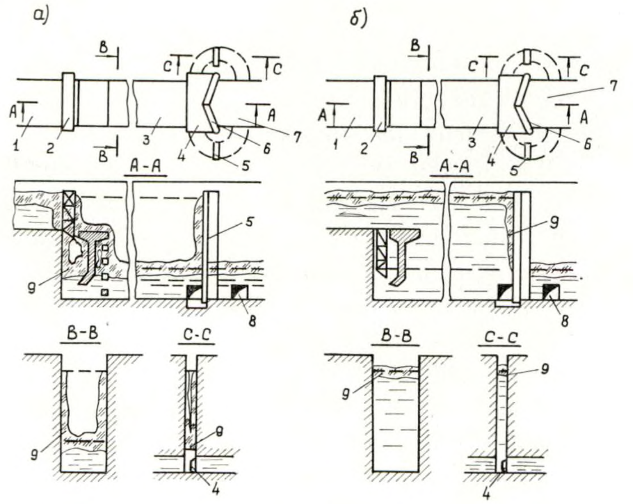


Fig. 1*a*.

Types of ice formation on the lock elements depending on the water level maintained in the chamber :

a) low pond level;
b) upper pond level.

1. Upper approach channel.
2. Upper end gates.
3. Lock chamber.
4. Box element of the lower end.
5. Valve of water conducting culvert.
6. Lower end gates.
7. Lower approach channel.
8. Discharge culverts of the lower end.
9. Ice sheet and icicles.

Nature de la formation de glace sur des éléments d'une écluse, suivant les différents niveaux d'eau maintenus dans le sas :

a) plan d'eau au niveau du bief aval;
b) plan d'eau au niveau du bief amont.

1. Chenal d'accès amont.
2. Portes d'amont.
3. Sas.
4. Boîtier aval.
5. Vanne de l'aqueduc.
6. Portes d'aval.
7. Chenal d'accès aval.
8. Aqueducs d'évacuation de l'extrémité aval.
9. Couche de glace et glaçons.

submergence in water; interruptions and subsequent complete failure of the floats with the rings due to icing of slideways and formation of ice in the shafts; more complicated, time-consuming and hazardous process of mooring by the float rings. The main problem in operation of ship lifts is the possible formation of ice on the surfaces with which the retractable seals should come into contact. Operation of waterway structures in a freezing temperature period is liable to promote failure of metal parts subjected to dynamic loads of these parts are manufactured of rimming (or wild) steel.

2.4. **Operation of Ports, Wharves and Ferry Crossings at Freezing Air Temperatures, with Ice Covering the Water Area.**

The main obstacle to movements within the water area of a port is the ice cover which is repeatedly broken by ships and, owing to emergence of hummocks, grows rapidly in thickness. The ice cover and fast ice at the piers makes a ship's berthing or mooring very difficult. Owing to ice cakes being trapped between the ship's hull and a pile, very high unprovided for horizontal stresses in the piling can arise. In ports with regular fluctuations of the water level in winter time considerable build-up of ice can appear on the piles which, besides making the pier hard to approach, promotes deterioration of the piles.

Ports situated in the mouths of north-bound rivers are subjected to high dynamic loads in cases of ice jam rupture. Note that formation of the jams and their subsequent rupture are prerequisits of the spring break on such rivers.

An important problem of the port operation is regelation of bulk cargoes. Use of cargo handling mechanisms lacking special heating devices becomes impossible. Besides, metal structures of cranes and other mechanisms are subjected to additional stresses.

Problems connected with winter operation of railway ferries include : formation of hard ice cover in the ferry berth; condensation of broken ice in the adjoining water area and in the ferry berth, also accumulation of broken ice at the abutments of the ferry's landing pier; icing of the pier and formation of the fast ice in the boot-top area; accretion of ice on the fender elements and icing of the bridge structures of the terminal.

As a result of pushing the broken ice by the ferry's hull into the berthing place and accumulation of broken ice in the vicinity of the abutments and mooring facilities, the ferry cannot fully fit into the berthing place, its mooring and engagement with the raisable landing apron becomes very difficult.

Certain types of the enumerated ice problems are more or less characteristic for both railway and car ferries operating either in the sea or on inland waterways.

2.5. **Winter Operation of Ships Lifting Facilities and Repair of Ships at Below-zero Air Temperatures.**

The most common and encountered at most repair yards ice problems include : penetration of masses of broken ice into the inner space of a floating dock during its submergence and entrance of ships; settling of the broken ice on the dock floor at surfacing (Fig. 2*a*) which is a major obstacle to repair of ships in the dock; accretion of broken ice under the bottom of the ship towed towards the dock which complicates positioning of the ship on keelblocks or even makes it impossible; formation of an ice envelope and fast ice around the ship's waterline also interferes with ship positioning on the keelblocks and hull repair operations; freezing of water in the dock's ballast tanks, in ballast and drain water-pipelines, icing of the dock floor and keelblocks; formation of a solid ice cover around the dock and adhesion of this cover to the dock — as a result, a large amount

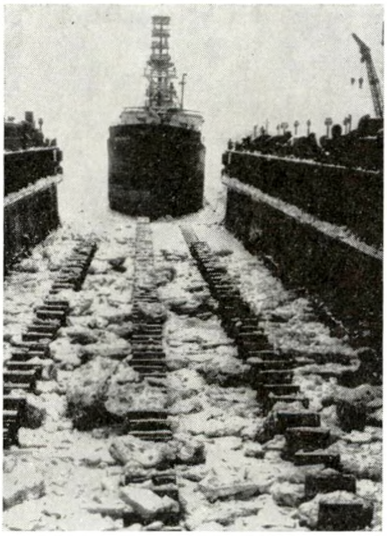


Fig. 2*a*.

a) ice which penetrated into the dock is setting down on the floor;

a) la glace, qui a pénétré dans la forme, se dépose sur le radier de cale;

of ice breaking operations is required; accumulation of hummocking at the dock's ends resulting in penetration of the ice cakes under the dock's bottom.

As a ship enters a graving or floating dock it can bring with it a large volume of broken ice into the dock chamber, and when the docking is carried out at a low air temperature and ice cover can form inside the chamber; thermal expansion of a strong ice cover can damage the dock gate or jam it and prevent opening (5).

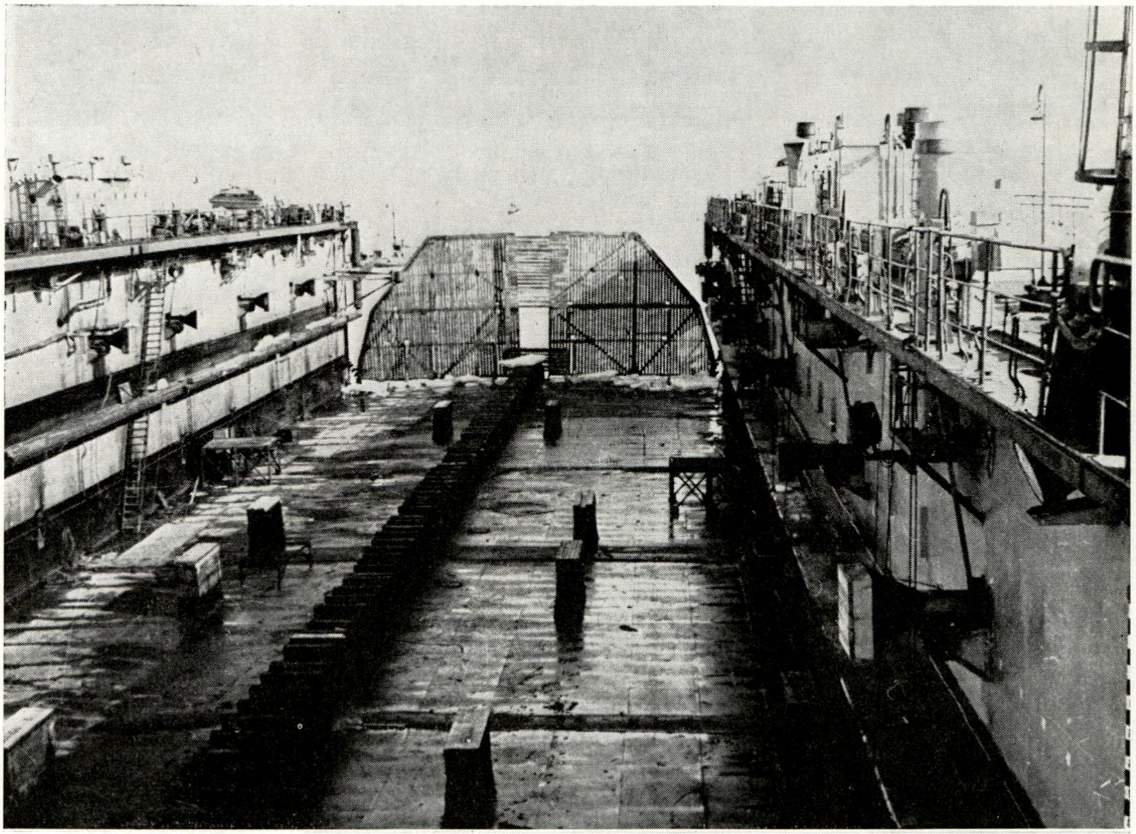


Fig. 2 *b*.

When flow generators are used, there is no ice on the dock floor after surfacing.

Grâce à l'emploi de dispositifs générateurs de courants, après émersion de la forme, il n'y a plus de glace sur le radier.

When an ice cover is formed at the yard's water surface, raising and lowering of the slip carriages becomes impossible. The presence of an ice envelope on the ship's hull forbids positioning of the ship on the carriages; breaking of the ice cover by an icebreaker usually stops short of the floe at the water edge where the ice has the maximum thickness and this continues to block the carriage movement.

Cost and man-hours of winter docking are increased by 24 to 50% in comparison with the summer conditions, and 15 to 40% of this increase is due to ice problems.

Multiplicity of the ice problem types and conditions varying with different ships, structures and waterways, eliminates the possibility of a single common solution to these problems. Selection of the most effective means and methods, or their combinations, should be carried out on the basis of a thorough analysis of the specific hydrometeorological factors and with the use of modern techniques of ice combating described below.

3. PRINCIPAL TRENDS OF INVESTIGATION AND TECHNIQUES OF SOLVING ICE PROBLEMS IN SHIPPING

Considerable development of ice navigation and such supporting services as ports, ship repair yards, etc. has become possible only owing to application of a great variety of means provided by modern science and technology for achievement of the desired goals.

Discussed below are the main technical developments directed to the solution of ice problems in shipping.

3.1. Maintenance of Ice Navigation on Inland Waterways and Extension of the Navigation Period.

Ice navigation on inland waterways can be improved by introduction of more realistic guaranteed navigation terms on the most intensive shipping routes and by timely delivery of cargoes to the lateral inflows in spring, because the flood there starts much earlier than the break on the storage reservoirs of the principal river.

To achieve the desired goals, special investigations and experiments (8, 9) were carried out which enabled us to establish realistic dates of beginning and end of the navigation for different parts of waterways and to choose the methods of maintaining the necessary conditions on waterways. To illustrate this, Figure 3 shows a diagram with terms of ice phenomena and navigation periods for some of the principal waterways in the European part of the USSR.

On the basis of the river stage and ice regime investigations, the pattern of icebreaking facilities arrangement was analysed revealing the need for an icebreaker fleet of the following composition (by engine output) : 10% of ice-breakers with power output of 4,000 HP, 30% with output of 2,400 HP and 60% of icebreakers and ships with an icebreaking attachment having power output of 600 HP. Besides, all sluices and locks are going to be equipped with a set of devices ensuring their continuous operation at sub-zero air temperatures.

Comparison of the calculated and actual mean periods of navigation in the previous years indicates that use of icebreakers will allow to prolong the navigation period for at least 20 days. Prolongation of this period at the expense of the

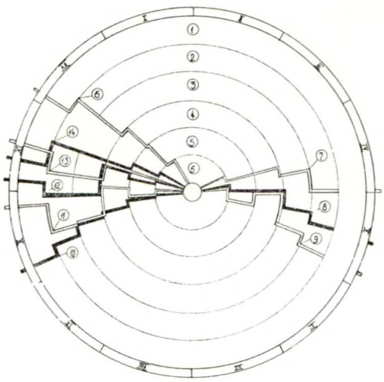


Fig. 3.

Diagram of ice phenomena and navigation period terms :
1. mouth of the Kama river (Perm'); 2. Rybinsk-Belomorsk; 3. Rybinsk-Leningrad; 4. Rybinsk-Moscow; 5. Kuibyshev-Rybinsk; 6. Astrakhan-Kuibyshev; 7. dates of beginning of icebreakers operation; 8. tentative dates of beginning of long route shipping; 9. mean dates of ice clearing; 10. earliest dates of ice breaking; 11. earliest dates of ice cover formation; 12. mean dates of ice breaking; 13. end of ship decommissioning for the winter (early formation of 30 cm thick ice cover); 14. mean dates of ice cover formation; 15. mean dates of 30 cm thick ice cover formation.

Diagramme du temps de la prise des glaces et de la navigation :
1. embouchure de la Kama-Perm; 2. Rybinsk-Belomorsk; 3. Rybinsk-Leningrad; 4. Rybinsk-Moscou; 5. Kouibychev-Rybinsk; 6. Astrakhan-Kouibychev; 7. dates de commencement du travail des brise-glace; 8. dates approximatives de début de navigation en transit; 9. dates moyennes de libération des glaces; 10. premières dates de début de la débâcle; 11. premières dates de début de la prise des glaces; 12. dates moyennes de début de la débâcle; 13. fin de mise à poste de la flotte (formation prématurée de glace de 30 cm d'épaisseur); 14. dates moyennes de commencement de prise des glaces; 15. dates moyennes de formation de glace de 30 cm d'épaisseur.

autumn months seems economically more reasonable than the earlier start of navigation.

It was also found out that on certain short (about 100 km) inland routes with high cargo-traffic intensity it is advisable to organize a year-round navigation — if the climate is suitable, as, for instance, in the middle course of the Dnieper. In this case the traffic of ships with small intervals should be maintained, to prevent the refreezing of broken ice in the channel.

Sludge navigability of icebreakers and other ships can be increased by utilization of rolling and hull heating devices (2).

3.2. Principles of Design and Development of Facilities for Prevention of Freezing of Water Areas.

In areas where the water surface is bound with a solid ice for a long spell of time the periodical breaking of ice by icebreakers is a rather inadequate solution of the problem as the resulting broken ice complicates operation of waterway facilities and the thickness of ice layer in the area increases considerably with time.

Besides, the ships manoeuvring in the area filled with ice can damage the weakest elements of the shore structures, e.g. the piling. The damage can also be caused by the thermal expansion of ice.

All this points out to the necessity of development of effective means allowing to keep the water areas free from ice. The results of investigations and experiments in this direction are described below.

3.2.1. *Thermal and Ice Regimes of Inland and Sea Basins.*

In most of fresh-water basins the temperature is constantly changing with time owing to the continuous heat exchange between the basin and the atmosphere via the basin surface and between the basin and the substrate via the bottom.

In deep basins near-bottom temperatures can be as high as +4 °C. When there is considerable overflow in the upper water layers the temperature variation with depth is rather slight until a certain level is reached and after that it increases sharply approaching the bottom. This property should be taken into account when selecting a way to keep the surface free from ice.

Maintenance of non-freezing water areas in sea basins is hampered by the following factors : considerable difference of characteristics from one basin to another; insufficient knowledge of physical processes accompanying the upwelling in a sea basin; insufficient number of completed experiments, uncertainty in prediction of efficiency of required installations. To obtain the reliable data necessary for the design of installations which would cause the up-welling in sea basins, a well-organized series of full-scale experiments with the use of high precision instruments.

The boundaries between sea and fresh-water basins, i.e. estuaries, are characterized by a very peculiar thermal and ice regime (10) which is determined by tidal phenomena, penetration of sea water into the river channel and effect of the river run-off on the thermal regime of the adjacent sea area.

The sea water cooled below 0 °C is driven by tides or inshore winds up the river flow. The contact between fresh water with temperature of 0 °C and sea water results in formation of fresh-water ice. During the ebb the fresh water flows down the river bed cooled by the influx of sea water and produces ground icing. Replacement of fresh water with salt water at the bottom surface of the ice cover changes the thermal regime of the ice and changes its thickness.

Mixing of fresh and salt waters having temperatures close to the freezing point results in below-freezing temperature of the mixture — the so called « concentration supercooling » of the mixture. The value of concentration supercooling is a difference between the actual and freezing temperatures of the mixture. Analysis of relationship between the concentration supercooling value, relative fresh and sea water debits and sea water concentration shows that this relationship has its maximum corresponding to the « dangerous regimes » of ice formation. The amount of ice formed at this supercooling condition is equal to about 4% by volume of the fresh water debit which may cause — and sometimes does — considerable difficulties for shipping.

The second cause of ice formation on the surface of the sea water wedge is cooling of the higher temperature layer owing to heat transfer to the colder layer. Volume flow rate for ice forming at the interface of layers with different density and temperature would average about 1.5% from the fresh water flow rate.

Amount of ice in the ground mound depends on the variations of the heat-containing active ground layer during the tidal cycle. Thickness of the ground icing for the duration of the tidal cycle amounts to about 1 mm (0.003% of the fresh water flow rate) and increases with new tidal cycles. The total thickness of ground ice in estuaries can reach 0.5 m or more during the winter months.

The amount of ice forming on the under surface of the ice cover when it is cooled by sea water, is proportional to the volume of ground ice.

3.2.2. *Utilization of Heat of the Deep Water.*

When there exists sufficient thermal stratification across the depth of the basin (temperature difference at the bottom and on the surface above 0.5°C) the most economical way of keeping a water area free from ice is the method of bringing the warm deep waters to the surface (1, 6, 10). It can be done with pneumatic installations, flow generators and pneumatic flow generators.

Pneumatic installations are preferable at great expansion of the area to be protected, sufficient depth (6-7 m) and full regularity of the water temperature distribution across the basin depth. The main advantage of pneumatic installations lies in the fact that their operation does not cause any difficulties in ship movements on the surface of the basin. At similar conditions but not so large expansion of the water area it is more advisable to use the flow generators of radial-axial type which produce a surface overflow capable of shifting floating objects (ice blocks, timber in the rafting areas, etc.). At sharp temperature difference between the bottom water layers and the main bulk of water — which is typical for basins with different overflow on the surface and at the bottom — pneumatic flow generators or flow generators with an elbow are the best proposition.

At the initial stage of pneumatic installation design one can use the data listed in Table 1. More detailed calculations of such apparatus should be carried out utilizing the relationships described in bibliography 1, 10.

TABLE I

1. Water basin temperature at the level of the air duct location, °C	4	2	1	0.5
2. Possible width of the lane as a portion of depth H	H	0.75H	0.5H	0.3H
3. Air consumption (in l/min per linear metre of the air duct) required for maintenance of the lane of specific size	1-3	3-6	6-12	10-20
4. Spacing of holes in the air duct as a portion of depth H.	H	0.75H	0.5H	0.3H

When flow generators are to be used, the possible length of water area L_o maintained in non-freezing condition can be assumed, as a first approximation with due margin, equal to

$$L_o = \frac{127 \cdot 10^3 R_o U_o t}{S} \qquad (1)$$

where R_o is radius of the flow generator nozzle, in m;
U_o is speed of the jet leaving the flow generator nozzle (assuming the uniform distribution of speeds over the cross-section), m/sec.;
t is mean (in vertical) water temperature at the ice edge approximately equal to mean (in vertical domestic water temperature, °C;
S is heat emission from open water surface, ccal/m²/h.

Width of the water area B_o maintained free by a flow generator can be defined as

$$B_o \cong (0.12\text{-}0.14)\ L_o$$

The area to be maintained free from ice by a pneumatic flow generator can be obtained, with due margin, using the equation :

$$\frac{S}{7{,}2\ .\ 10^3\ t} = \frac{Qb \frac{\gamma}{\gamma - \gamma_1}}{2\sqrt{2\ \pi\ robo}} \cdot \frac{ro}{ro + x\ \eta} \sqrt{\psi\left(\frac{bo - y}{2\ a\ x\ \eta}\right) + \psi\left(\frac{bo + y}{2\ a\ x\ \eta}\right)} \quad (2)$$

where Qb is air consumption, m³/sec.;
γ_1 is unit weight of water/air emulsion in the delivery pipe, t/m³;
γ is unit weight of the water, t/m³;
ro is radius of the pneumatic flow generator discharge opening, m;
x_η is distance (along the radius) from the discharge opening to the ice edge, m;
bo is height of the pneumatic flow generator discharge opening, m;
ψ is Kramp function;
a is a coefficient approximately equal to 0.4;
y is vertical coordinate.

3.2.3. *Artificial Heating of Water Areas.*

Of paramount importance for shipping is the task of maintaining canals free from ice which can be achieved by rational location along the canal of appropriate heat sources such as steam electric stations using the canal as a cooling pond.

Distance X between the adjacent stations over which the water temperature is to change from t_o °C to t °C, can be found approximately using the following expression (10) :

$$X = \frac{C\ \gamma\ Q}{M}\ ln\ \frac{Mt_o + N}{Mt + N} \quad (3)$$

where Q is water consumption, m³/sec.;
M & N are coefficients from the heat emission formula which are used for terms depending and not depending on temperature, correspondingly;
C is water heat capacity, t/cal/t°C.

A more thorough analysis of the problem of temperature variation with length and depth of the canal can be carried out using the equation in bibl. 10.

To utilize heat reserves more economically, especially on a free-flowing river, it is advisable to find a way to separate the non-freezing ship channel from the rest of the river.

At warmer seasons, when a more intensive cooling is required, it can be achieved within the scope of the same arrangement by removal of the ship channel guarding devices and including all the basin area into the cooling surface.

To maintain a non-overflowing water basin in a non-frozen condition with minimum expenses it is necessary to feed it with water of moderate temperature ($\sim$ 20 °C) but of increasing flow rate, and to distribute the warm water uniformly over the basin area. The most appropriate design for this purpose is a system of perforated pipes laid out on the bottom of the basin. As the physical and convective heat conductivity of water in dead or only slightly overflowing basins is very low, it is necessary to obtain a higher turbulization of the flow thus saving a considerable amount of heat at the initial heating of the water mass and providing at the same time the transfer of the necessary amount of heat to the surface.

The task of freezing the water surface from already formed ice cover can be described by the equation given in Bib. 10 :

$$T = \frac{-\beta \gamma \eta \delta \eta}{(kgtc\ \gamma)^2} \left[\frac{kgtc\ \gamma}{\lambda\eta} \left(h_2 - h_1 \right) - tbln \frac{tb + kgc\ \gamma\ t \left(\frac{1}{\alpha} + \frac{hc}{\lambda c} + \frac{h2}{\lambda\eta} \right)}{tb + kgc\ \gamma\ t \left(\frac{1}{\alpha} + \frac{hc}{\lambda c} + \frac{h1}{\lambda c} \right)} \right] \qquad (4)$$

where T is time in sec.;
- β is latent heat of ice formation, t.cal/t;
- λ_1, λc are the corresponding coefficients of thermal conductivity of ice and snow, t.cal/m. sec. °C;
- h_1, h_2 is ice thickness at the beginning and the end of the time period in question, m;
- g is specific flow rate of the water, m³/sec.;
- k is a coefficient;
- c is heat capacity of water, t. cal/t. °C;
- γ is volume weight of water, t/m³;
- α is coefficient of heat emission from snow to air, t. cal/m sec. °C;
- t is water temperature, °C;
- tb is air temperature, °C;
- hc is thickness of snow cover on ice, m.

Equation (4) shows that the quickest and most economical clearing of water area from ice at low air temperatures can be achieved by maximum possible increase of temperature and flow rate of the feeded water.

As an example of solution of the above task an installation utilized at one of ship repairing facilities is described below (see also Fig. 4). It consists of two systems of perforated pipelines laid out on the bottom of the basin, of which one serves for warm water delivery and the other supplies the compressed air used for turbulization of the water mass and lifting the warm water to the surface. Design and calculations of the elements of the above system were carried out in accordance with the recommendations provided in Bibl. 10.

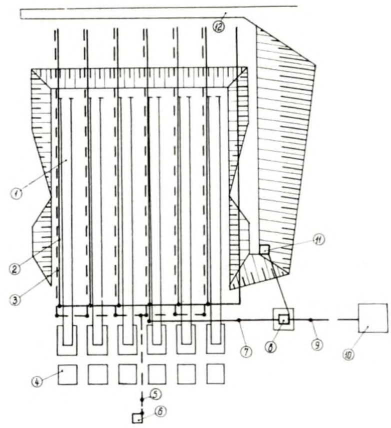


Fig. 4.

Diagram of arrangement of an artificial heating installation for maintaining ice-free water area around a slipway : 1. slipway runners; 2. perforated pipeline supplying hot water; 3. perforated air duct; 4. slipway winches; 5. air main; 6. air distribution well; 7. hot water main; 8. heat exchanger for water heating; 9. steam pipeline; 10. boiler room; 11. water intake; 12. dam surrounding the slipway water area.

Schéma d'installation de réchauffement artificiel devant maintenir à l'état non gelé le plan d'eau de la cale de halage : 1. plans inclinés de halage; 2. tuyauterie perforée à eau chaude; 3. conduite d'air perforée; 4. treuils de la cale de halage; 5. canalisation d'air; 6. puits pour distribution d'air; 7. canalisation d'eau chaude; 8. appareil échangeur de chaleur pour réchauffer l'eau; 9. conduite de vapeur; 10. compartiment de la chaufferie; 11. prise d'eau; 12. jetée protégeant le bassin de la cale de halage.

In recent years a principally new method of maintaining ice-free water areas was developed and tested in full scale (USSR certificate of authorship No. 279446); the method is in many respects superior to the previous design. The two systems of perforated pipelines are replaced with one supplying an equal mixture of heterogeneous agents : a heat carrier and a non-condensable gaseous usbstance. Instead of a compressor installation a jet apparatus is used — for instance, an injector for which the working medium is a heat carrying agent (steam) drawing a non-condensable gaseous agent (ambient air) into the apparatus. The steam-air mixture produced by the injector is then fed into the signle system of perforated pipes.

The main condition of operational efficiency of the installation is preparation of steam-air mixture with such parameters and proportion of mixed agents that would allow the delivery of the mixture to the outlet via the supply pipe at temperature and pressure preventing condensation of the mixture on the way. One of the ways to meet this condition is to manufacture the underwater part of the pipeline of a hot resistant plastic, e.g. polypropylene, heat conduction properties of which reduce the heat losses at the transfer of mixture to the outlet. Besides, the use of plastic as a material for the underwater pipeline eliminated the corrosion problem and increases the service life of the installation. Automatic control can be provided for the system.

For melting of the ice cover the consumption of steam and compressed air should be increased up to the maximum allowable limit. No constant supervision of the system's operation is required in this case. After breaking of the ice cover the system is controlled automatically. Control is performed by a director unit of which the main element is a sensor of heat emission from the water surface. It is designed as an electric hot-wire anemometer sensible to variations in wind speed, temperature and air humidity. The director unit allows to maintain a dynamic balance between the hydrosphere and atmosphere and achieve the optimal regime of the system's operation.

Full-scale experiments with creation and maintenance of ice-free water areas were carried out in the mouth of the N. Dvina; some are still continued in the Vanino harbour. Efficiency of installations of this type exceeds 50%. The most economical mode of system's operation is the one leading to formation of a thin — 5 to 10 cm — ice layer on the lane surface. This layer reduces heat losses to the atmosphere 2 to 4 times those observed on the open water surface.

For making limited size lanes in water basins lacking the heat reserves of near-bottom layers the best solution is use of flow generators with heating elements in the suction chamber and a nozzle for generation of a directed flow of heated water on the blowing side. Depending on availability of either electric power or a heat carrier (hot water or steam), tubular electric heaters, perforated pipelines, or steam-water jet apparatus (ejector) can be used.

In the last case, delivery of the heat carrying agent by a jet apparatus provides additional head before the pump screw which increases the flow generator output (USSR certificate of authorship No. 242691).

3.2.4. *Maintenance of Ice-Free Water Surfaces with the Use of Heat-Insulation Covers.*

Application of anti-freeze films and foaming componds for insulation of water surfaces is rather limited because a uniform layer of coasting can only by maintained for a short time and is inefficient at low temperatures.

For parts of water areas protected from high seas, winds and currents a new method has been developed and full-scale tested which prevents ice formation on water basin surfaces by creation of a heat-insulation surface layer consisting of grains of a non-water-absorbing material — like foamed polystyrene or keramsite (USSR certificate of authorship No. 341906). Thickness of the layer is selected on the basis of the forecasted air temperature and heat insulation properties of granular material.

Results of full-scale experiments carried out in the mouth of the N. Dvina in winter of 1970 indicate that a 35 cm thick granular layer of the type ∾Cb foamed polystyrene is sufficient for prevention of ice formation on the water surface. The experiments continued for two months (January and February); the mean air temperature was — 14.7°C, minimum air temperature was — 35.1°C, wind speed varied from 3 to 4 m/sec, mean relative humidity was 63%. When the heat insulation layer is not needed any more it is removed by air ejection and the granular material is stored in a ventilated room throughout the winter. This method can be successfully applied to prevent ice formation in front of slips, docks and similar water engineering structures.

Besides, the above method is well suited for protection of hydraulic structures and floating facilities by maintaining non-freezing trenches in the ice cover around them, as well as fire leads and ice-holes in fish ponds.

To prevent adfreezing of piling into the ice cover a special device was designed (USSR certificate of authorship No. 293922) which consists of a split floating box surrounding a pile or a group of piles and extending the whole depth of their possible joint with the ice cover. The space between the box walls and the piles is filled with granular heat-insulation material of foamed polystyrene or keramsite type.

The box walls are manufactured of polystyrene sheets insuring buoyancy of the box and ice-free water surface inside it. Equal spacing of all the walls from the piles is achieved by use of adjusting bolts. The box is submerged to the required depth by weights fastened in its lower edge.

3.3. **Principles of Design and Development of Facilities for Arresting and Controlled Displacement (Evacuation) of Broken Ice.**

As noted above, water areas of most water transport enterprises and organizations in winter period are covered with broken ice of varying compactness and thickness.

Selection and maintenance of parts of water areas in ice-free condition is a problem that cannot be solved without efficient and reliable means of arresting and controlled displacement of broken ice masses. In majority of cases uninterrupted operation of such enterprises can only be achieved by combination of different means.

3.3.1. *Influence of Ice on the Hydrotechnical Structures.*

The ice has a considerable influence on the stability, strength and durability of the hydrotechnical structures. In the USSR when projecting and constructing the hydrotechnical structures, taking into account a great importance of this problem and the need of the most complete registration of ice destructive action, the official and departmental normative documents were worked out and introduced into practice to registrate quantitative criteria and design values stipulating the demands to hydrotechnical concretes and constructive elements.

In accordance with the instructions in force, when projecting, the hydrotechnical structures and piers, the following ice loadings must be taken into account :

a) dynamic loadings :

a loading arising from contacts of separate ice-floes;
a loading arising from ice-blocking and ice-jam;

a loading arising from ice-floes friction against the surface of a structure;

b) static loadings :

a loading arising from a compact ice cover at its thermal expansion;
a loading arising from pressure of ice field on structures under the influence of the wind and current;
a loading transmitted by ice cover freezing to a structure with fluctuations of water level.

The instructions and guides for the determination of ice loadings on the structures recommend design formulae permitting to define and calculate the ice loadings on the following types of structures :

a) supports with vertical front sides;
b) supports with inclined front sides;
c) vertical walls;
d) slopes;
e) separate piles and piled groups.

When calculating, it is necessary to take into account the following initial factors : ice thickness, area of ice field, its mechanical strength, velocity and direction of ice drift under the influence of current and wind.

The operation of reinforced concrete structures in conditions of repeated alternative freezing and thawing has a considerable influence on the duıability of structures. The durability of hydrotechnical structures operating in conditions of negative temperatures is secured by the following measures : using a stable concrete to outside physical factors; constructive means; thermo-hydro-insulating protection of concrete to rise its frost-resistance.

The resistance of hydrotechnical concrete to the influence of outside physical factors is determined by the complex of its characteristics. The concrete must have a proper frost-resistance, a little water-absorption and a little linear change with wetting and drying.

The frost-resistance of concrete is characterized by the greatest number of cycles of alternative freezing and thawing sustained by 28-days samples when testing without reduction of strength more than 15%.

The marks of hydrotechnical concrete by frost-resistance are determined according to Table 2.

TABLE II

Number of freezing and thawing cycles sustained by concrete when testing, no less than. .	50	100	150	200	300	400	500
Marks of concrete by frost-resistance	Mp3 *) 50	Mp3 100	Mp3 150	Mp3 200	Mp3 300	Mp3 400	500

*) Mp3 is a frost-resistance of concrete.

Taking into account operating conditions, marks by frost-resistance of hydrotechnical concrete of a zone with alternative level of water and a spillway border of river hydrotechnical structures depending on climatic conditions and a number of designed cycles of alternative freezing and thawing during a year (according to data of long-term observations) are fixed according to Table 3 (provided the use of surface — active additions).

For river structures with designed average monthly temperatures of the coldest month from 0 to — 20°C and with number of more than 200 of alternative freezing and thawing cycles during a year, the mark of hydrotechnical concrete by frost-resistance is fixed in each particular case.

TABLE III

Climatic conditions	Mark of concrete by frost-resistance with the greatest number of cycles of surface freezing and thawing				
	to 50	from 50 to 75	from 75 to 100	from 100 to 150	from 150 to 200
Temperate	Mp3 50	Mp3 100	Mp3 150	Mp3 200	Mp3 300
Severe	Mp3 100	Mp3 150	Mp3 300	Mp3 300	Mp3 400

In addition, in case of need, special measures are taken to protect the concrete from a dangerous action of low air temperatures. Nevertheless, a mark of concrete by frost-resistance must be taken no less than these indicated in Table 4.

TABLE IV

Climatic conditions	Mark of concrete by frost-resistance, no less than	
	with thermo-hydro-insulation	without thermo-hydro-insulation
Temperate	Mp3 200	Mp3 300
Severe	Mp3 300	Mp3 400

When the average monthly temperature of the coldest month is below — 20°C, the mark of concrete by frost-resistance is based on the conditions of structure's operation.

The climatic conditions are characterized by the average monthly temperature of the coldest month : temperate — from 0 to — 10°C; severe — from — 10° to — 20°C; extra-severe — below — 20°C.

The average monthly temperatures of the coldest month is determined according to Building norms and rules or field observations of many years.

Constructive solutions have a great importance to rise the durability of hydrotechnical structures. The choice of its scheme is made with regard for influence of strained state of constructions materials. In the regions of severe (difficult) working conditions in the parts of constructions, situating in a zone with variable horizon and non-protected by thermo-hydro-insulation, the working (acting) tensions must not exceed 0.2 $R^{H}np$, and compressing tensions must not be more 0.4 $R^{H}np$ for ordinary concretes and 0.75 $R^{H}np$ for concretes with air-drawing and gas-generation additions.

Notes : 1) Acting tensions are determined with influence of normative loadings taking into account the normative characteristics of materials.

2) Tension of compression is determined with regard for outside loading and tension of pressure from prestressing armature.

The surface of constructive elements, subjected to alternative freezing and thawing, must have the least relation to the volume with minimum quantity of projections and joints.

The thickness of reinforced concrete strained and non-strained elements of constructions is defined by calculation, but from the conditions of their work with negative temperatures; it must be no less than 15 cm for casing piles and no less than 20 cm for grooved piles, elements for upper structure and corner walls.

For elements of constructions situated in the zone with a variable level, the thickness of protective layer of constructive armature must be no less than 5 cm.

Thermo-hydro-insulating covers are an effective means against thawing, especially in the zone with a variable level.

The following types of thermo-hydro-insulating protection were worked out and are used :

— thermo-hydro-insulating cover of bitumen-slag mixture in form of a monolithic belt, screen or revetment by finished plates;
— impregnation of finished elements by a hot bitumen at high or atmospheric pressure;
— revetment of concrete surfaces by reinforced concrete plates, impregnated by the bitumen;
— revetment by arboreal plates, impregnated by phenol-formaldehyde resin.

A thermo-insulating revetment is placed on the constructions with using special elastic mastics. The construction and the type of a thermo-insulating protection depend on local conditions, shape of a structure and other factors.

The practice of the operation of sea and river hydrotechnical structures in hard conditions confirms the efficiency of a thermo-insulating protection.

Taking into account a great importance of a more precise determination of ice influence on different types of structures, scientific, research institutes do work to specify design formulae and propositions provided by normative documents and in this connection, they are corrected and republished periodically.

3.3.2. *Mechanical Means of Arresting the Broken Ice.*

For protection of navigation locks ice-holding booms are used in front of the gate recesses (3,4). To let a ship pass the boom is lowered to the bottom, in operating position its upper edge is raised 15 to 20 cm over the water level. The total height of the boom is 1.5 m. When designing an ice boom three kinds of possible loads should be considered : a dynamic impact of a separate ice-block driven by currents which emerge in the sluice chamber at its emptying through the by-pass galleries in the lower head; pressure of a mass of broken ice filling the chamber by the action of the same currents; pressure of ice displaced by a ship moving inside the chamber.

Loads of the first kind can be calculated on the basis of the kinetic energy equatio; the following formula for determination of the force P acting on the boom is to be used :

$$P = 2 \sin\alpha \sqrt{\frac{ES}{B}\left(\frac{h\,\Omega\,\gamma_{\eta}\,V_{\eta}^{2}}{2\,g} - P_1\,f\right)}$$

where h is ice-block thickness in m;
Ω is ice-block area, m²;
g is acceleration of gravity, m/sec³;
γ_{η} is specific weight of ice, t/m³;
B is ice-boom span (chamber width), m;
E is cable elasticity modulus, t/m²;
S is cross-section area of the cable holding the ice-boom, m²;
P_1 is weight of a linear meter of the ice-boom, t;
f is initial sag of the ice-block, m;
α is angle between the ice-boom cable and perpendicular to the lock axis, deg.

Load in tonnes per linear meter of the ice-boom P — at the second kind of loading can be determined by the relationship :

$$P = \left(\alpha\,\gamma\,\delta + 0{,}172\,\beta\,\gamma\,B^{2}\right)\frac{V^{2}\,surf\,f}{2\,g} \qquad (6)$$

where α is coefficient depending on the ice block butt shape and varying from 1 to 2;
γ is specific weight of water, t/m³;
δ is ice thickness, m;

$V_{surf.}$ is surface velocity of the flow, m/sec;

β is coefficient taking into account friction of the flow against the bottom surface of the ice and varying from 0.05 at $\frac{\delta}{H} = 0.1$ to 0.2 at $\frac{\delta}{H} = 0.45$;

H is depth of water in the chamber at the moment, m.

Load in tonnes per linear meter of the ice-boom — P — produced by a ship's pressure on ice accumulated before the ice-boom is to be considered only in cases when the distance between the ship and the boom is less than 3B. The maximum value of this load can be determined by the equation.

$$P = \frac{R\left(1 - \frac{f}{tg\alpha}\right)}{B} \tag{7}$$

where R is ship pressure produced by the thrust of ship propellers, t;

f is a coefficient of ice friction against the concrete;

α is angle of flare of ship's bow.

Load values obtained for typical conditions of the middle part of the USSR and for a ship of 5000 t dwt, using the above formulas, are listed in Table 5.

When the lock is long enough the load produced by a ship's movement can be eliminated by stopping the ship at a distance above 3B from the ice-boom. For locks about 30 m wide the limiting factor will be the pressure of a mass of broken ice, and for locks 18 m wide — the impact of separate ice-blocks.

The existing types of mechanical barriers in most cases cannot ensure passage of ships with simultaneous reliable arresting of ice. In areas with low-intensity traffic, floating booms are ordinarily used which, to let a ship pass, are drawn aside by tugs or shore winches. During this operation a considerable amount of broken ice penetrates into the enclosed water area.

TABLE V

Type of load	Load		Stress in the ice-boom cable, t	
Width of the lock	B = 30 m	B = 18 m	B = 30 m	B = 18 m
First type — Formula (5)	0.6t	1.9t	5.6	10.7
Second type — Formula (6) . . .	0.06t/lin. m	0.05t/lin. m	8.4	2.5
Second type — measured in a full-scale test	0.07t/lin. m	—	10.0	—
Third type — Formula (7)	0.25t/lin. m	0.42t/lin. m	35.0	21.0

Recently, new designs of floating booms were introduced for the purpose of arresting the broken ice at ship's entering the enclosed water area of a port, a ferry berth or a floating dock. One of such designs is an adjustable floating barrier consisting of a system of floats — one or more compact rows of floats extended along the whole boundary of the protected water area (Fig. 5).

When broken ice is driven against them, the rows of floats are pressed together forming a reliable barrier. As a ship passes through such a barrier the floats which are situated directly in front of the ship are parted by its hull and form compact accumulations at its sides.

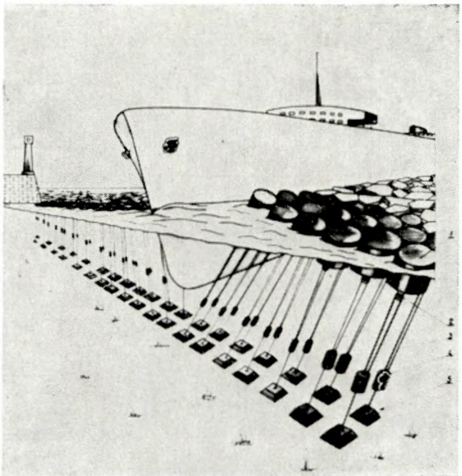


Fig. 5.

Adjustable floating boom for water area of a port :
1. floats; 2. block; 3. cable; 4. weight; 5. anchor.

Masque latéral à glissière du bassin du port :
1. flotteurs; 2. poulie; 3. câble; 4. poids; 5. ancre.

After the ship has passed through or there is no more pressure of the broken ice the weights are lowered down and the floats return to the initial position.

For removal of broken (but non-adhered) ice from under the ship's bottom before dry-docking, a special device was developed and tested (USSR certificate of authorship No. 227117). There is a scrubber mounted on the pontoon deck which consists of two symmetrical elements forming (in plan) an angle with its vertex directed towards the towed ship and aligned with the ship's center line. Each of the scrubber elements is pivotable around the axis and the part located lower than the axis is equipped with a balance weight helping to decrease the expenditures of energy on cleaning the hull from ice and pressing of the scrubber to the bottom when the ship's draught varies along its length due to ship's trim. The upper edges of scrubbers have nozzles for delivery of directed jets of water, steam or compressed air. The scrubber base can be adjusted for different height which provides for higher efficiency and better fit of the scrubber to the bottom at different deadrise of ships to be docked.

For protection of water areas — and, particularly, ferry berths — a special device has been developed (USSR certificate of authorship No. 337295) consisting of a net which is spread along the contour of the ferry berth (Fig. 6). The net is fastened to two supporting cables the ends of which are connected to the balance weights via a pulley block system anchored on the foundation mat of the ferry berth. Pileworks of the central and side piers forming the ferry berth carry the trusses with built-in guiding roller holders. The supporting cables are passed

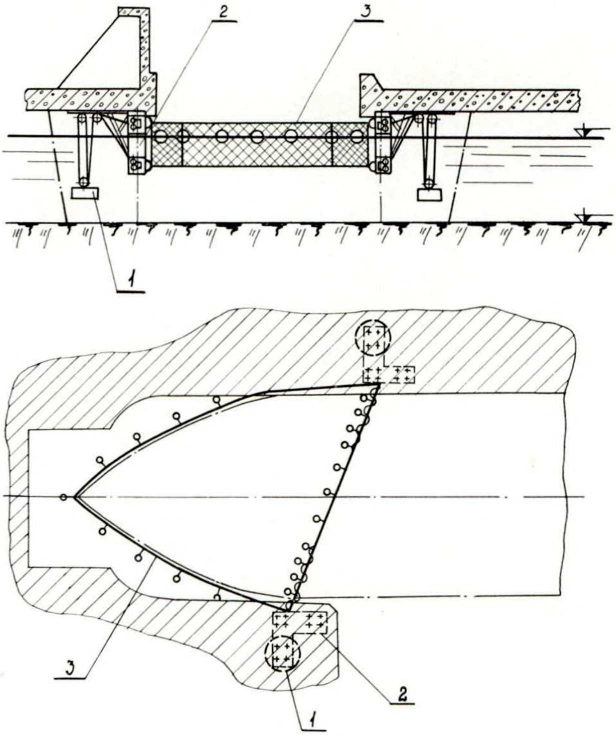


Fig. 6.

Movable ice-keeping boom protecting a ferry berth :

1. Weight suspended from a system of cables and blocks;
2. Trusses with guiding rollers;
3. Net screen with floats.

Barrage mobile de retenue de glace protégeant un lit de bac :

1. Poids commandé par câble et poulies;
2. Poutres avec galets de guidage;
3. Masque à filets avec flotteurs.

through the appropriate rollers. The ends of supporting cables are fastened to balance weights via multiple pulley blocks including double pulleys. The net is suspended from the cables on free-sliding rings and the ends of it are fastened to the piles or trusses. The floats supporting the net are fastened below the lowest water level on the side of the protected water area.

When the ferry is coming in it gets into contact with the net and, moving forward, is pushing the ice together with the net. The net is sliding on rings along the cables constituting a barrier for the ice which is pushed by the ferry. Due to the balance weights the supporting cables are kept taut all the time. The multiple pulley blocks permit the cables to lengthen by the required amount. The guiding roller holders ensure constant vertical position of the net.

When the ferry leaves its berth, the net returns to its initial position under the action of the balance weights and ejects the broken ice from the berth. Further, it protects the berth from drifting ice. The water area of the berth is kept in non-freezing conditions using one of the techniques described in Chapter 3.2.

3.3.3. *Pneumatic and Flow-Generating Installations for Arresting and Controlling Displacement of Broken Ice.*

Pneumatic installations for arresting the broken ice are well known in many countries. Their principal arrangement was described above (item 3.2.2). Kinematics of the flow generated by a pneumatic installation and some dependences which can be used for design of such installations are described in detail in Bibl. 1,10.

These installations are mounted on sills of dry docks and at the end faces of floating docks for arrest of the broken ice. At ice thickness of up to 50 cm the rated consumption of compressed air is 0.8 to 1.1 m^3/min per linear meter of the installation. The main drawback of such installation is interruption of the protective breaker created by the installation when a ship enters the dock and penetration of considerable amount of ice into the dock chamber with the ship. Besides, these installations have no capability for removal of ice blocks accumulated under the ship bottom at ship's approaching the dock.

A very effective means of protection of water areas and structures from broken ice is systems of flow-generating installations. Besides arresting and directed displacement (evacuation) of broken ice, flow generators prevent ice formation on water areas by creation of directed surface water flows. Sealed flow generators are used for removal of broken ice from under the ship bottom before putting the ship into a dry or floating dock. Depending on the design of the structure, its location and function specific systems and arrangements of flow generators have been developed (USSR certificates of authorship Nos. 266608, 290991, 312786, 319671). These arrangements ensure automatic operation of flow generators at varying water levels in the docks (at submergence and surfacing of floating docks, at flooding and pumping out of dry docks, at ships' entering a dock).

An approximate calculation procedure has been developed for determination of optimum number and parameters of flow-generating installations and selection of their distribution arrangement depending on the design particulars of the structures and hydrometeorological conditions of the water areas. Such a procedure in respect to a floating dock is described in Bibl. 7,10.

At the moment of a floating dock submersion the following forces act on the surrounding field of broken ice : friction of the flow against the underside of ice blocks (F_1); hydrodynamic pressure on the underwater part of the ice field edge face (F_2); friction of air against the upper surface of ice blocks (F_3); a force due to the slope of the free surface (F_4); friction of ice against the internal walls of the dock sides and various appendages (F_5).

As force F_5 is equally opposed to both the forces pushing ice into the dock and the hydrodynamic action of the artificially generated flow in floating ice blocks, it is assumed possible to leave it out.

The drawing force of flow F_{no} created by the flow generators is a sum of forces F_1 and F_2 which push the ice out of the submerging dock. Force F_{no} must be equal or slightly exceeding the total pushing-in force F_b to be able to ensure the backward displacement of the ice at the required distance. Taking into account the above factors, the formula for calculation of the surface current velocity V_n (m/sec) to be created by the flow generators will lock like this :

$$V_n = \sqrt{\frac{0.8\,(1.2\,V_d^2\,B + 18.4\,V_d^2\,h + 0.24\,B + 4416\,Bh\,\dfrac{V_D}{L_D}}{B + 30\,h}} \qquad (8)$$

where V_d is surface velocity of the flow filling the inner space of the dock, m/sec;
B is distance between the inner walls of the dock sides, m;
h is average ice thickness, m;
V_D is average speed of dock submergences, m/sec;
L_D is dock length over the pontoon deck, m.

The average speed of water ingress into the dock at submergence speed of V_D can be calculated in terms of flow rate of water coming in at one of the two open ends, and surface velocity V_d of the incoming flow is best found using the diagram for = 90° (Bibl. 7).

Studies of propagation of underwater hydraulic streams in a limited space (dock chamber) permitted to find a dependence between velocity V_n and thrust developed by the hydrodynamical complex of flow generator P_y :

$$V_n = \frac{1.54 \sqrt{P_y}}{L + 14.3\,R} \tag{9}$$

where R is radius of flow generator screw propeller, m;
L is distance from the cross-section of the flow generator nozzle to any cross-section along the length of the flow, m;
P_y is thrust of hydromechanical complex varying between 20 and 28 kg per one kilowatt of electric motor capacity.

Knowing the relationship for parameters of a jet propelled from a nozzle into a mass of the same liquid — which is based on the equation of liquid transfer with varying flow rate — one can obtain :

$$L_p = K_p \left(\frac{V_o}{V_{cp}} - 1 \right) \tag{10}$$

where L_p is distance between the nozzle exit cross-section and the analysed cross-section;
V_o is average velocity of efflux;
V_{cp} is average velocity of the flow at the given cross-section;
K_p is experimental factor.

Equations (9) and (10) are very helpful for rational location of flow generators over the dock's length — minding that the surface velocity of the flow generated thereby in a cross-section where the next pair of flow generators is to be mounted, should not be less than V_n.

Distance L_2 (m) between the rows of flow generators (Fig. 7) is determined taking into account parallel propagation of two streams in the wake created by the previous rows of generators; the following formula is used :

$$L_2 = m_g \left(\frac{1.54 \sqrt{P_y}}{V_n} - 14.3\,R \right) \tag{11}$$

where m_g is multi-jet factor depending on the distance between the axes of adjacent parallel jets.

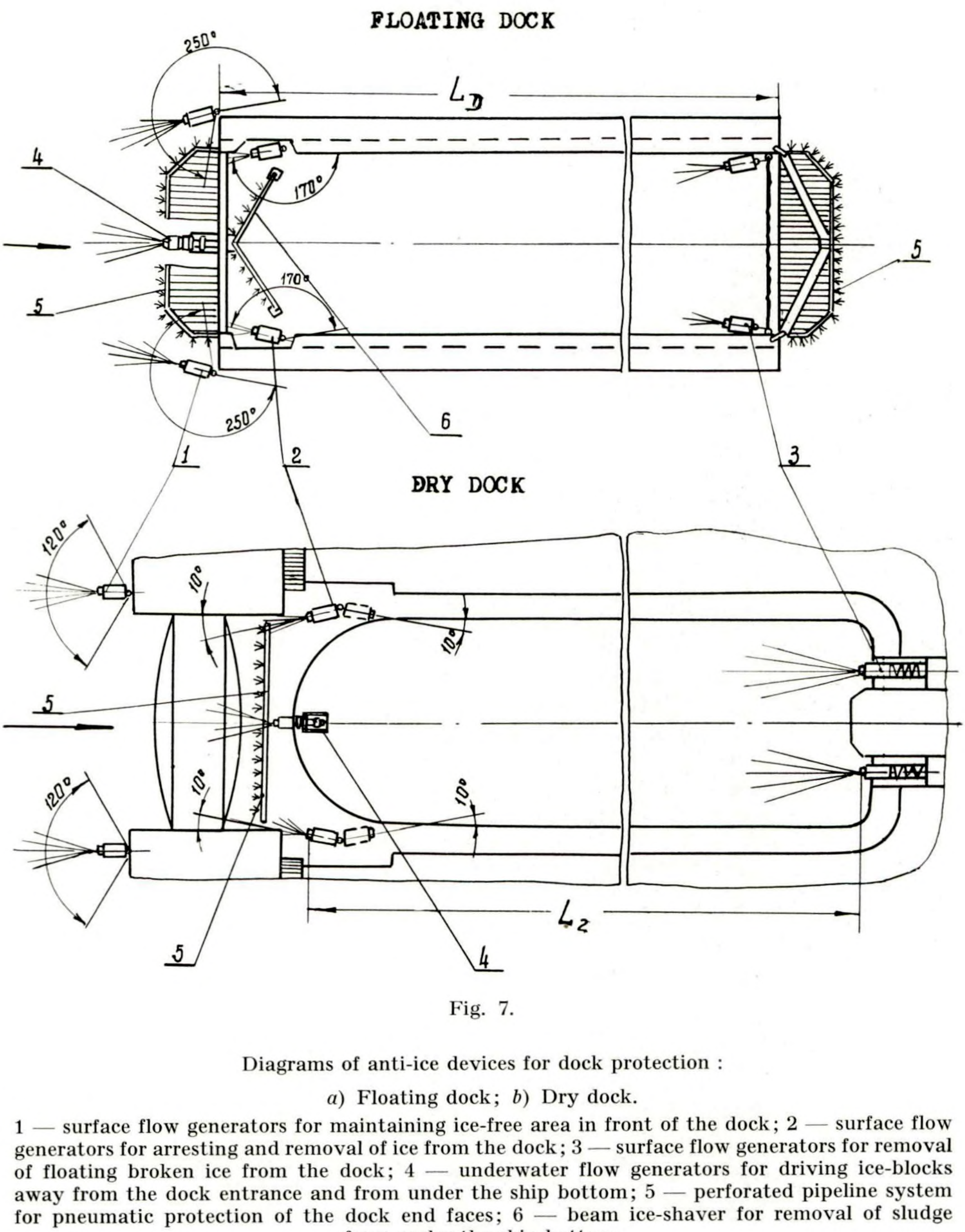


Fig. 7.

Diagrams of anti-ice devices for dock protection :

a) Floating dock; *b*) Dry dock.

1 — surface flow generators for maintaining ice-free area in front of the dock; 2 — surface flow generators for arresting and removal of ice from the dock; 3 — surface flow generators for removal of floating broken ice from the dock; 4 — underwater flow generators for driving ice-blocks away from the dock entrance and from under the ship bottom; 5 — perforated pipeline system for pneumatic protection of the dock end faces; 6 — beam ice-shaver for removal of sludge from under the ship bottom.

Schémas des dispositifs destinés à combattre les glaces dans un dock flottant :

a) forme flottante; *b*) forme de radoub.

1 — générateur de courant hors de l'eau pour maintenir une partie du plan d'eau, devant la forme, dégagée des glaces; 2 — générateurs de courant au-dessus de l'eau pour retenir et évacuer les glaces de la forme; 3 — générateurs de courant au-dessus de l'eau pour évacuer la glace morcelée flottante; 4 — générateurs de courant submergés pour chasser les glaces devant l'entrée de la forme et les évacuer du dessous du fond du navire; 5 — tuyauteries perforées du système de protection pneumatique des parements de la forme; 6 — racloir à balancier pour éliminer la glace finement morcelée du dessous du fond du navire.

Operation of anti-icing devices developed in accordance with the above procedure and installed in actual docks proved their high efficiency in ensuring uninterrupted ship docking in ice conditions (Fig. 2*b*).

3.4. **Use of Aircraft Gas Turbines (after Termination of their Flying Life) as an All-Purpose Solution of Ice Problems**

A surface-adapted aircraft engine is a universal power plant which can ensure winter operation of large waterway structures or a group of structures without additional power sources.

For such adaptation usually the most common mass-produced engine is selected — a gas turbine engine, as a rule The fuel system is converted to a heavier — and cheaper — diesel fuel. A system for utilization of hot compressed air produced by last compressor stage is provided.

As the hot exhaust gases have a low exit pressure ($\sim$ 0.4 kg/cm^2), it is raised by an injection chamber mounted at the engine outlet into which chamber high-pressure air from the compressor is introduced.

The heat carrier produced in the injection chamber — a mixture of air and exhaust gases — can be utilized by different heating installations and ejector pumps. The clean hot compressed air produced by the aircraft engine compressor is used for heating of operational areas of the structure.

The shaft power of the surface-adapted engine is now utilized, instead of propulsion, for driving an electric alternator with output of about 1500 kW or an additional air compressor. Other design solutions are also possible.

The main characteristics of the converted aircraft engine are given below :

— diesel fuel consumption . . . . 800 kg/h;
— fuel heat output . . . . 10150 kcal/kg;
— properties of gas mixture produced in the injector :
  output . . . . 20 kg/sec;
  temperature . . . . 320^{o}C;
  pressure . . . . 1.5-2.0 kg/cm^2
  heat content . . . . 8.12-10^6 kcal/h.

3.4.1. *Winter Operation of Ferry Lines in Hard Climatic Conditions.*

Problems arising in operation of ferry lines at below-zero temperature periods and described in 2.5 above can be solved by using a system of ice combating devices capable of :

— creation and maintenance of ice-free water areas at the ferry berths;
— dispersion or thinning of broken ice in front of the berth to ensure proper manœuvring of the ferry;
— arresting and evacuation of broken ice from the ferry berth area;
— prevention or elimination of ice formation on the elements of liftable gangway and fenders;

— prevention or elimination of fast ice on the piers in the boottop area.

Since a great majority of ferry crossings is operated in water basins devoid of heat accumulated in near-bottom layers, the most efficient way of ice combating at present is the artificial heating of the water area.

A converted gas turbine aircraft engine is the most suitable power plant for this purpose.

A method has been developed for operation of the ferry line in winter periods using devices which are supplied with hot gases from the aircraft engine.

Maintenance of a ferry berth water area in ice-free condition is achieved through the heating of water with exhaust gases.

To remove the ice blocks brought to the berth area by the approaching ferry, some water-gas ejectors are installed along the pier in the boottop area which create directed surface flows of water. To arrest broken ice in front of the ferry berth, a perforated pipe is laid on the bottom of the basin which delivers compressed air creating a powerful protective breaker on the water surface. To prevent icing of fenders and damping devices, pier walls, moving elements of ferry bridges, hot exhaust gases are also used which are delivered through special channels and ducts.

Besides serving the anti-icing devices, the thermogas generator based on the aircraft engine meets other requirements of the facility : it produces electric power, hot compressed air, heated water, etc.

3.4.2. *Winter Operation of Docks in Hard Climatic Conditions.*

To ensure uninterrupted operation of docks in below-zero periods it was proposed to use an aircraft gas-turbine engine converted, after the termination of its flying life, as described in Ch. 3.4. One aircraft engine is capable to meet operational and maintenance requirements of a whole group of docks, as docking of ships in the latter case is usually carried out in each of them in turn.

In this case the thermogas generating installation includes two aircraft engines of which one is a stand-by. The system of pipelines for intake and distribution of head carrier consists of a manifold for hot compressed air received from the engine compressor and a manifold for gas-air mixture produced in the jet apparatus (injector).

The hot compressed air is used for the following purposes :

— heating of the work area of the dock, drying of the ship hulls under repair, mild drying of the painted surfaces of ship structures — for this purpose a system of perforated air ducts is laid out on the bottom of a dry dock or the pontoon deck of a floating dock;

— air protection of the dock end faces from wind and creation of a powerful water-air barrier preventing penetration of broken ice from the surrounding water area into the dock at its submergence — for this purpose the end faces of the dock are equipped with air ducts having slots for discharge of compressed air.

The gas-air heat carrier is used for the following purposes :

— heating of water area in front of the dock and maintaining it in ice-free condition;
— removal of fast ice and ice bowl from the ship's underwater hull before putting the ship into a drydock by first placing the ship over the water area heating system;
— prevention of water freezing in the ballast compartments and pipeline systems of floating docks, as well as elimination of ice mounds on the pontoon deck by discharge of gas-air heat carrier into the ballast compartments of floating docks or into a special pipeline system installed inside the basement of dry docks;
— supply of outside water (with simultaneous heating of it) for hydrostatic testing of repaired ship compartments by ejection of water with the use of hot compressed air.

When an aircraft engine is used, as described above, the problem of winter drydocking is solved in an integrated way, by application of a single universal means. The fullest utilization of thermal and mechanical energy resulting from the burned fuel is then achieved, capital investments and operational expenditures are reduced considerably.

3.5. **Experience Gained at Practical Application of Methods and Means for Solving Ice Problems in Shipping.**

3.5.1. *Effect of Consideration of Ice Conditions in Shipping.*

Practical utilization of the data obtained in investigations of influence of environmental conditions on shipping and, in particular, of dependence between ships' speed and ice cover conditions, can yield considerable economic effect.

On inland waterways a very essential activity from the national economy point of view is the annual expeditions connected with transportation of industrial products and consumer goods up the side rivers. The convoys have to pass over water storage basins still covered with a strong ice layer which cannot be overcome without a line icebreaker assistance. Such escorting operations are now customary in the upper Volga, upper Kama and a number of other areas. Transportation costs involved in this case are considerably lower than in transportation by road.

Utilization of icebreakers plays an important part also on the principal inland routes as it allows to speed up the opening of the navigation period on those lengths of the routes which are the most critical in this respect — such as the Volgo-Baltic canal on the Leningrad-Astrakhan route, etc. In the autumn period icebreakers make it possible to extend the navigation and ensure the planned distribution of the fleet among the wintering bases which, in its turn, would make it possible to start the next-year navigation at the proper moment.

3.5.2. *Combination of Measures Insuring Lock Operation at Sub-Zero Temperatures.*

The above combination (3,4) first of all includes maintenance of the headwater level in the between lockages which prevents ice formation on most lock elements (Fig. 1*b*). This measure is particularly effective in locks with chambers situated in the headwater (in relation to the head front of the hydroengineering complex) as it provides the most favourable operational conditions for all the elements except the lower gate. Composition and location of the principal devices for a typical combination are shown in Fig. 8.

This combination is for the upper head main gate of the vertical-lift type which between lockages is in the lowered position. In the slots under the bottom of the gate nozzles are mounted through which air is pumped with a rate of 0.01-0.05 m^3/min per nozzle. Besides, across the lock bottom a perforated pipeline is laid for delivery of air with a rate of 0.005 m^3/min per linear metre. This ensures non-freezing water area over the gate and removal of broken ice from the area. In case of small variations of the headwater level the pneumatic installations can be replaced with submerged pumps having water output of 160 m^3/h driven by 20 kW motors; the pumps are fixed on the gate in the vicinity of the heel posts.

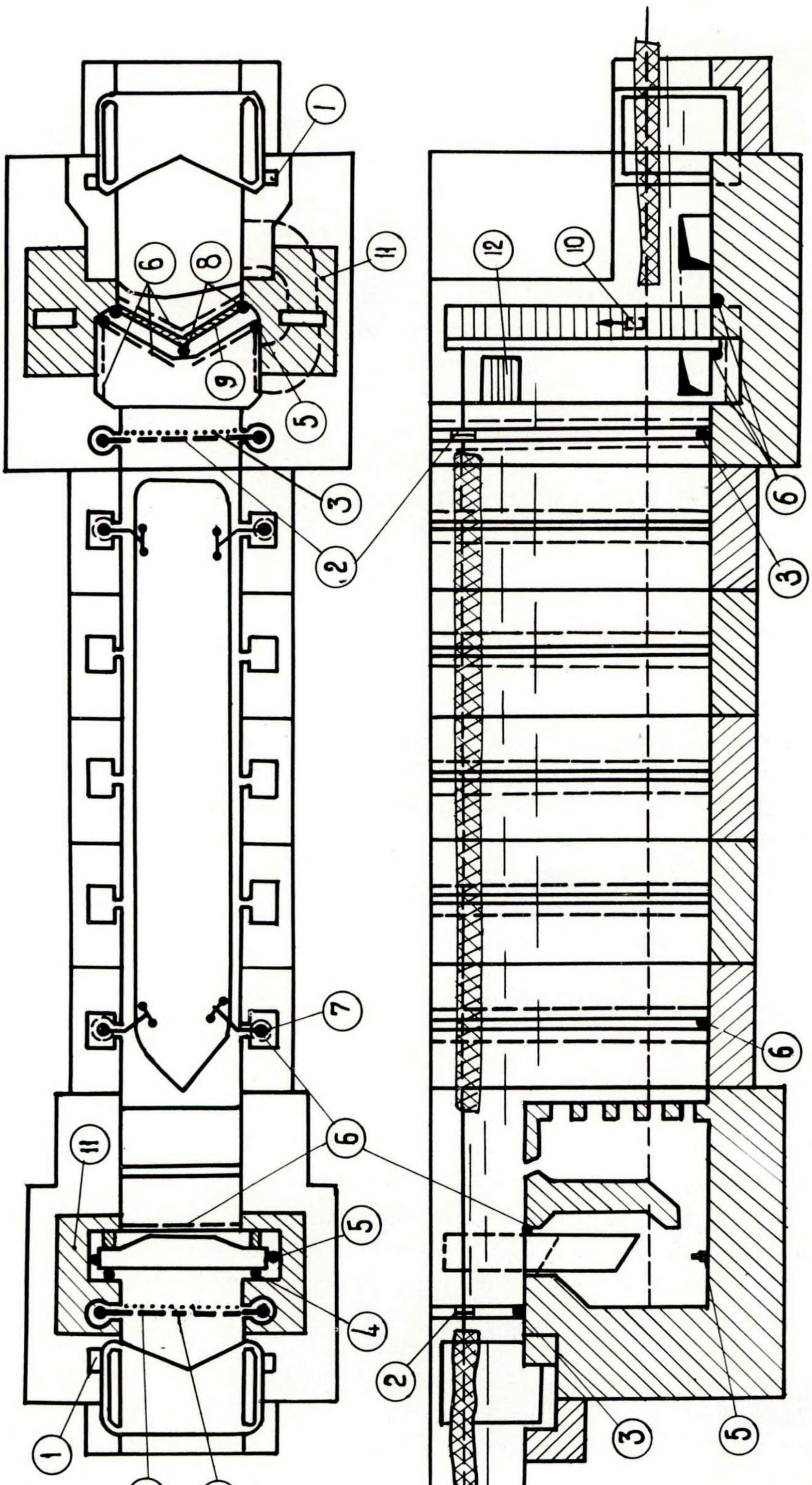
Heating of lifting chains and cables is carried out by electric air heaters; chains and cables above the water surface are placed inside boxes isolating them from the ambient air. Height of lifting of the main sluice-door for filling the chamber is selected with the purpose of eliminating the possibility of ice-block penetration under the door and damaging the seals. If such an arrangement is not possible, in front of the gate during the chamber filling period an ice-arresting boom is put on with a metal net fastened on cables. To let a ship pass, this boom is lowered on to the sill by means of winches. To avoid icing of the boom in non-operational condition it is also stored on the sill, and an ice-free water area over it is maintained by a pneumatic installation mounted across the sill and nozzles fixed in the slots. Under particularly difficult conditions heating of the boom elements within the slot may be required, with power consumption amounting to 1.5-3.0 kW.

When the upper head is provided with a mitred gate its anti-icing equipment is similar to that of the lower head gate described below.

Floats with mooring rings mounted inside the chamber are usually provided with heating devices (Fig. 9) of 1.5-5.0 kW output; the number of floats in this case is limited to a necessary minimum. In each float shaft a nozzle is fixed with air flow rate of 1.0-1.5 m^3/min.

As, at the above arrangement, the lower head gate operates almost continuously under pressure and at sub-zero air temperatures; it should be manufactured of a killed steel.

The design of the lower gate seals should provide for closedcycle heated zones, with filtered-through water running into the lower pond without forming an ice mound. Power output required for the heating is about 5 kW.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The outward side of the gate is lined with an insulation coating to avoid icing of the side facing the chamber. The coating is made up of synthetic thermal-insulation materials. Whenever necessary, the spàce between coats is heated by electric stoves of 1.5-3.0 kW.

To maintain the water area inside the gate recesses in ice-free condition, to drive away the floating ice from the gate movement area and to prevent ice mound formation on the recess walls, perforated pipelines with air flow rate of 0,01-0,05 m^3/min per linear metre are laid down along the walls and under the gate leaf bottom edges. In the strut-gate parts of the recess either nozzles with air flow rate of up to 5.0 m^3/min or submerged pumps with a 160 m^3/h output are installed. The latter are employed in cases when the lower pond level variations are insignificant (e.g. the lock is on a canal). In particularly hard conditions, installation of heating elements along the recess walls and pressure side of the gate (at about the headwater level) may be required.

A perforated pipeline should also be provided on the lower pond side of the gate leafs to prevent adherence of the leafs to the ice cover in the downstream approach channel.

To prevent penetration of ice from the chamber into the recess area an ice-holding boom is provided which is fastened to heated floats placed inside special shafts and moving up and down following the water level in the chamber. The boom, similarly to the one at the upper gate, in supplemented with a pneumatic blower.

In machinery compartments of the lock a temperature of at least + 5°C is maintained by electric stoves. To ensure safe lockage of ships at dark hours, snowfalls and blizzards, a more intensive lighting is employed, as well as heating

←

Fig. 8.

Diagram of a lock equipped for operation at sub-zero air temperatures :

1. Recess for flow-forming device.
2. Ice-boom.
3. Perforated airline with nozzles.
4. Heating of the upper part of the gate sealing.
5. Air nozzle.
6. Perforated airline.
7. Heated floating mooring ring.
8. Heating of the saddle beam and mitre sealing.
9. Insulation plating.
10. Heating of interplating gate space.
11. Heated rooms.
12. Heaters of supplied water.

Schéma d'une écluse équipée pour fonctionner à des températures d'air ambiant inférieures à zéro.

1. Enclave pour le dispositif de début d'écoulement.
2. Poutre de protection des glaces.
3. Canalisation d'air perforée, avec tuyères.
4. Chauffage de la partie supérieure de la fourrure d'étanchéité de la porte.
5. Tuyère à air.
6. Canalisation perforée.
7. Anneau d'amarrage flottant et chauffé.
8. Chauffage de la fourrure d'étanchéité du busc et de la poutre en forme de selle.
9. Bordé isolant.
10. Chauffage de l'espace entrebordé de la porte.
11. Chambres chauffées.
12. Appareils de chauffage de l'eau d'appoint.

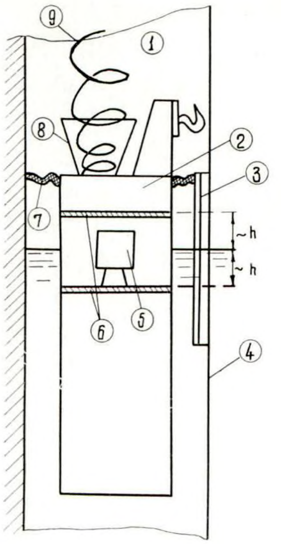

Fig. 9.

Diagram of mooring float heating devices used at below-zero air temperatures : 1. mooring float shaft; 2. float; 3. screen for protection of the shaft from penetration of floating objects; 4. lock wall face; 5. electric heater; 6. heat insulation membranes; 7. rubber flap; 8. container for coiling of flexible cable; 9. electric cable; h. distance between the membrane and water level (about 25 cm).

Schéma d'équipement d'une boucle flottante utilisée à des températures d'air inférieures à zéro : 1. rainure de boucle flottante; 2. flotteur de boucle flottante; 3. masque de protection de la niche de la boucle contre objets flottants; 4. face frontale du bajoyer; 5. réchauffeur électrique; 6. diaphragmes calorifuges; 7. tablier en caoutchouc; 8. magasin de logement du câble souple; 9. câble électrique; h. distance du diaphragme au niveau de l'eau : 25 cm environ.

of sensors of the automatic devices and prevention of ice formation in the float shafts. All auxiliary installations (floating booms, pneumatic blowers, etc.) are connected to the automatic control system of the lock; operation of the heating installations and devices for maintenance of ice-free water areas is automated including adjustment to the ambient air temperature variations.

The chamber and approach channels of the lock are periodically cleaned from ice by icebreakers (at ice thickness above 0.15 m). Under favourable temperature conditions an ice-free fairway in the outer harbour is maintained due to upwelling of warm deep water.

The typical arrangement described above can be modified in accordance with climatic conditions, required duration of lock functioning at sub-zero air temperatures, lock design and equipment features. The most important aspects in this respect are the type of feed system and design of the gate. For instance, at a distributing feed system with delivery of water into different parts of the chamber through different culverts it becomes possible not only to eliminate the current directed to the lower gate at emptying of the lock, but even to create an oppositely directed current. In this case the boom in front of the lower gate is unnecessary and the whole set of devices for the lower head is much simplified. It will be still simpler in pit-type locks with a flat lifting gate in the lower head and a concrete baffle in front of it. In the USSR a classification system for locks operating at below-zero air temperatures has been developed and fitting of locks with appropriate anti-icing devices has commenced.

3.5.3. *Combination of Ice-Combating Means for Docks and Mooring Facilities of Ferry Berths.*

Combination of anti-icing devices should be selected in correspondence with design features and specific conditions of winter operations of the structures to be protected.

Thorough investigations of different ice-combating devices have been carried out and efficiency of their operation checked in actual locks, dry and floating docks; research has been undertaken on measures of insuring winter operation of facilities for marine railway ferries.

Depending on hydrometeorological conditions of water areas, location and design features of floating and dry docks, a special combination of ice-prevention means is established in each particular case. For the most common operational conditions some typical arrangements of dock protection devices have been developed (Fig. 7). As the most common and permanent of ice troubles is penetration of broken ice inside the docks, the main type of dock protection devices in these arrangements is flow generating installations (5) operation of which was described in 3.2.2. Special attachments have been introduced for automation of their operation.

Flow-generating installations of different design are now put in operation in a number of dry docks, as well as in floating docks of varying capacity — from 600 to 27,000 t. They proved to be reliable and efficient for protection of structures operating in heavy ice conditions.

The method of hydromechanization of the process of broken ice removed by means of flow generators is employed also in design of new docks intended for operation in ice conditions. Besides, this method can be realized with the use of the dock ballast pumps by delivery of additional amount of outside water into the dock, thus creating a head and a surface current directed from the dock outwards.

For protection of the end faces against broken ice various designs of mechanical barriers have been developed including sliding nets and sliding floating booms.

Besides the installations mentioned above some dry docks are equipped with special heating devices built into the floor base and intended for prevention of icing in the ship erection area. Such a device consists of a close-loop pipe system with a heat carrier pumped around inside. Operation of such devices is fully automatic and controlled by temperature relays.

As installation of such pipelines in the existing docks involves high capital costs, in some case a special keel-block design (USSR certificate of authorship No. 281196) can be utilized instead, worked out mainly for ship lifting structures with docking positions prone to icing. To reduce manpower required for rearrangement of the docking blocks on the iced floor the new keel-block is designed as a space truss consisting of the upper and lower belts. The lower belt is equipped with electric heaters and filled with heatemitting liquid circulated inside the hollow elements of the truss. The heat emitted by the lower belt surface is utilized for melting the ice around the keelt-block. Location of electric heaters insures continuous natural circulation of the heat-emitting liquid and uniform heating of the lower belt of the keel-block space truss.

In some cases it is advisable to clear up the adjacent water area and maintain it in ice-free conditions using one of the techniques described in 3.2.

As a result of combinations of anti-ice devices being applied on twelve dry and floating docks of different ship repair facilities the main difficulties caused by ice have been eliminated. Use of these devices permitted to increase the degree of dock utilization, reduce cost and time of dry-docking, eliminate hard manual labour required for removal of ice from the dock. The dock owners have now taken a decision authorizing mandatory inclusion of anti-ice devices into a list of necessary dock equipment when designing and building new docks.

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RÉSUMÉ

Les problèmes posés par la nécessité de combattre énergiquement les difficultés que présentent les glaces pour la navigation et l'exploitation en période d'hiver des chenaux, des écluses des voies navigables de l'U.R.S.S., ont un caractère de plus en plus important au fur et à mesure du développement toujours plus accentué des régions septentrionales et orientales du pays et de l'accroissement du nombre et du tonnage des navires.

Pendant la période qui s'est écoulée depuis le XIXe Congrès, un travail important de recherche et d'observation pratique a été effectué en vue d'étudier quelle est la nature essentielle des difficultés créées par les glaces pour telles ou telles installations et d'élaborer des mesures d'ordre technique visant à prévenir et à surmonter les difficultés.

On a étudié l'action exercée par les glaces sur la stabilité, la résistance et la longévité des ouvrages hydrauliques.

Au cours des cinq dernières années furent poursuivies, en U.R.S.S., des études théoriques et expérimentales sur le givrage des œuvres mortes et vives des navires.

On a étudié les causes et les suites fâcheuses des difficultés créées par les glaces lors de l'exploitation en période d'hiver des chenaux, des écluses, des dispositifs d'accostage des passages d'eau, tant sur les voies maritimes que fluviales.

Des recherches et des travaux pratiques complexes sont effectués en vue d'assurer l'exploitation normale des organes de levage et de réparation des navires lorsque les températures tombent sous zéro.

Le rapport passe en revue les tendances principales des solutions techniques apportées au problème de la lutte contre les difficultés dues aux glaces dans le transport par eau :

1. Le service de recherche et opérationnel de la navigation en eaux congelées est sans cesse perfectionné. Sur la base de relevés établis dans des conditions normales, on a observé la régularité et la durée des phénomènes de congélation, ce qui a permis de fixer les dates de début et de fin de navigation et de conduite des navires dans des glaces continues et dérivantes.
2. De nouvelles méthodes sont étudiées et mises au point en vue de réaliser et de maintenir, à l'état non gelé, les bassins des ports et des chantiers navals. Les conditions de départ, qui déterminent le choix d'une méthode, sont : les régimes thermique et des glaces de zones particulières situées dans des bassins d'eau douce ou d'eau de mer. Parmi les méthodes actives de maintien des plans d'eau à l'état non gelé, on peut citer l'utilisation de la chaleur des eaux profondes des bassins ainsi que le réchauffement des plans d'eau grâce à l'intervention d'un agent porteur de chaleur spécialement préparé (mélange vapeur-air, eaux réchauffées, gaz chaud, etc.). On a également étudié l'efficacité du maintien, à l'état non gelé, de régions locales du plan d'eau au moyen de revêtements calorifuges, et notamment grâce à l'emploi de granulés composés d'une manière n'absorbant pas l'eau, du genre mousse de polystyrène.
3. Dans le programme actuel de recherches complexes, une place importante est réservée à l'étude des moyens de retenue et de déplacement orienté (d'évacuation) de la glace morcelée flottante. On a mis au point des méthodes de calcul et découvert des solutions visant la réalisation de barrages de retenue de glaces et de pannes flottantes. On a vérifié, par des essais dans des conditions réelles, l'efficacité d'installations pneumatiques et génératrices de courants pour la retenue et le déplacement orienté des glaces. Divers types de dispositifs générateurs de courant ont été élaborés et trouvent une large application pour la protection contre la glace morcelée des bassins de carénage, des écluses et d'autres ouvrages. Une méthode de calcul de l'ensemble générateur de courant a été proposée.
4. Des études ont été entamées concernant l'utilisation de moteurs d'avion à turbine à gaz (mis hors service) pour résoudre l'ensemble du problème de la protection contre les glaces des chantiers de réparation, des écluses et des passages d'eau.

Aux stades de l'élaboration d'un projet de construction, on étudie et on fixe systématiquement les normes concernant la définition et le contrôle de l'action destructive des charges de glace et des facteurs d'agression hydrométéorologique (tels que gel et dégel répétés, humidification et séchage, action chimique de l'eau marine, etc.) sur les ouvrages en béton armé des installations hydrauliques.

La partie finale du rapport traite de l'analyse de l'expérience pratique acquise par l'application, dans la pratique, des méthodes et des moyens de lutte contre les difficultés dues aux glaces dans le transport par eau.

L'utilisation de la méthode de planification de parcours à parcours, basée sur la connaissance des conditions de formation de glace et sur les prévisions certaines des phénomènes y associés, présente des avantages économiques importants.

On a mis au point et expérimenté, *in situ*, un ensemble de dispositifs techniques assurant le fonctionnement ininterrompu des écluses en période de températures inférieures à 0°, dans des conditions de navigation prolongée.

Dans un certain nombre de docks flottants et de cales sèches on utilise, depuis plusieurs années, divers genres d'installations pour combattre les glaces. Sur la base de cette expérience, on a élaboré des schémas-types d'équipement de dispositifs anti-glace tant pour les cales existantes que pour celles projetées. Ces équipements ont démontré la fiabilité et l'efficacité de protection des ouvrages appelés à fonctionner dans de dures conditions de glace.

La réalisation de ces mesures a augmenté la capacité de rendement des docks, a réduit le coût et le temps de carénage en hiver, a supprimé les travaux manuels pénibles, nécessaires pour dégager les cales des glaces.

Pour faire face au développement de l'économie nationale, prévu au plan quinquennal de 1971-1975 et exigeant le perfectionnement des moyens de transport, — et, en premier lieu, des transports par eau, — on prête une attention particulière aux recherches et mesures pratiques susceptibles d'assurer l'exploitation normale des navires et des ouvrages à des températures inférieures à zéro.

S. II - 4

PAPER

by

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THE ICE REGIME AND CORRESPONDING PROBLEMS ON THE DJERDAP (« THE IRON GATE ») NAVIGABLE-HYDROELECTRIC SYSTEM, ON DANUBE RIVER IN YUGOSLAVIA

1. INTRODUCTION

The Danube river is one of the largest and most important waterways in Europe. Ships from eight Danubian and other European countries sail along the Danube. Navigation conditions in this river are not the same in the whole course — in some sections they are considerably more unfavourable as compared to average conditions. In this respect, the Djerdap section of the Danube, on the border between Yugoslavia and Rumania where the river bed is deeply cut into the Karpathian mountain, is a particularly outstanding one. Natural and technical conditions of navigation through Djerdap are limiting factors for transport along the Danube. Natural hydraulic-morphological characteristics of the Djerdap section — narrow bed, submerged rocks, high speeds and the ice regime, with ice dams — make this section very unfavourable for navigation.

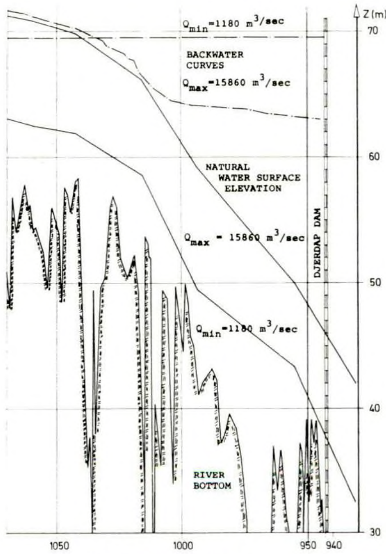

Fig. 1.

Longitudinal cross-section of Djerdap section of Danube river.

Construction of the Djerdap hydroelectric and navigation system — being one of the largest in Europe — considerably improves navigational conditions in this section of the Danube. The changes in the ice regime on the Djerdap section of the Danube after the construction of the

Djerdap hydrosystem, and effects of those phenomena on navigation through this section in winter are analyzed in this paper.

2. THE ICE REGIME IN THE DJERDAP SECTION OF DANUBE RIVER BEFORE CONSTRUCTION OF THE DJERDAP HYDROELECTRIC SYSTEM

a) Characteristics of ice phenomena.

As known, the first condition for ice formation in a river is the determined temperature regime of a watershed with negative air temperatures. Since the Danube flows through the region with continental climate, characterized by pronounced winters with relatively low air temperatures, ice in the Danube regularly occurs almost every year.

Ice on the river surface is generally classified as drift ice and ice cover. Ice formation usually begins as drift ice — floating ice formation on the surface of flow. At higher intensity of cold, drift ice gets denser, gradually entailing the whole surface of a river and forming ice cover. Drift ice consequently is more frequent phenomenon than ice cover, which needs higher intensity of cold for its occurrence. There is also a qualitative difference between these two forms of ice : ice drift is exclusively caused by meteorological factors, while hydraulic-morphological parameters of a watercourse play an important role in ice cover formation.

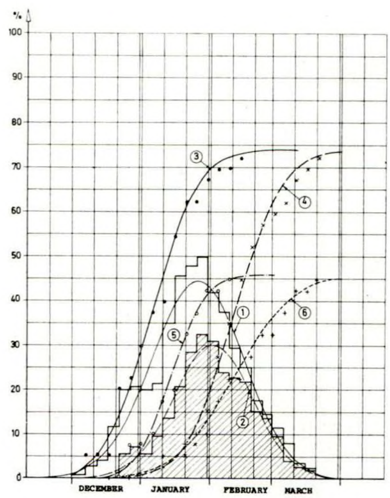

Fig. 2.

Empirical and theoretical probability of ice occurrence on Djerdap section of Danube River (before construction of Djerdap dam).
Probability of :
Presence of ice on river surface (1), presence of ice cover (2); the first occurrence of ice in the river (3) and the last one (4) before a certain date of winter; the first occurrence of ice cover (5) and the last one (6) before a certain date of winter.

Figure 2 represents probability of ice presence as well as the probability of first and last occurrence of ice and ice cover, in the Djerdap section of the Danube before the dam was constructed.

b) Hydraulic-morphological factors of the ice regime.

The Danube in the Djerdap section has morphological characteristics of a canyon watercourse, with a narrow, deep bed. Such morphological conditions are very unfavourable from the aspect of the ice regime, because of difficult ice discharge. The most critical points in the ice regime mentioned in all documents and reports concerning ice in the Danube, are on this section. With regards to the narrow river bed and relatively high velocity of flow (up to 2 m/sec.), ice dams very often appeared in the past in the Djerdap section.

Ice dams are one of the most interesting and most dangerous phenomena in rivers since they considerably decrease the discharge capacity and represent a potential cause of the ice flood. Canadian researchers PARISET and HAUSSER (2), after analyzing hydraulic conditions of production and stability of ice dams, have defined theoretical criterion of the possibility of ice dam formation in watercourses:

$$\frac{V}{\sqrt{2gH}} \geqslant 0.109$$

where V is flow velocity, H — mean depth of a watercourse in the ice dam section. Figure 3 represents the graph of parameters $V/\sqrt{2gH}$ for the Djerdap section at mean discharge in the Danube. It may be concluded that natural hydraulic-morphological conditions of the ice regime in this section are well reflected on the graph. Particularly notable and characteristic are high oscillations of parameters $V/\sqrt{2gH}$, corresponding to the transitions from the watercourse sections with broad bed to sections with narrow, deep bed. Such abrupt transitions are critical points for ice choking and formation of ice dams. Possible places where ice dams will form, according to the given theoretical criterion, coincide with occurrence of ice dams observed in the past.

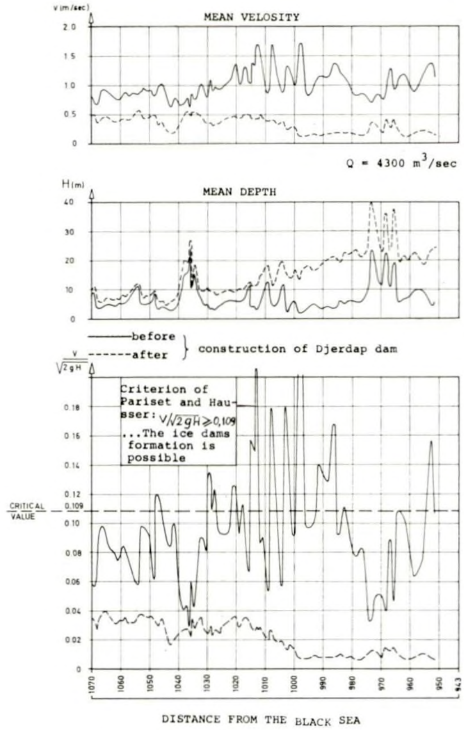

Fig. 3.

Hydraulic-Morphological factors of the ice regime in the Djerdap section of Danube River, before and after construction of the Djerdap hydroelectric system.

3. CHANGES IN THE ICE REGIME AFTER CONSTRUCTION OF THE DJERDAP HYDROELECTRIC SYSTEM

a) Change of hydraulic-morphological characteristics of the watercourse in the backwater zone of the Djerdap dam.

By constructing the Djerdap dam, a large reservoir is created. Conception of the operation regime of the Djerdap hydroelectric system is based on alternative backwater elevation on the dam, so that water level in the reservoir is highest at low discharge, while it gradually falls with the increase of the Danube discharge. Consequently, the length of the backwater zone varies from 72 km at high discharge to 212 km at low discharge.

Creation of the Djerdap reservoir resulted in important changes of hydraulic-morphological characteristics of the watercourse in the backwater zone — the width and depth of the river bed are increased, while slopes of water level and velocity of flow are decreased. In regards to a canyon-type of the Djerdap section of the Danube, increase in depth is considerably more pronounced than the width of the river. As for the ice regime, a most important consequence of the construction of the dam is the considerable decrease of flow velocity in the backwater zone (Fig. 3).

b) **Effects of the Djerdap Hydroelectric system on the ice regime.**

In the dam zone of the reservoir, due to specific hydraulic conditions — very low velocities and high depths — ice phenomena have lake-type characteristics. Owing to weak turbulence and, consequently, poorer circulation and heat exchange between surface and deep strata there is thermal stratification of water in the reservoir.

Fast cooling of the surface layer results in ice formation shortly after the beginning of negative air temperatures. Slow velocity in the reservoir is favourable for fast surface spreading of ice crust and rapid formation of stable ice cover. The first change in the ice regime in the Djerdap reservoir, in relation to the natural state, consists in the earlier occurrence of ice cover.

In the case of the Djerdap, creation of ice dams in backwater conditions is of particular importance. Analysis of the ice dams formation possibility in the Djerdap section, after the dam construction, has been done on the basis of the hydraulic criterion given by Pariset and Hausser. As seen in Figure 3 — parameter $V/\sqrt{2gH}$ does not exceed the critical value of 0.109 in any place, there are no high oscillations in the value of this parameter, as in the natural regime. It may be concluded that, according to this theoretical criterion, there are no hydraulic-morphological conditions for ice dams in the Djerdap section after construction of the Djerdap dam.

4. EFFECTS OF THE ICE REGIME ON NAVIGATION IN THE DJERDAP SECTION OF THE DANUBE

Ice in a watercourse is one of the main disturbances for navigation, since creation of ice cover in a river may completely hinder navigation. However, with the use of ice breakers, navigation is possible even in periods of ice occurrence, but the maintenance of navigation with the use of ice breakers can be reasonable and efficient only if the river is covered by a compact ice cover of a relatively uniform thickness. It, actually, means that hydraulic-morphological conditions in a watercourse have to be such as to enable the creation of ice cover on the river surface. In such conditions of ice regime in winter, it is possible to realize reasonable organisation of ice breakers patrolling around the watercourse, aimed at maintaining the navigation route. However, if hydraulic-morphological conditions in a watercourse enable the formation of ice dams, the use of ice breakers in winter have no effect.

The ice regime in the Djerdap section of the Danube before construction of the Djerdap dam excluded the possibility of maintaining navigation by the use of ice breakers. Several successive ice dams in this section with huge quantity of accumulated ice prevented the efficient application of ice breakers. In the natural regime, before the construction of the dam, interruptions of navigation in this section of the Danube were inevitable in winter.

Since there were changes in the ice regime after construction of the Djerdap dam, navigation is possible even in ice periods. The change of hydraulic-morphological conditions excludes the possibility of ice dam occurrence in this section, as a result of which navigation is facilitated through the use of ice breakers.

The effect of the change in ice regime, after construction of the Djerdap dam, on navigation in winter lead to the following conclusion : although the period of ice occurrence is prolonged due to earlier ice formation in the reservoir, disappearance of ice dams and possibility of maintaining navigation by ice breakers make the ice regime more favourable for navigation than it was before construction of the Djerdap hydroelectric system.

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RÉSUMÉ

Le régime des glaces dans la section de Djerdap (« Porte de fer ») du Danube, en Yougoslavie, fait l'objet de ce rapport. Au point de vue du régime des glaces du Danube, cette section est la plus défavorable et difficile — l'apparition des embâcles dans celle-ci rend impossible le maintien du parcours navigable, au moyen de brise-glaces, pendant l'hiver. La construction du « Système navigable et hydroélectrique de Djerdap » a changé considérablement les conditions hydrauliques et morphologiques de cette section du Danube. D'après l'analyse de ces changements et leur influence sur le régime des glaces on peut conclure que celui-ci est devenu plus favorable pour la navigation. C'est surtout dû au fait que la formation des embâcles sera impossible, selon les critères hydrauliques et morphologiques, après la construction du barrage de Djerdap.

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