PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
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ICE PROBLEMS IN THE DUTCH RIVERS AND ESTUARIES

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1. INTRODUCTION

Scope of Paper

It is generally known that for centuries the Netherlands have been marred by flood disasters. The great damage that was done by the severe storm of February 1, 1953, is still well remembered by many people.

It may be less well known, however, that regarding ice problems Holland gets its fair share also, and that for the design of hydraulic and coastal engineering structures ice conditions often are an important governing parameter.

During the last five decades a number of projects have been executed that have had a great influence on the ice conditions. At the same time ice considerations have been of great significance in determining overall design criteria for a number of projects.

The most important of these projects are:

a. Closing of the "Zuiderzee"
b. Construction of barrages in the Lower Rhine
c. Deepening of Rotterdam Waterway for navigation and development of Europoort
d. Delta Project

In this paper attention will be paid to the consequences of the above mentioned projects on the ice conditions. Special considerations will be given to the impact of the Delta Project on ice conditions and to the design criteria for the large sluice in the Haringvliet dam. The research that was carried out to find answers to some of the pertinent problems will also be mentioned.

Climatological Conditions

Holland is situated in the temperate zone; its latitude is about 52° N.

Similar to other parts of northwestern Europe, Holland is subjected to the beneficial effects of the Gulf stream and consequently average winter conditions are relatively mild. The presence of ice on the Dutch estuaries is therefore not a very common occurrence. In the central part of the country temperatures remain below zero on an average of 10 days a year. Because of the ice discharge in the estuaries toward the sea, small craft navigation is hampered about 8-10 days a year and for the larger ships, 4-7 days a year.

The above values are averages; occasionally winters are much more severe and the handicap to navigation and general discharge conditions becomes much greater. This situation occurs when the country comes under the influence of stable high pressure areas of the European continent, when cold air is transported toward the country by easterly or northeasterly winds.

In severe winters ice on the rivers will become land fast; this will occur on the average of once in five winters. The lowest temperature recorded is a value of -27.4° C at Winterswijk (central part) in 1942 (Reference 11).

2. ICE CONDITIONS IN THE DUTCH RIVER AND ESTUARY SYSTEM

When serious winter conditions occur, the ice formation on the rivers gives rise to backwater effects which changes the flow distribution over the various river branches.

Three rivers discharge through the Dutch estuary system, viz the Scheldt, the Meuse (Maas) and the Rhine. It is principally the river Rhine that is adversely affected by ice formation. The source of the Rhine is in the mountains of Switzerland; its average discharge is about 2000 m^3/sec, but under extreme conditions this value can run to over 13000 m^3/sec. Not far west from the border between Holland and Germany the river Waal branches off, carrying about two-thirds of the total discharge. Of the remaining part, again about one-third is carried northward along the river Yssel and two-thirds along the river Rhine itself. This part of the Rhine is called Lower Rhine, and further seaward its name changes again into Lek (see Figure 1).

The Rhine, Waal, and Maas discharge through the estuaries in the southwestern part of the Netherlands. During winter conditions the river branches also carry ice into the estuaries which may cause restrictions to the discharge of river water both in the rivers and in the estuaries. These restrictions, such as ice jams may greatly increase water levels and jeopardize the stability of river dikes.

In the past such hazardous high water conditions have led to breaks in river dikes with consequential flooding of adjacent low areas. The dangers of flooding due to ice has given rise to the organization of a special warning system, whereby the inhabitants and local authorities are alerted regarding conditions to be expected.

For the rise of the water level in the rivers, several causes play a part. Due to the formation of a solid ice deck, friction forces will work underneath the ice deck and will increase the hydraulic resistance. The hydraulic radius of the cross-section decreases to about one-half of its original value.

Observations during ice conditions have shown that besides a change in hydraulic radius the discharge coefficient of the river, expressed in terms of the Chezy coefficient, is also reduced considerably. A third cause is the formation of ice jams or hanging ice dams. The reasons for the formation of ice jams have long been a matter of study and concern.

Recent investigations have shown that the results of Canadian studies (Kivisild, 1959) are applicable to Dutch river conditions as well. Kivisild's studies have shown that the value of the Froude number, $F = \frac{V}{\sqrt{gh}}$, in which V is the average velocity and h the local depth of the river, is likely to be a criterion for the formation of ice dams (Reference 6). When a river section has a land fast ice deck, ice floes that are carried on by the flowing water at the surface may either stay at the surface, whereby the ice deck grows in upstream direction or dive underneath the existing ice deck and form an ice jam or hanging ice dam. The latter conditions occur for the higher Froude numbers, above an average critical value of about 0.08.

For the formation of ice jams on the Dutch rivers the critical Froude numbers have been calculated during seven severe winters from 1929 to 1963; they range from 0.06 to 0.09. Figure 2a shows observed water levels on the river Waal during the winter of 1954. The locations of ice jams are shown in Figure 2b. Whenever an ice jam has been formed the water level upstream of the dam rises considerably to overcome the increased hydraulic resistance due to the ice jam, whereas the levels downstream are temporarily lowered.

An additional adverse effect of the formation of ice jams in the temporary decrease in discharge of the lower river section, whereby water is stored in upper river sections, with result that saline water moves stream upwards thereby threatening fresh water intakes in the estuary area. Such situation developed during the winter of 1962-63; the formation of an ice cover in the period January 17-22 caused a sudden drop in the lower river discharge of about 150-200 m^3/sec. At the intake of the municipal drinking water system at Rotterdam a chlorinity of 3000-4000 ppm was observed at M.L.W. (Reference 9).

The rate of growth of ice covers on the Dutch rivers ranges from about 9 to 36 km per 24 hour. An average figure is 1 km per hour. To eliminate restrictions to river runoff, ice breakers have been used on the Dutch rivers since 1861. The first ice breakers were regular steamboats. Only after 1940 special devices like an ice breaker nose were added, and the ship was specially designed to give higher ice breaker performance. Figure 3 shows ice breakers in action during the winter of 1962-63.

The breaking of ice for maintaining navigation conditions came into use at a later date. In 1929 several ice committees were organized to consider the possibilities of keeping navigation routes open.

Water in the Rotterdam harbor area is brackish and will therefore not freeze so easily. Harbors further inland are severely handicapped when ice conditions on the rivers prevail.

A comparison of ice conditions of recent years and of several decades ago shows a trend of diminishing ice hazards which was most likely due to a number of power plants that have been built along the rivers, whereby the river water is used for cooling. The added calories from the power plants have raised the temperature of the river water some 1.5 - 2^{o} C and it is believed that this has been a factor of significance regarding the decrease in ice hazards.

3. EFFECTS OF LARGE PROJECTS ON THE DISCHARGE OF WATER AND ICE

Zuiderzee Project

The first project in this group is the closing of the Zuiderzee, which was accomplished by the construction of a closing dike to separate the Zuiderzee from the North Sea. The former was renamed Yssel-lake after the closing of the barrier dam in 1932. The barrier dam was provided with a number of sluices to allow discharge of excess fresh water carried to the lake by the river Yssel. The change from salt to fresh water changed ice conditions on the Yssel-lake fundamentally. The rather shallow (about 10 ft) Yssel-lake gets a solid ice deck soon after freezing starts; this ice cover prohibits ice floes from the river Yssel to be discharged through the sluice system. Consequently, the river Yssel also becomes covered with ice floes rapidly; the ice floes freeze together and form a continuous ice deck on the river Yssel. Consequently, the discharge distribution of the river system is affected, whereby part of the Yssel discharge flows along the Rhine and Waal rivers.

Climatological studies have furthermore indicated that a frozen Yssel-lake exerts a noticeable influence upon the average day temperature of the surrounding land areas, particularly to the east.

Rhine Canalization

The second project that had a significant effect on discharge conditions is the construction of three barrages with movable gates in the Lower Rhine (Figure 4). They serve as a regulating device for the discharge distribution over various river branches; when closed the barrages will force more water to pass along the river Yssel under normal conditions, thereby increasing the fresh water supply to the northern provinces. They also improve navigation conditions on the Lower Rhine.

The three barrages have been provided with vizor gates. When the gates are open during freezing conditions, adverse effects may be limited to the reduced discharge width and the possibility of ice jamming.

Rotterdam Harbor

Since World War II the port of Rotterdam has been growing toward becoming the largest port in the world. Simultaneously the depth of the Rotterdam Waterway, Rotterdam's link with the North Sea was increased step by step. From a hydrological point of view the deepening of the Rotterdam Waterway had some serious consequences because salt water intrusion was favorably affected. Consequently, it became more and more difficult to use the river water in the vicinity of the Rotterdam area for drinking and for irrigation of the adjacent areas.

The increase in channel depth decreased the resultant ebb velocities which reduced drift velocities of ice floes on the Rotterdam Waterway. The need for deeper harbors has led to the development of a deep sea port (Europoort) at the entrance of the waterway, which made it possible to reduce depths of the waterway further inland again with a beneficial effect to salt water intrusion. Measures to effectively reduce the depth of the river near Rotterdam were started recently.

The deepening of the navigation channel from Europoort to the North Sea may have small adverse effects on the discharge of ice floes toward the North Sea, because of the reduction of resultant ebb flow velocities.

Delta Project

Among the projects considered the Delta Project has the largest effect on ice and discharge conditions in the estuary system. The project entails the closing of the estuaries between Rotterdam Waterway and West Scheldt. It was born out of the storm flood disaster of 1953.

The project outline is presented in Figure 5. Because of navigational interests, the two major fairways to the ports of Rotterdam and Antwerp, the Rotterdam Waterway and the Western Scheldt, were not closed. Along both estuaries, the dikes were to be raised to prevent future dike breaks.

To increase the safety of the areas north of the Rotterdam Waterway, it was suggested that the Hollandsche IJssel River, branching off to the north from the Rotterdam Waterway just east of Rotterdam, was to be provided with a storm surge barrier at its entrance which could be closed when high storm tides are expected.

Main features of the Delta Project are the construction of primary barrier dams across the Haringvliet (6), the Brouwershavensche Gat (7), the Oosterschelde (Eastern Scheldt) (8), and the Veersche Gat (3). (The numbers indicate the order of construction of the projects; see Figure 5.) After those dams are completed, the danger by flooding will be adequately averted for the area between the Rotterdam Waterway and the Western Scheldt.

Damming the tidal inlets in the southwest is of such a large scope that it did not seem possible to undertake construction of all dams simultaneously. Building the barrier dams in succession, however, requires taking additional measures, such as constructing a number of secondary dams in order to obtain a number of independent tidal basins. Thus, the closing of each inlet can be carried out independently. Such secondary dams were projected for the Zandkreek (2), the Grevelingen (4), and the Volkerak (5).

After completion of the project, two separate basins will have been formed. The southern basin will be converted into a lake, the Zeeland Lake, supplied with fresh water by an intake sluice in the Volkerak Dam. Discharge works are projected in the barrier dams of the Eastern Scheldt and the Brouwershavensche Gat.

The northern basin remains in free communication with the North Sea by the Rotterdam Waterway. Storm tides can still enter this inlet, but because of the large area of the storage basin and of the hydraulic resistance of the tidal channels that connects it with the North Sea, storm tides will be considerably lower after the northern part of the Delta Project (Haringvliet Dam and Volkerak Dam) has been completed.

A technical evaluation of the project revealed that realization of the Delta Project can be within about 25 years time.

Change in Hydraulic and Hydrological Conditions.--A change in hydrological conditions will result from the Delta Project. Figure 1 shows the distribution of Rhine runoff along the various branches in the original situation.

Most runoff flows along the Rotterdam Waterway and along the Haringvliet on its way to the North Sea. In order to maintain the possibility of discharging river flow along the Haringvliet, which under normal conditions carries 55 percent of the runoff of the Rhine and Meuse, the barrier dam across the Haringvliet estuary was to be provided with discharge sluices of ample capacity. The gates of such sluices must be closed during storm tides and opened during times of high runoff.

During the dry season, the gates of the Haringvliet discharge sluice will be closed and the Rhine runoff passes by way of the New Waterway (Figure 5). This has a beneficial effect on the salinity on the New Waterway in the vicinity of Rotterdam. This is important because fresh water is withdrawn from the river in this area. In this way the execution of the Delta Project contributes towards the improvement of fresh water management in the southwestern part of the country. Unfortunately, some of these benefits are partly and gradually lost again due to the increasing salinity of the Rhine water. The depth of the New Waterway is also an important parameter, as discussed in the previous section.

In the Volkerak Dam an intake sluice will supply fresh water to the Zeeland Lake. The capacity of this sluice is small if compared to the discharge capacity of the Haringvliet discharge sluice. (Cross-sectional areas relate as 1 to 10.)

Figure 6 shows the distribution of river flow along the Rotterdam Waterway and the Haringvliet after completion of the Delta Project. As outlined before, the Delta Project serves as a regulating device with respect to water management. It increases the effect of the canalization of the river Lek discussed before.

The Haringvliet Barrier Dam.--The Haringvliet barrier dam complex is one of the most spectacular structures of the Delta Project. Figure 7 shows the lay-out of the completed project. Damming up of the final opening between the sluice and the northern river bank was completed in 1970.

A main feature is the large discharge sluice, construction of which began in 1958. Both the steel and concrete components were completed in 1967. The large discharge-sluice complex contains 17 openings, each 56.50 meters wide and 5.50 meters below M.S.L. The huge openings facilitate the discharge of ice floes during extreme winter conditions. Each opening is provided with two taintor gates as shown in Figure 8.

Seaside and riverside gates are not identical. The outer gates facing the sea are two meters lower than the riverside gates and act as a wave barrier during extreme storm tides. Under such conditions both gates will work together, the space between both gates forming a stilling basin for the dissipation of wave energy.

4. EFFECTS OF DELTA PROJECT ON ICE REGIME

It can easily be seen that the execution of the Delta Project will have a very significant influence on the ice regime, not only for the estuaries proper but also for the contributing river branches. The consequences of the project include the following:

- A radical change in discharge distribution over various branches
- Changing large salt water estuaries into fresh water lakes
- Change in discharge conditions for ice floes

The types of problems that are involved are two-fold, viz the effects of the dams on the ice regime and the effects of the ice on the design of certain structures.

In trying to formulate the problem satisfactorily, a detailed knowledge of the behavior of ice in the estuaries is required and this amount of knowledge unfortunately did not exist when some major decisions regarding the design criteria for certain structures had to be made.

A significant example is the design criteria set for the large Haringvliet sluice and its meaning in discharging ice floes from the river system into the North Sea.

In the early stages of the design of the Haringvliet project it was felt that after closing of the Volkerak, which had been the major discharge route of the ice before, the Haringvliet would take over as the major discharge channel for ice. The sluice was therefore designed in such a manner that discharge of ice floes of relatively large size would be possible. Recent studies have shown that discharge of ice floes will only be possible under special conditions as will be discussed below. After the complete realization of the Delta Project the following conditions regarding ice prevail.

In the southern part of the estuary, the Zeeland Lake, a solid ice cover is going to be formed rather quickly after freezing conditions have set in. The effect on hydrological conditions will be minor because river discharge through this section will be small. Similarly to what has been observed in the areas bordering the former Zuiderzee, some noticeable climatological changes may occur. Where the relatively warm water of the estuaries presently has a moderating influence on low air temperatures the change from salt water into fresh water and the reduction in current velocities will promote the ice formation on the future Zeeland Lake.

The situation will be somewhat different on the Haringvliet estuary and will depend largely upon the operation characteristics of the Haringvliet sluice. The following possibilities have been considered:

a. During severe freezing conditions the gates of the Haringvliet sluice are all opened so that the tidal motion on the Haringvliet is restored, and freezing of the ice cover to the banks is prevented. Computations show that this manipulation leads to a restored tidal motion of about 80 percent of the original value.

However, discharge of ice floes in sufficient quantities can only be expected if a drift current of sufficient magnitude (e.g. 0.1 m/sec) will carry the ice seaward. The opening of the sluice alone will not generate such drift flow.

b. The opposite approach may also be possible: during severe freezes the gates are all entirely closed. The Haringvliet changes into a fresh water lake without significant currents and quickly freezes at its surface.

The formation of a continuous ice cover is an efficient way to reduce further heat losses of the water body to the air. The thickness of the ice cover will therefore grow only slowly and in most cases will not become greater than 1 foot. After the formation of a solid ice deck, discharge of water underneath the ice deck and through the sluice will be possible, if the gates remain operable.

c. A third alternative involves manipulating the gates of the sluice in such a way that discharge through the sluice is promoted at the cost of increased flood flow through the Rotterdam Waterway to the northern Delta channel system. Although model experiments and computations have shown that the required results of discharging ice floes through the sluice can be obtained in this way because of the increased drift flow on the Haringvliet the accompanying effects of increased flood flow on the northern channels and a simultaneous and rapid salinization of a large part of the estuary make this scheme unworkable.

It seems that scheme "b", whereby the gates of the sluice are kept closed when freezing sets in, offers the best opportunities for a sound ice discharge management scheme. Because the ice deck to be formed will have limited thickness it is felt that it can be easily broken up with ice breakers after thaw has set in. Ice floes can be discharged through the sluice, if the river discharge rises sufficiently to justify opening all or part of the gates.

A consequence of the scheme is that ice discharge from the rivers Rhine and Waal must take the northern route along Beneden Merwede, Oude Maas and Rotterdam Waterway. Studies have shown that ebb drift velocities along the Oude Maas are very small, so that additional measures to aid in this scheme may be required. More study on this is needed.

Observations showed that before the closing of the Volkerak, the latter channel provided the major discharge route of ice. Prevailing easterly and northeasterly wind were probably a contributing factor.

5. DESIGN CRITERIA OF THE HARINGVLIET SLUICE WITH SPECIAL REFERENCE TO ICE CONDITIONS

In the foregoing chapter it has already been mentioned that in the design criteria for the Haringvliet sluice much emphasis had to be given to the discharge of ice through the sluice. At the same time considerations must be given to the forces that are exerted by ice floes on the structure (piers and gates).

Distance Between Piers

In order to let the sluice be of sufficient capacity, the total effective discharge opening was fixed at 5300 m^2 with the floor of the sluice at a depth of 5.5 m below M.S.L.

The distance between the piers, that is the width of the individual openings, is on one side governed by the requirement that ice floes must be discharged through the sluice. On the other side the width of the openings is limited by what is technically and economically feasible as far as construction is concerned. In view of the heavy wave forces on the outer sluice gates and the corresponding heavy gate construction, it was concluded that the limit for the width of the openings should be of the order of 60 m. This led to the division of the total width into 17 openings, each 56.5 m. wide, with piers of 5.5 m. in between.

For the discharge of ice floes this opening was already on the small side. Ice floe observations through reconnaissance flights had shown that floes can easily reach 100 m. and that even larger size floes can be found.

Ice Breaker Nose on River Side of Piers

In order to avoid possible difficulties with discharge of larger ice floes the sluice piers have been constructed as ice piers on the river side so that they can break up the ice easily (Figures 7 and 8). The top of the ice piers is provided with a sloping vertical steel edge; ice floes will easily be broken when they move on the sloping nose of the pier.

Provision For Ice Breaker Action

Despite all the provisions taken chances are that additional help from ice breakers may be needed to clear the ice near the sluice. For this reason the lower side of the central middle beam of the sluice, to which the gate arms are attached, is placed at an elevation of 6 m. above M.S.L. in order to allow ice breakers of standard form to operate in the sluice openings underneath the beam.

Provision To Sluice Gates

As depicted in Figures 8 and 9 sluice gates on both sea and river side have obtained double plating, with reinforcement in between. From a purely structural point of view it would have been possible and more economical to construct the gates of single plating. However, ice floes could then easily have attached themselves to the gates, because the reinforcing elements would have provided an irregular surface to which easy attachment seemed possible.

The double plated gate structure is therefore chosen to facilitate the raising and lowering of the gates through possible ice masses in the sluice.

Provisions To Gate Arms

Both sea side and riverside gates are attached to the central beam by means of four gate arms. Each gate arm consists of a upper and lower beam as shown in Figure 9.

The lower beams of the gate arms are provided with triangular sections that act as ice breakers, in case the gates are lifted or lowered through ice floes in the sluice.

Heated Side Seals

Intensive studies were made regarding the measures that would be required to operate the gates under severe winter conditions. Although in prevailing conditions, thawing usually begins from the influence of depressions over the North Sea it is not entirely impossible that conditions occur, whereby in the upper parts of the river Rhine the discharge is suddenly increased due to thawing, whereby in the lower portion of the river and on the estuaries freezing still prevails. Operating conditions for the gates are therefore required under all possible circumstances.

After considering various possibilities it was decided to provide the side seals of the river side gate with electrically heated seals in order to secure operating of the river gates at all times.

Similar provisions on the sea side gates were more complicated from a technical point of view. Since the concurrence of ice conditions on the estuary and a heavy storm from the west on the North Sea is very unlikely it was felt that there would always be sufficient time available to leave the sea side gates above the water so that operation under freezing conditions would then be conducted by using the river side gates only.

Additional measures for the river side gate such as the heating of the inside of the gate and the use of an air bubbling system have been considered but were not put into practice. It was felt that the added measures were not sufficiently justified because of technical complications involved.

Re-establishing Tidal Motion of Haringvliet Estuary During Freezing Conditions

One of the various ways that has been considered in coping with the ice discharge problem on the Haringvliet estuary is the condition of re-opening all sluice gate to re-establish tidal motion on the estuary. This method was discussed in the previous section. A technical necessity for this method is the protection of the adjacent sea bottom on both sides of the sluice. The protection will protect the sea bottom from scouring when tidal motion is re-established. Although at this moment this method seems a very unlikely way of handling the ice discharge problem, there are other reasons that necessitate the construction of the protective aprons. On the sea side the apron will function to protect the bottom against scour during large discharge conditions. On both sea and river sides, the protection is needed during the final months of the closing operation of the Haringvliet Dam, when the sluice will function as a relief opening and tidal currents will flow freely through the openings of the sluice. In this way head differences and tidal currents in the final closing gap will be reduced. The constructed aprons stretch to 180 m. from the structure on the sea side and to 150 m. on the river side.

6. INVESTIGATIONS

In view of the many problems that had to be solved, numerous studies were undertaken to guide the development of the Delta Project. Among these, studies of ice were of great significance.

Field Studies

Whenever ice had begun to form on the Dutch rivers and estuaries, field measurements were carried out to obtain vital information on ice behavior. The following types of studies were conducted:

a. Measurement of the movement of ice floes through the estuaries toward the North Sea. To identify individual ice floes, bags with dye were used whereby, the position of the floes was determined with the aid of aerial photography.

The results of these investigations showed a clear tendency for the majority of the ice floes to move seaward through the Volkerak. There was little or no tendency to move along the Haringvliet in seaward direction. After the closing of the Volkerak this channel is no longer available for the discharge of the floes; the limited discharge possibilities via the Haringvliet route therefore pose a real problem. The predominantly easterly and northeasterly wind seems to be a governing factor for the direction of movement of the ice floes. The percentage of ice coverage is also of importance.

During the field observations of the winter 1962-63 the ice coverage of the nearshore area of the North Sea was small. North of the Hook of Holland ice has been observed up to 12 km from the coastline. Near the Haringvliet estuary ice coverage of the North Sea was minor. An important observation during these studies was that ice production in the Delta area started earlier than in the upper river sections. The consequence is that ice breaking in the Delta area without sufficient discharge in seaward direction is of no value at all. It will only tend to increase ice production rather than decrease the ice problem on the estuaries.

b. In order to obtain a better understanding of the heat content of rivers and estuaries, temperature measurements in vertical profiles were taken over prolonged periods of time, both on the upper rivers and the Haringvliet estuary.

c. Measurements of temperature gradients in air, ice and water were taken in a pond to obtain more information on the physical properties of the freezing process of fresh water.

d. The change in Chezy coefficient of a river section after the formation of a solid ice deck is a matter of importance and therefore regular measurements were taken relating to discharge conditions to water level behavior from which the Chezy coefficient could be computed. A strong reduction of the value of this coefficient was observed.

e. During several winters, experiments were carried out with the use of air bubbling systems to keep movable gates free of ice. The method was found to give adequate results and thus worthwhile for further exploring.

f. During each of the severe ice winters ice breaking was carried out to provide passage for the river runoff. In earlier periods one started breaking after thaw conditions had set in; in later years ice breaking was started as soon as land fast ice was observed in some areas. It was felt, however, that traditional ice breaking was a rather inefficient process and that additional techniques for enhancing the removal of ice barriers had to be looked for. Among those new techniques, various methods were evaluated experimentally such as:

1. Use of ice-saw
2. Use of explosive methods

For the latter, various ways to make holes in the ice to provide room for the explosive charges were investigated. A study was made regarding the relationship between the amount of charge, the diameter of the resulting hole in the ice, the thickness of the ice and the depth of the water and also what requirements had to be made regarding safety regulations. Reference is made to (7).

Special Studies for the Haringvliet Sluice

In the design of the Haringvliet sluice a number of problems arose that required special study. In the foregoing chapters the special design criteria regarding sluice and gates have been discussed. In this section some of the studies that were made to secure operating conditions of the sluice gates will be discussed.

Although in the original design no special measures were foreseen to keep the gates operable, further analysis showed that special measures would be required. The experience in countries like Sweden and France had demonstrated that heating of seal plates (side seals and bottom seals) could be done very effectively. The author and two of his colleagues made a special trip to Sweden in the middle of the winter in order to study possible measures of seal and gate heating and other measures that seemed applicable.

It was concluded that in order to avoid freezing of the side seals, the use of a side seal heating system would be required. Otherwise, forces in the lifting arms would exceed acceptable values. Other measures like the use of an air bubbling system was less practical because of the curved alignment of the side seals.

In a foregoing chapter it was observed that although consideration had been given to heating the side seals of sea and river side gates, the choice was made to heat the seals on the river side only.

Figure 10 shows the heating arrangement. The seal itself consists of a type similar to an inflatable car tire. By pumping air into the seal, the latter pressed itself against the pier plates.

The heating element consists of a box construction which is divided into compartments. The compartments are completely filled with oil and in each compartment an electric wire is installed. The available power is more than adequate to obtain a required value of 0.5 kw per m^2 over the area between 2 meters below and 2 m. above mean sea level. The required power can be regulated in steps. For maintenance purposes each wire can be taken out of its box at the upper side of the box element.

Heating of bottom seals was not considered necessary because the water at this level would never get below freezing temperatures. In addition to the use of heated side seal plates, research was done regarding the heating of the inside of the river side gate. The studies on this problem were conducted by the Technical Scientific Service (T.N.O.) at Delft. See References 2 and 8.

Because of the complex form of the gates and the irregular boundary conditions the temperature gradients inside the gate are difficult to compute mathematically. One method of approach was based on the analogy between electric and thermal conductance in homogeneous materials. Analogous units are: temperature → voltage, heatflow → electrical current, and thermal conductance → electric conductance. The electrical analogue was built out of metal foils with electric conductance in correspondence with the thermal properties.

Figure 9 shows a cross-section of the river side gate in which the water level test conditions are depicted. Through holes in the bottom plates and in the inside panels the inside of the gate is in open connection with the river water. The danger of the freezing of the water inside the gate is not only the possible damage to the gate by internal pressures, but the closing of the openings by ice will also lead to an additional weight of ice and water to be lifted when the gate is lifted out of the water. The selected boundary conditions provide maximum opportunity for the formation of ice inside the gates and consequently for the closing of the openings in the panels with ice. The water in the gate was assumed to move very little. The coefficient for heat conductance of water at 0^{o} C is 0.48 kg cal/ hm^{2} ^{o}C for conditions at rest. In relation to certain minor movements of the water the coefficient for heat conductance was set at 0.9-1.0 kg cal/hm^{2} ^{o}C.

For homogeneous ice, the value of this coefficient amounts to 1.8 kg cal/ hm^{2} ^{o}C. It was furthermore assumed that water motion outside the gate would eliminate temperature difference in the water that surrounds the gate.

Figure 11 gives a schematical representation of the test conditions, whereas Figure 12 depicts the electric analogue that was used. One of the results is shown in Figure 13. Heat is supplied to the inner part of the gate by a plane element in the middle. With a power supply of 380 kw for all 17 gates a condition as depicted in Figure 13 is predicted to develop.

The above mentioned tests with the electric analogue could not provide adequate information about the process of ice formation inside the gate. Therefore mathematical computations have been carried out to obtain insight into this problem.

In order to check the amount of power necessary to keep an opening of a certain dimension in the ice, tests with a scale model 1 : 10 in a freezing chamber were conducted. Although the interpretation of scale models of this nature meets with certain difficulties the experiments provided valuable information.

It was concluded that during severe winters inside the gate an ice cover of 0.5 m. thickness can be formed at the girders. Along the gate walls the ice thickness can grow to 0.25 m. By constructing heated cables through the openings in the girders, cylindrical areas can be kept ice free. In order to maintain an ice free openings of 0.1 m. diameter a supply of 120 w per m. would be sufficient.

However, a further study of the forces on the gates, including an analysis of the forces that would be required to tear a gate loose from a solid ice cover (considering ice an elastic medium), indicated that the available lift force would be adequate to tear the gate loose from the ice and to lift the additional ice and water inside the gate.

It was concluded that heating the inside of the gate, although technically feasible, could be omitted for the time being because of the technical complications involved. The risk in doing so was considered acceptable.

Use of Electric Analogue for the Study of Ice Floe Movements After Completion of the Northern Part of the Delta Project

In previous chapters it has been shown that after the completion of the closing of Haringvliet and Volkerak discharge of ice is not likely to occur along the Haringvliet unless measures of special nature (manipulation with the Haringvliet gates) will be applied.

The northern route is the most desirable one to discharge ice into the North Sea. In order to determine the technical feasibility of this way of discharge resultant ebb drift velocities were determined in the various river sections of the northern Delta area by using the large electric analogue computer of the estuary and river system (Deltar). From measurements with the Deltar in the various river sections the development of vertical and horizontal tide (current) was measured and printed on tape. After this the path of water particles was computed with the use of digital computer using 5 minutes time steps. These computations confirmed that after completion of the northern part of the Delta plan drift velocities on the Oude Maas will be extremely small and that discharge of ice floes along this route will be difficult to achieve. Discharge of ice along the Rotterdam Waterway seems to be given greater chances of success.

In the interpretation of these tests it has to be realized that the motion of a water particle not necessarily agrees with the motion of an ice floe. In the first place average profile velocities of the water have been used for the calculation, whereas in nature surface velocities determine the movement of ice floes. Secondly, the influence of wind on the movement of ice floes may also be of significance, and is not included in the computations.

7. CONCLUSIONS

a. Several large projects carried out in the Netherlands during the last decades have caused a marked influence on discharge behavior of ice.

b. Climatic conditions in the Netherlands give rise to severe winters only infrequently; however, in the design of coastal structures ice problems play a predominant part.

c. Many studies have been carried out to predict the behavior of ice after completion of the Delta Project. These are still uncertainties regarding the most desirable way of ice discharge.

d. In the design of the Haringvliet sluice many considerations have been given to the functioning of the sluice under ice conditions and to the special requirements that are necessary to keep the river side gate operational under all conditions.

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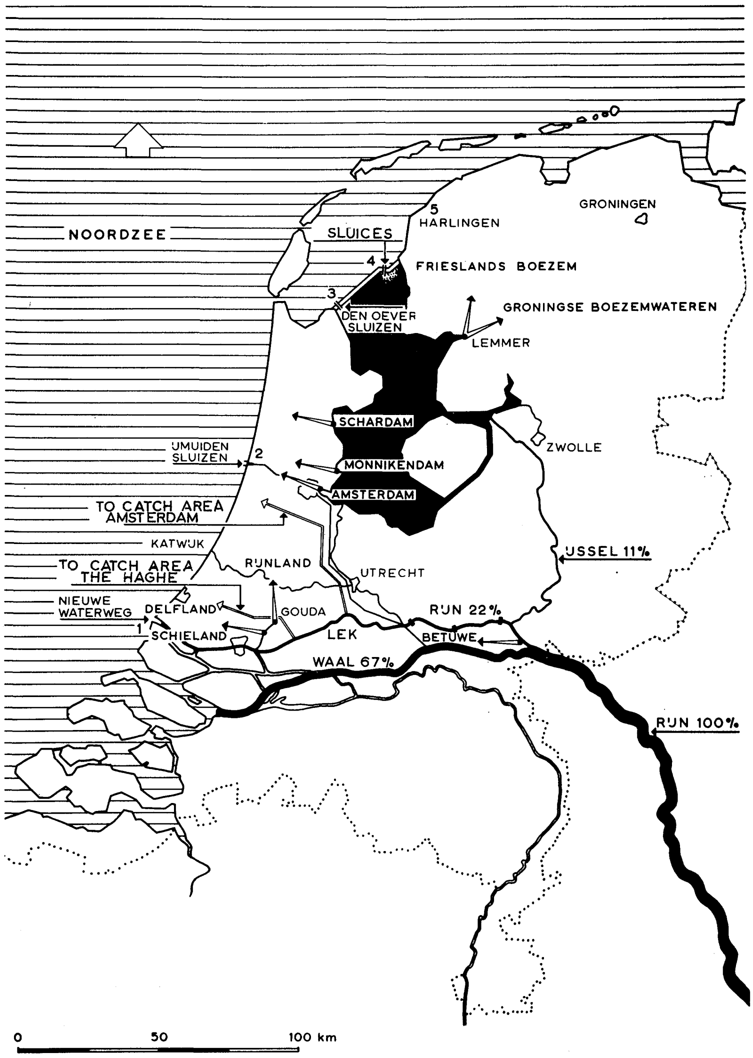
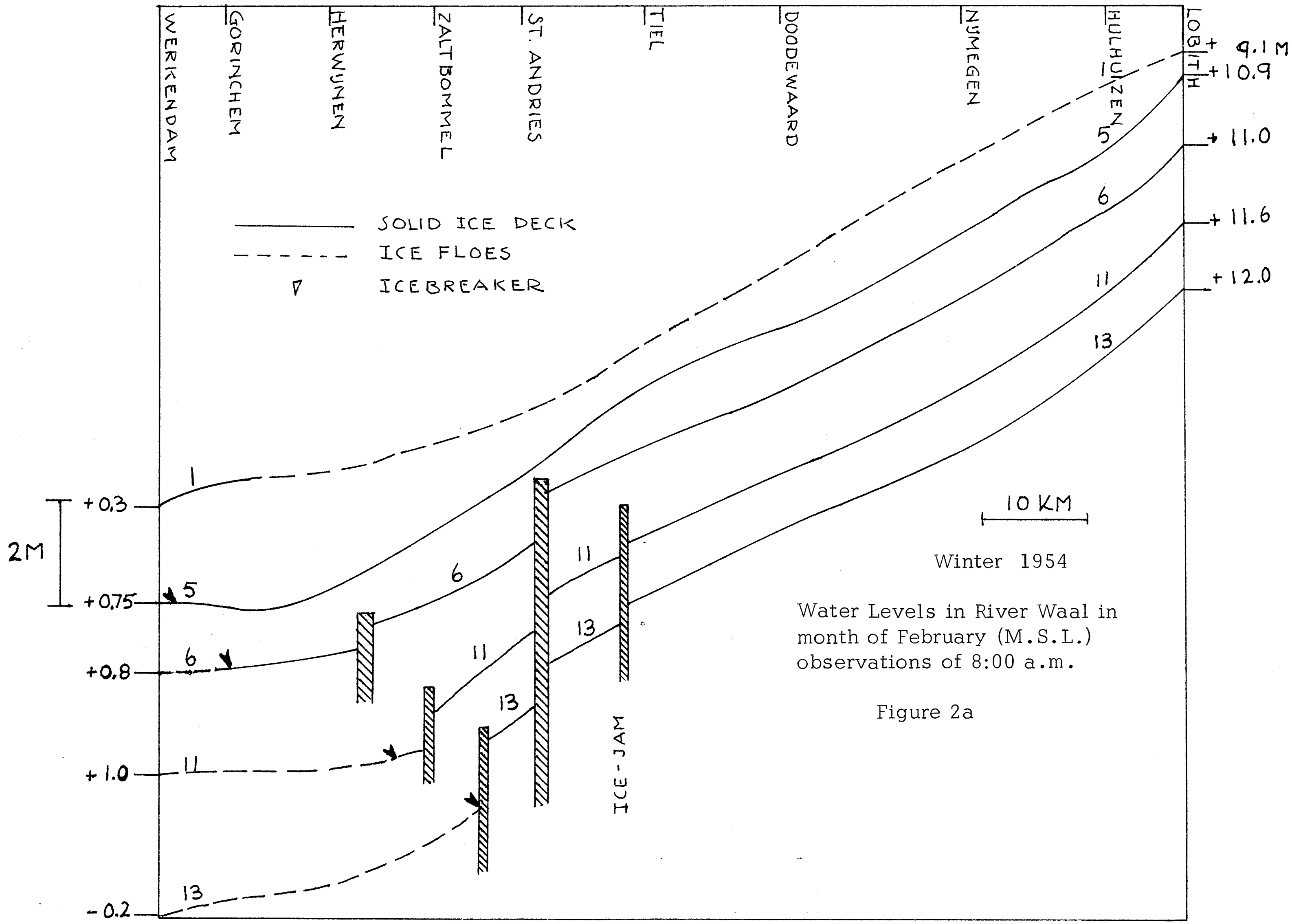


Figure 1 Dutch Rivers and Estuaries



Winter 1954

Water Levels in River Waal in month of February (M.S.L.) observations of 8:00 a.m.

Figure 2a

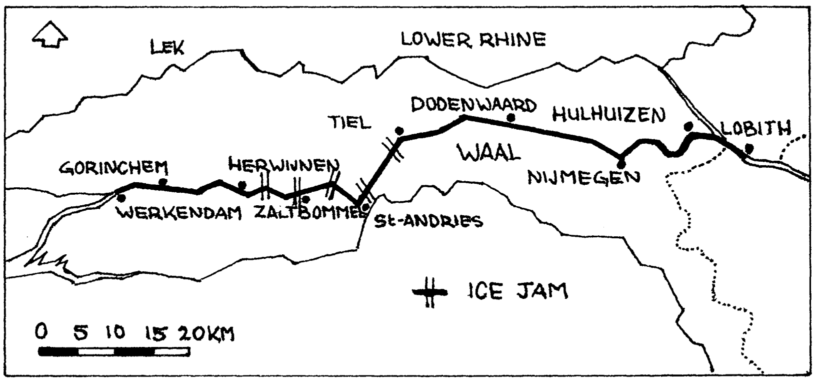


Figure 2b Location of Ice Jams

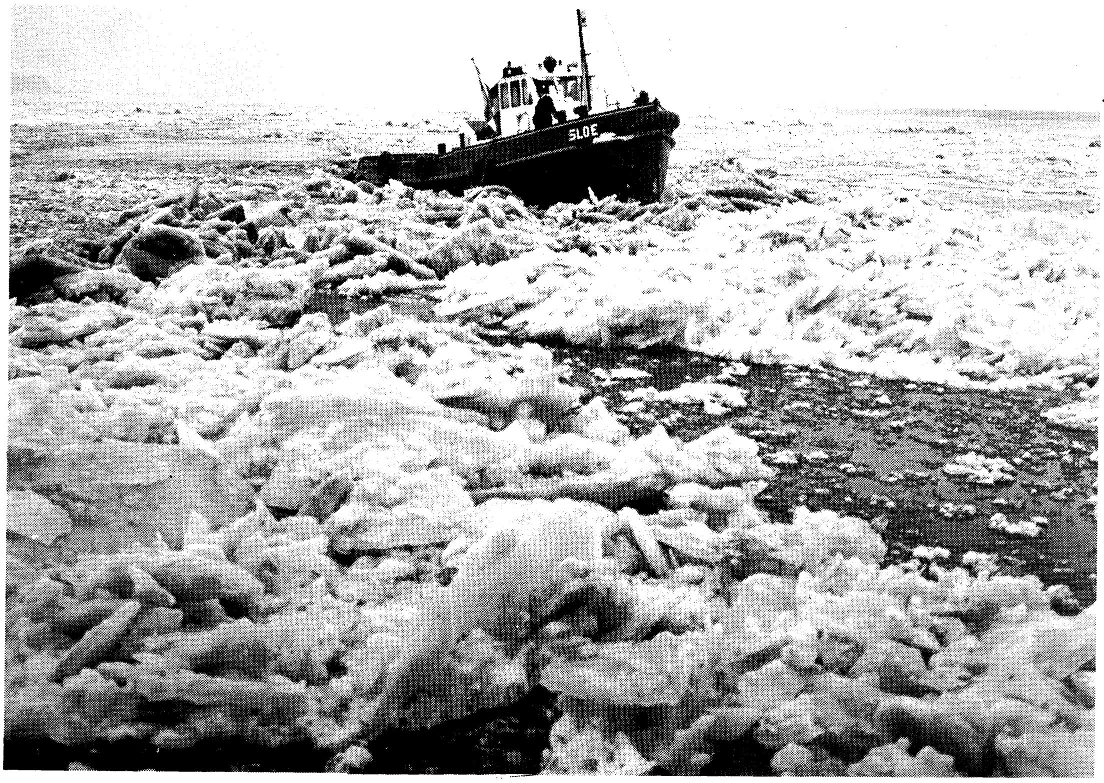


Figure 3 Ice Breaker at Work on Dutch Rivers

Figure 4 Barrage in River Rhine

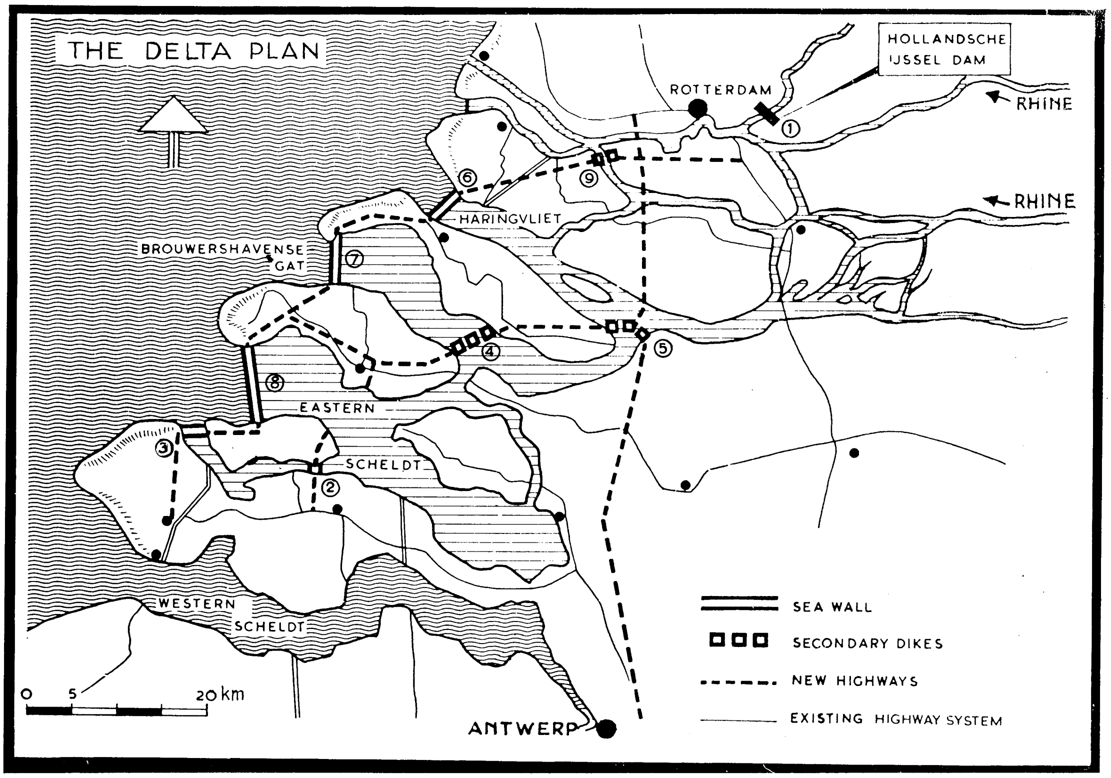


Figure 5 Delta Project

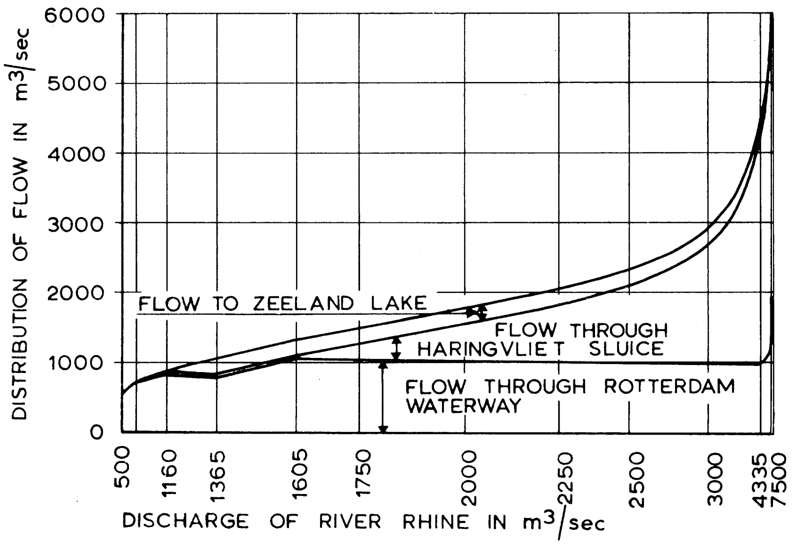


Figure 6 Discharge Distribution After Completion of Delta Project

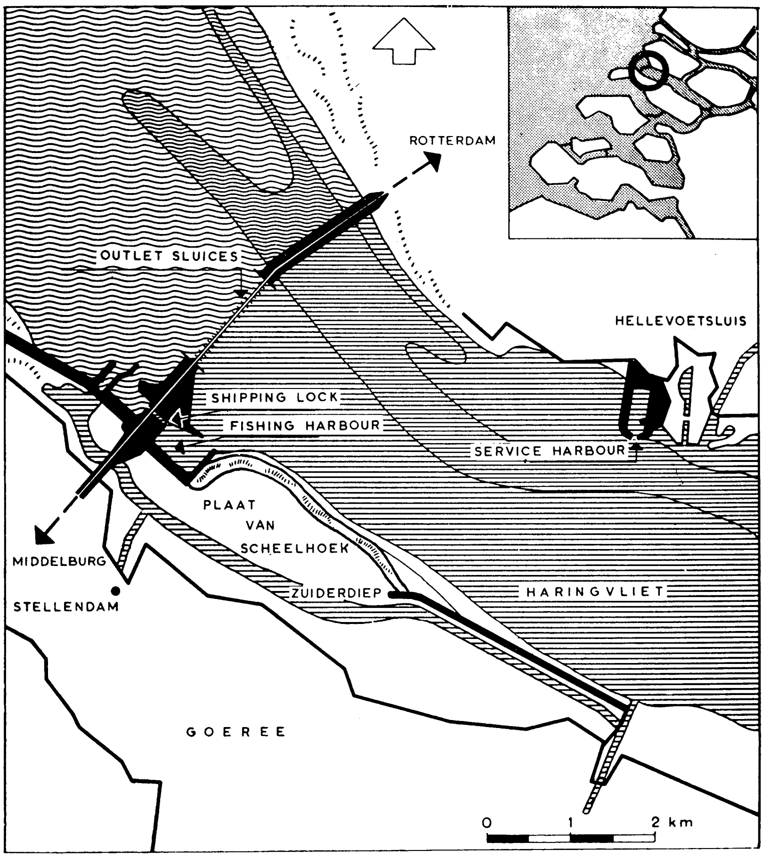


Figure 7 Haringvliet Barrier Dam Complex

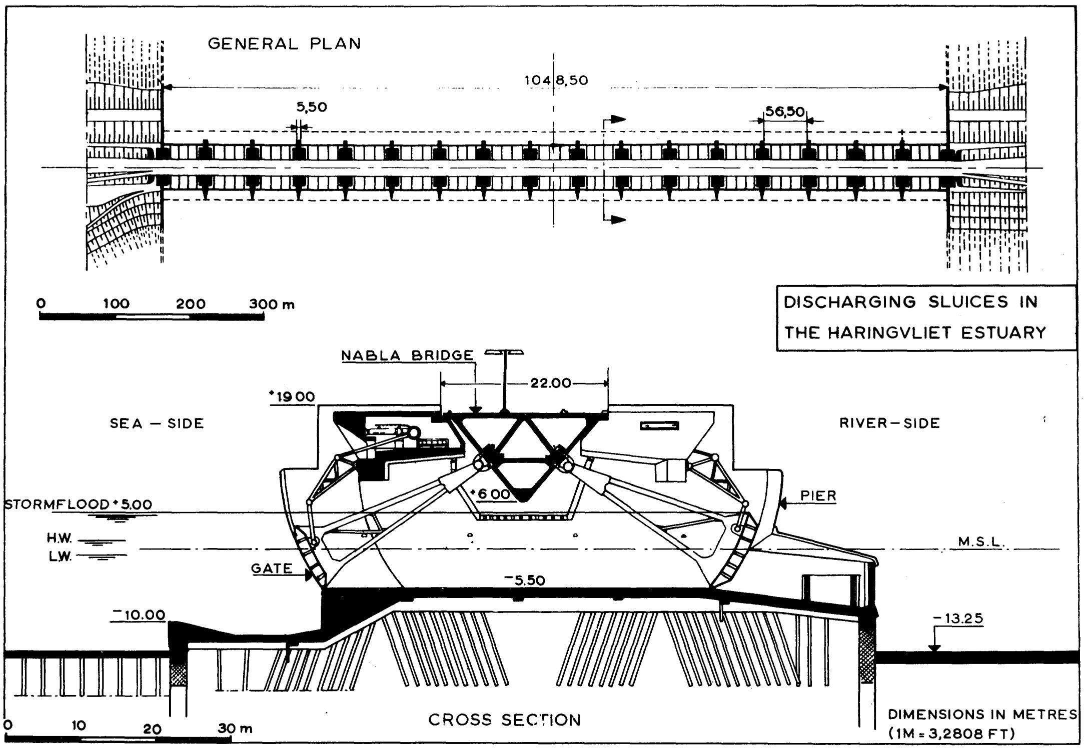


Figure 8 Cross-section Over Discharge Sluice

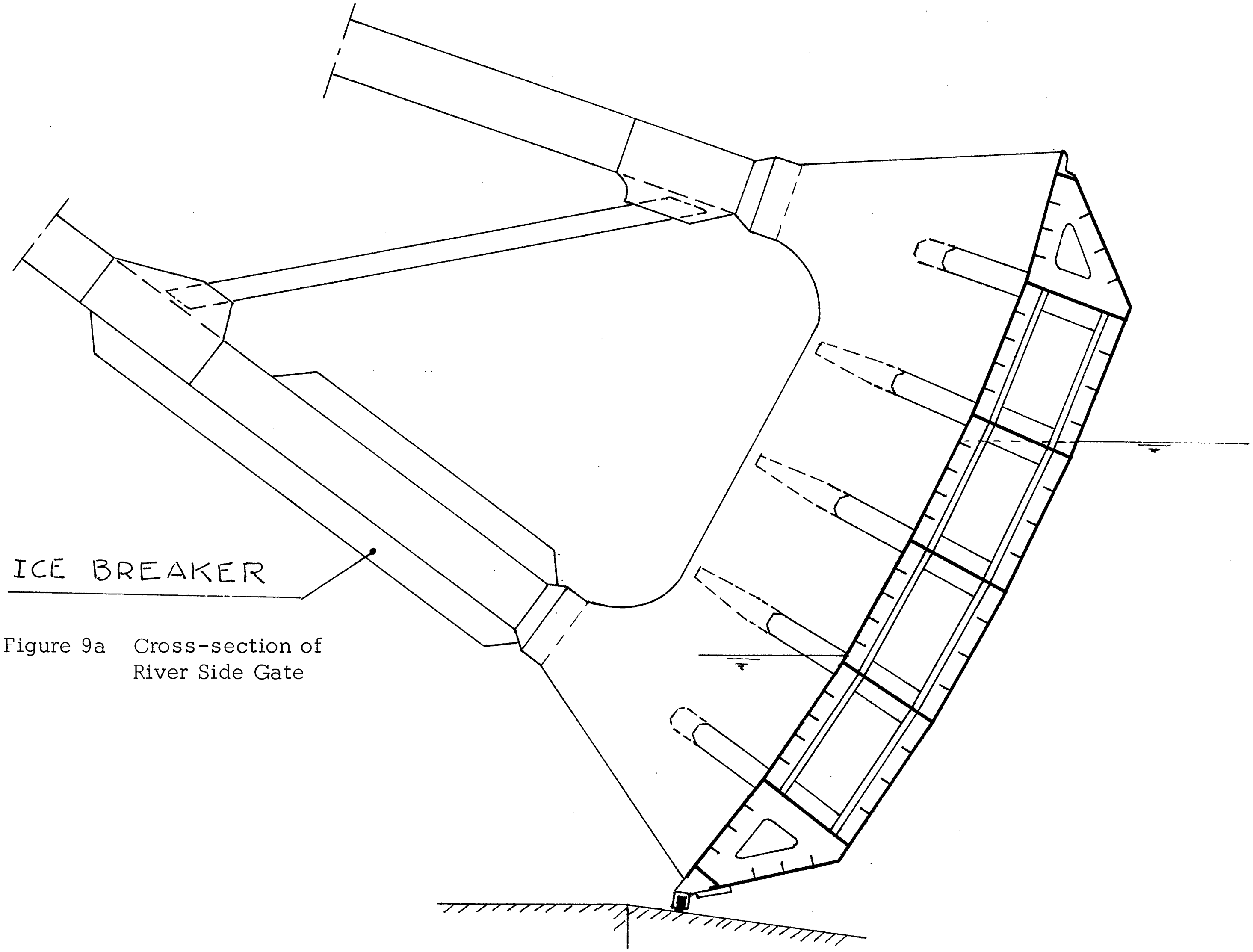


Figure 9a Cross-section of River Side Gate

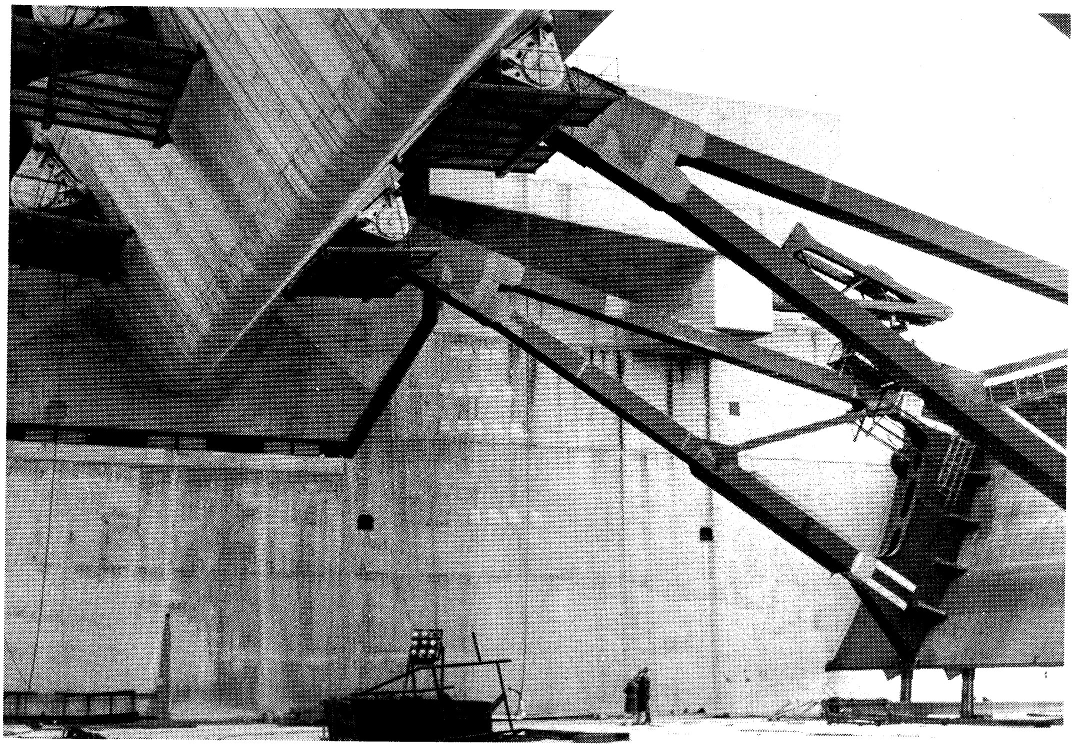


Figure 9b Photograph of River Side Gate

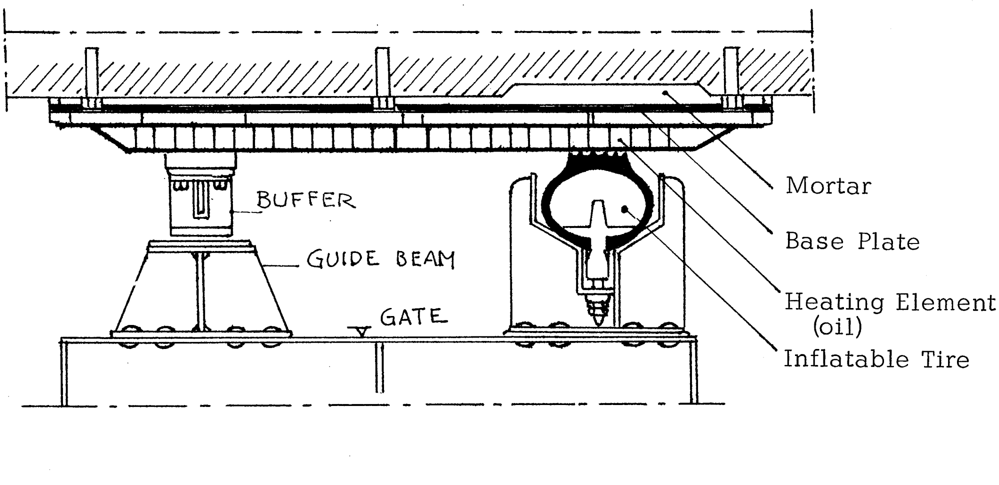


Figure 10 Heating Elements for Side Seal

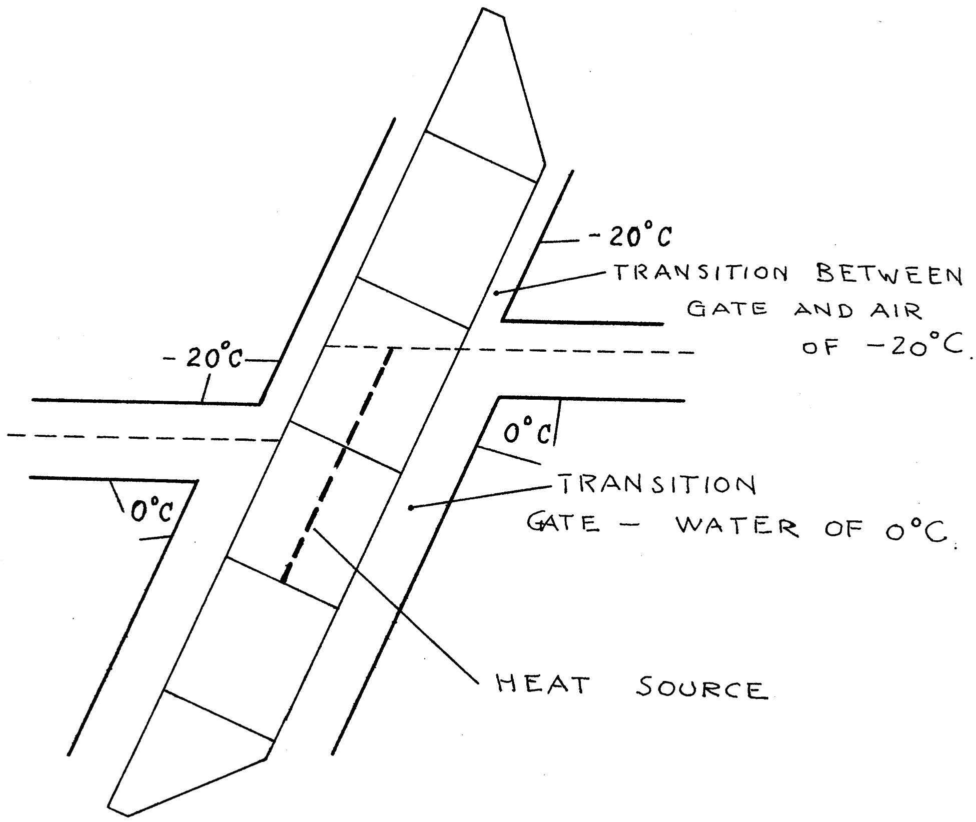


Figure 11 Schematic Test Conditions

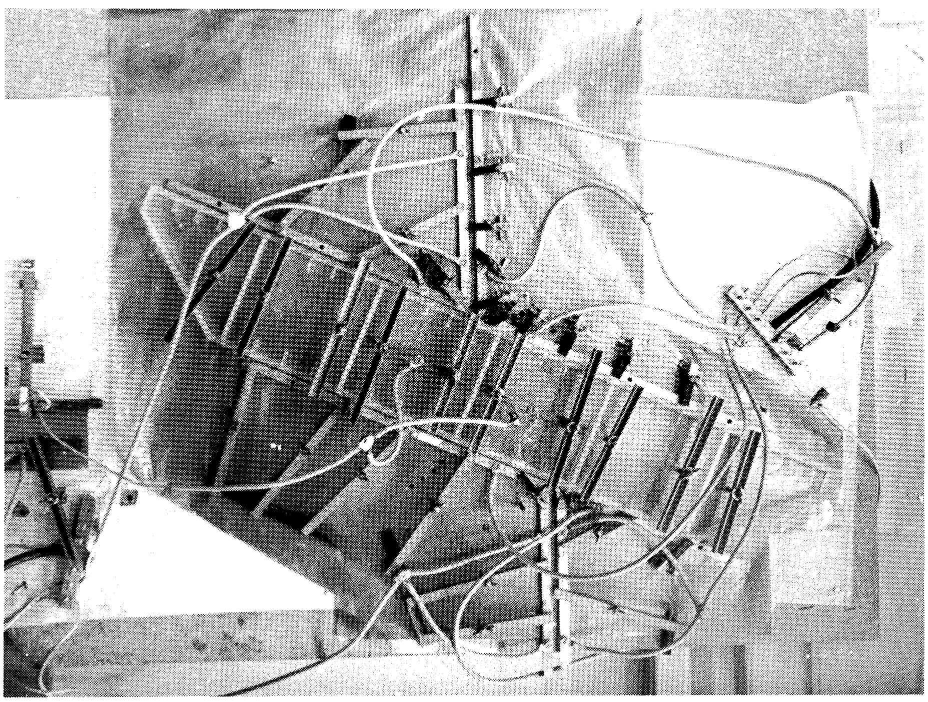


Figure 12 Electric Analogue

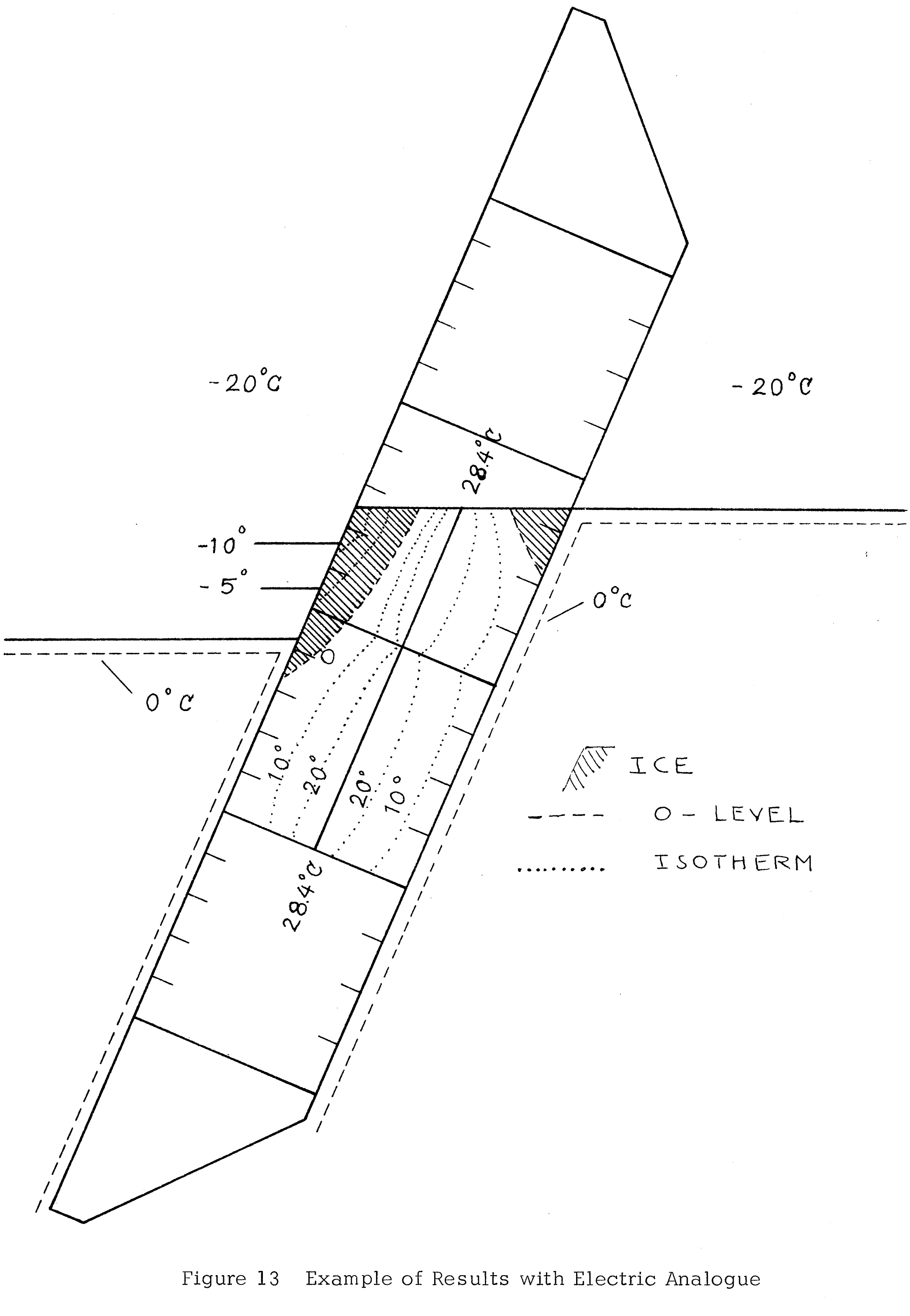


Figure 13 Example of Results with Electric Analogue