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THE KREEKRAK LOCKS ON THE SCHELDT-RHINE CONNECTION

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by

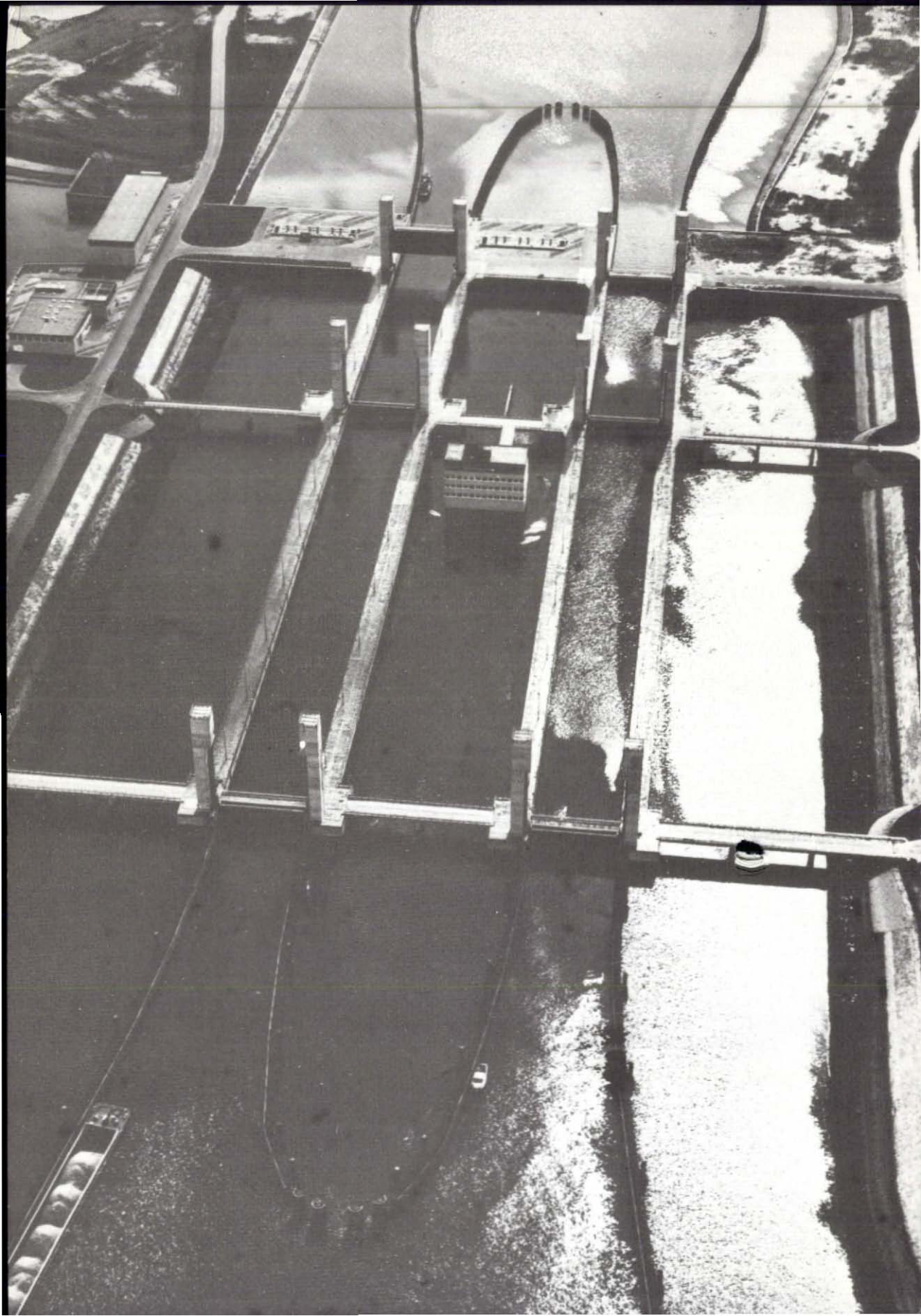
IR. P. A. KOLKMAN

and

IR. J. C. SLAGTER

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ON THE SCHELDT-RHINE CONNECTION



by

IR. P.A. KOLKMAN

Delft Hydraulics Laboratory

and

IR. J. C. SLAGTER

Rijkswaterstaat

Locks and Weirs Directorate

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All correspondence should be addressed to

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The views in this article are the authors' own.

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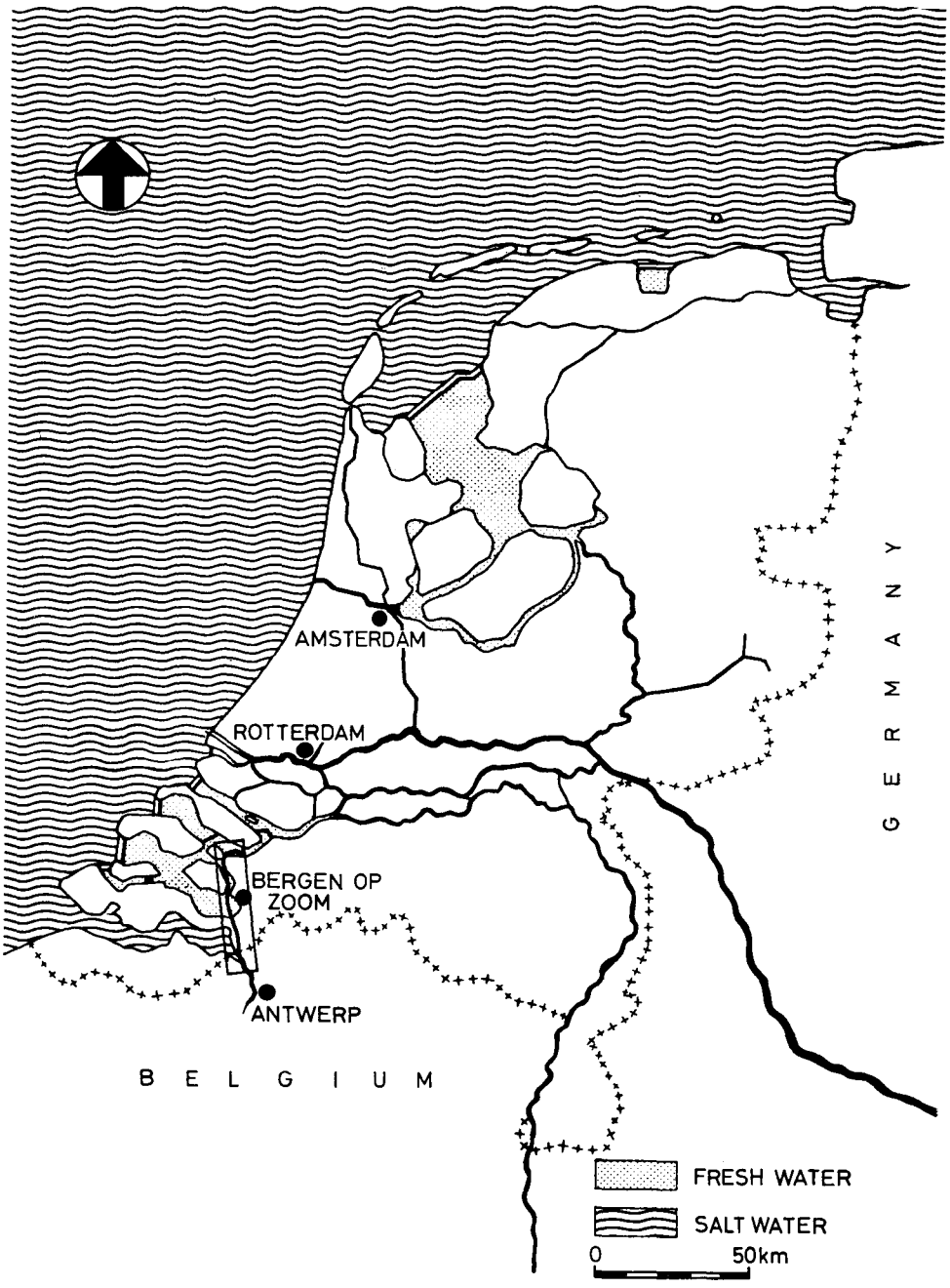


Figure 1. The new Scheldt-Rhine connection in the Netherlands.

1 General outline

1.1 Introduction

On 13 May 1963 a treaty was concluded between the Kingdom of the Netherlands and the Kingdom of Belgium concerning the connection between the Scheldt and the Rhine. The treaty was ratified on 23 March 1965.
This connection comprises a navigable waterway which is connected near Zandvliet with the Antwerp harbour system, then runs to the Eastern Scheldt, crosses the latter in an approximately northerly direction, passes through the Eendracht, then cuts through the Slaakdam and the Prins Hendrikpolder east of St. Philipsland and debouches into the Krammer (figures 1 and 2).
The treaty stipulated that a system of locks should be constructed in the canal section extending from the port of Antwerp to the Eastern Scheldt (figure 3). The system of locks was called the 'Kreekrak locks' from the tidal gulley that once existed in this area. The lock system had to be designed in such a way that when it was in use virtually no salt water would pass from the higher Antwerp Canal section into the lower-lying fresh-water Zeeland Lake which would be created after the closing of the Eastern Scheldt. A further requirement was that fresh-water loss should be kept to a minimum in order to prevent salinization.
Unless precautions were taken the contents of the lock chamber, filled with salt water when vessels passed through in the direction of the Zeeland Lake, would be almost entirely discharged into it, and the locks would fill up with fresh water.
The fresh water would be lost when the locks operated in the opposite direction, since being less dense it would spill like a nappe over the salt-water canal pound.
In the meantime, as a result of the government's decision to close the Eastern Scheldt by means of an opening dam, the situation has changed in that a fresh-water 'Zeeland Lake' is not to be created, but a salt-water tidal basin is to be maintained.
However, compartmentalization is to be employed in the Eastern Scheldt.

No decision has yet been taken on the manner in which this is to be done; although the compartment dams are to be so arranged that in any case the Scheldt-Rhine connection will be situated in a fresh-water compartment – hereinafter referred to as the 'Eastern Basin' – shut off from the tidal basin.
The need for an effective salinization-prevention system in the Kreekrak locks is as great as ever, and perhaps acquires even greater significance, for owing to the smaller area of the Eastern Basin it is much more susceptible to salinization than the much larger Zeeland Lake.

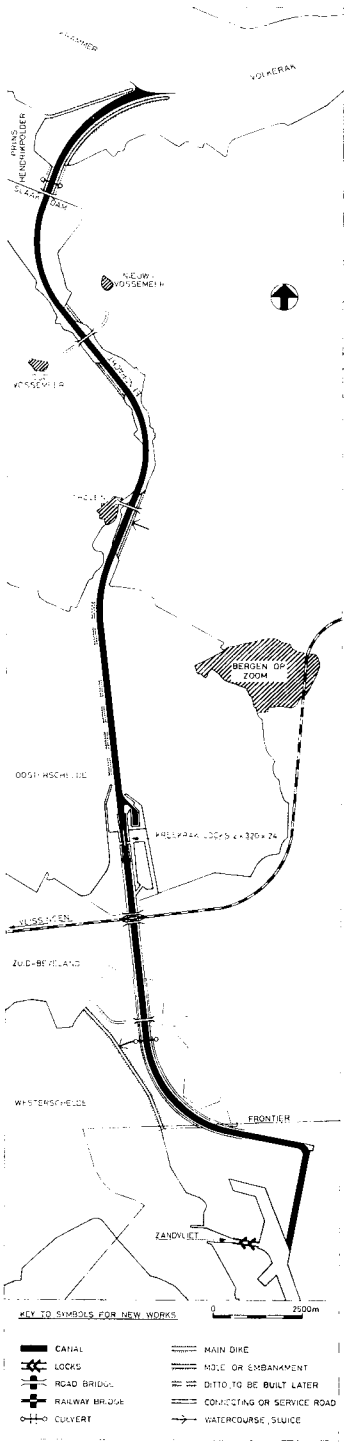


Figure 2. The route of the new Scheldt-Rhine connection.

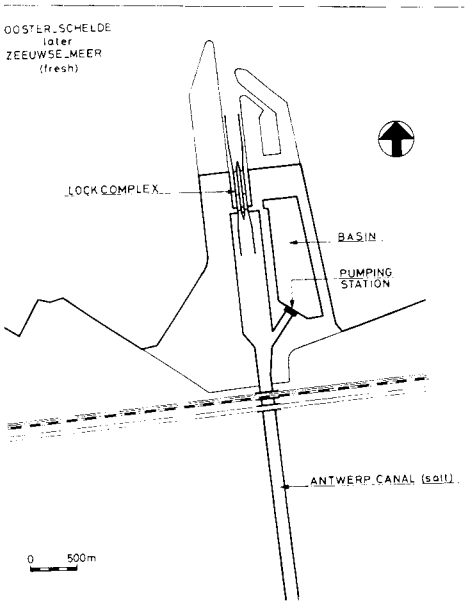


Figure 3. General view of the Kreekrak lock system.

In order to eliminate salinization of the Eastern Basin near the locks on the Scheldt-Rhine connection more or less completely, an exchange system is employed on which very detailed hydraulic research has been conducted. From the design point of view the appropriate system of filling and discharge implied a great deal of adaptation and development. The chapters that follow give a detailed report on both the hydraulic investigation and the design of the lock system.

1.2 General requirements

Initially the system was to comprise two locks having an effective length of 320 m and a width of 24 m; the lock chambers have to be divided into two parts by an intermediate lock.
The design had to allow for a third lock, which in the event of continuous operation can be constructed if the capacity of two locks is no longer adequate.
A capacity of some 60 millions tons of cargo a year per lock is achieved.
The canal, which is also designed for pushed-barge traffic, requires a minimum navigable depth of 5 m. This determines the sill level of the intermediate lock and the lock on the Eastern Basin side at N.A.P. — 6.25 m and the level of the canal lock at N.A.P. — 3.20, since a low-water level of N.A.P. — 1.25 is taken for the Eastern Basin and the low-water level on the Antwerp Canal is N.A.P. + 1.80 m.
Navigation in the direction of the Eastern Basin is in this case similar to the situation at the Volkerak locks.
As long as the Eastern Scheldt is still open a high-water level of N.A.P. + 5.50 must be allowed for. But lock operation stops above N.A.P. + 3.00 m.
After the closing of the compartment dams the maximum level in the Eastern Basin will be N.A.P. + 0.70 m. The water-level on this fresh-water lake is therefore liable to vary by about 2 metres. The maximum water-level on the Antwerp Canal is N.A.P. + 2.00 m.
It is not certain what kind of difference in density should be allowed for when the final stage is reached with fresh water in the Eastern Basin and salt water in the Antwerp Canal. For this reason the model tests were carried out taking density differences of $3^0/_{00}$ to $12^0/_{00}$

($\Delta\varrho = 3 - 12$ kg/m^3).

It was specified for the lock complex that the salinization prevention system design should not result in an unduly lengthy locking cycle.
The overall time for equalizing, emptying and filling the chamber for lock operation in both directions should not exceed 24 minutes.
The forces generated by the exchanging of water to which vessels are subject should not produce undue berthing stresses.

1.3 Lock systems suitable for the prevention of salt-water intrusion and fresh-water loss at the Kreekrak locks

1.3.1 *Requirements for the salinization prevention systems*

The following requirements must be satisfied in the selection of the locking system:

a. The locking capacity had to be more or less the same as the capacity of the Volkerak locks. Since the dimensions, which are adapted to the needs of pushed-barge traffic, broadly correspond to the dimensions of the Volkerak lock, this means that the part of the complete locking cycle carried out with gates closed (equalizing in both directions and other operations) must be limited to about 24 minutes.
b. The amount of salt-water intrusion into the delta lake must be kept as small as possible, because discharging in the opposite direction demands a relatively large fresh-water loss.
c. The fresh-water loss due to locking must be limited as far as possible.

The salt intrusion into the fresh section which occurs unless special precautions are taken at the lock is caused by the locking water and exchange flow. The intrusion of salt water due to the locking water can only be prevented by returning it to the salt section, if necessary by pumping. The systems described below are possible ways of reducing salt intrusion due to exchange.
Owing to a, alternatives such as rolling bridges, series of locks one behind another etc. were unsuitable.

1.3.2 *Air-bubble screen system*

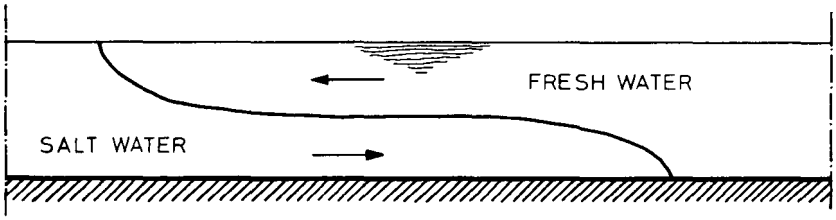
Figure 4 illustrates the principle of the air-bubble screen [1]. It consists in having a perforated air line fitted to the sill of the lock gate at each lock entrance whereby compressed air is released during the exchange flow phase.

When the lock gates are opened and the water level is the same, a current is created by the difference in the density of the water on either side of the gate, resulting in the salt water forcing its way under the fresh; being on top the fresh water will replace the receding salt water. Theoretically at the smallest cross-section the flow rate of fresh water alone (or salt water alone) is

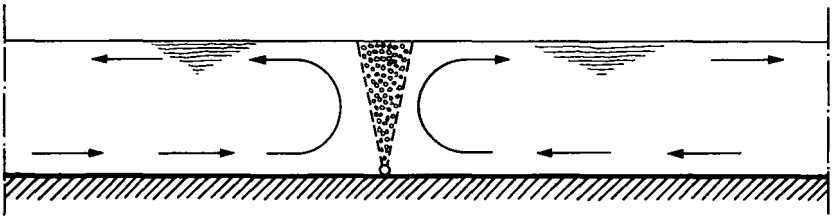
$$^1/_4\left(\frac{\Delta\varrho}{\varrho}\right)gh^3)^1/_2W.$$

($\Delta\varrho/\varrho$ is the relative difference in density, g = acceleration du to gravity, W = width, h = water depth).

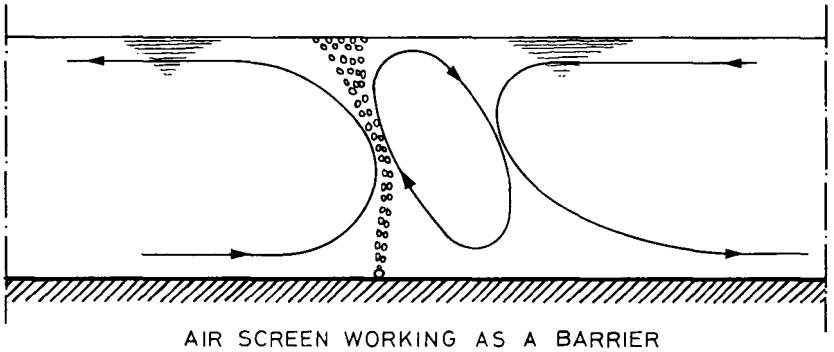
When the lock water volume is V, after time $T = {}^{4V}/\left(\frac{\Delta\varrho}{\varrho}\right)gh^3)^1/_2W.$
the entire chamber will be exchanged, i.e. the water in the chamber will then have been replaced by water from the adjoining canal pound.



EXCHANGE CURRENTS WITHOUT AIR SCREEN



AIR SCREEN: HOMOGENEOUS CONDITIONS



AIR SCREEN WORKING AS A BARRIER

Figure 4. Air-bubble screen: flowpattern in homogeneous condition and working as a barrier.

Actually the time will be somewhat longer, while in addition there is always a residue of the original water as a result of mixing.

By the releasing of air bubbles, preferably at the narrowest cross-section whers water velocities are maximum water from the undercurrent will be entrained upwards, while a countervailing current from the top layer flows downwards. The vertical currents cause water particles to flow in the opposite direction. The requisite acceleration forces can be converted to a shear resistance between the layers. Consequently, the air bubbles increase the shear resistance roughly in proportion to the air flow rate. Hence the exchange time is lengthened. Figure 5 illustrates how the

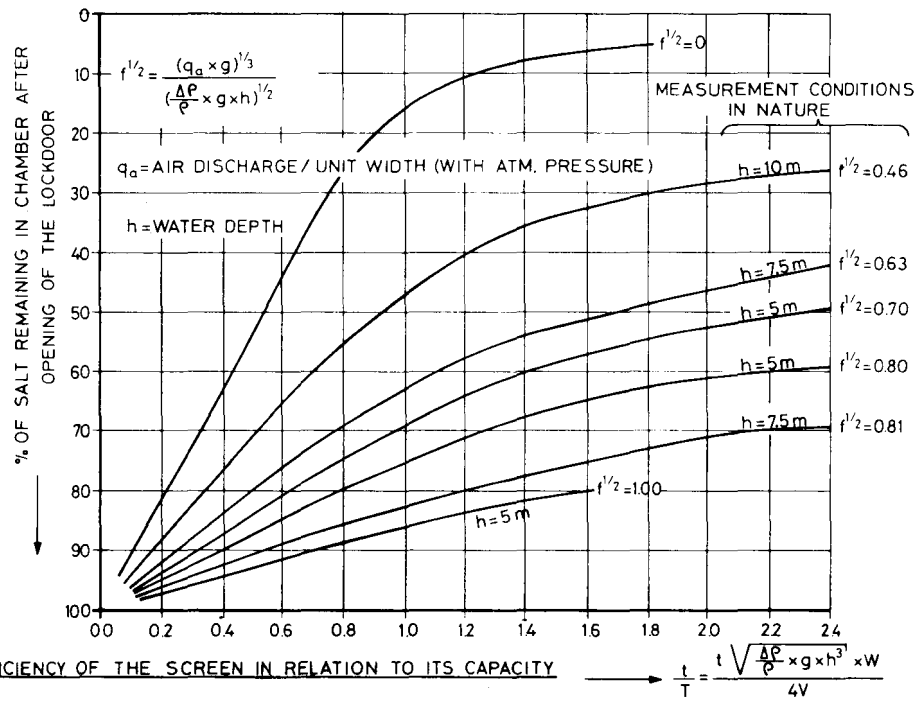


Figure 5. The effect of the air-bubble screen.

quality of the water in the chamber alters as a function of time for various air discharge rates. The time is related to a reference time T in which theoretically the chamber should be exchanged.

Since in homogeneous water conditions an air-bubble screen produces surface velocities directed away from the screen, this, combined with the natural exchange occuring in salt and fresh water flow, means that on one side of the screen the two currents retard each other, whereas on the other side the current is in fact accelerated. This is an additional drawback especially for small vessels and at low speeds.

The above, together with figure 5, shows that:

- air-bubble screens effect a reduction in the volume exchanged, provided the gates do not remain open too long,
- the volume of water which is displaced by the entry and exit of vessels passes through the screen in any case,
- there is additional mixing of fresh and salt water,
- circulation currents are created (this is a disadvantage when small vessels enter at low speed),
- energy is required to compress the air in the line submerged at depth,
- the drawbacks to navigation are increased.

Previous experience has been acquired at the big lock of IJmuiden and at the Ter-

neuzen locks. It shows that overall, when gate opening times are short, salinization du to exchange can be halved. At the same time it must be accepted that entry and exit must take place in quick succession. When the lock is not fully occupied this results in longer waiting times.
Collection of the salt-water intrusion in a lock sump (enabling it to be discharged separately) is less effective; owing to the resultant mixture some of the canal water in the fresh-water pound will also be contaminated.

1.3.3 *System of direct evacuation of the salt intrusion (Terneuzen system)*

This system is used at the gates of the fresh-water canal pound. When circumstances are such that when the water level between the chamber and the fresh-water pound is the same and the gates are opened, the chamber is more or less salt. This depends on the length of time the other doors have been open and whether air-bubble screens have been used. When the doors are opened the fresh water tries to escape below and again the salt intrusion described in A is created with a flow rate

$$Q = {}^1/_4\left\{\left({}^{\Delta\varrho}/_{\varrho}\right)gh^3\right\}^{1/2}W.$$

By now evacuating at a rate equivalent to Q just past the gate, salt water can theoretically be prevented from travelling up the canal (figure 6).
However, owing to the passage of vessels, the salt water supply may vary and possibly may not be evenly distributed across the width. This means that the rate of evacuation must be adapted to the movement of vessels, even then there is a likelihood of fresh water from the surface being drawn off along with the salt as a result of „short-circuit" currents. For navigation this system means that vessels travel with water velocities similar to natural exchange. A situation of this kind is more troublesome than usual.
At the Terneuzen sea lock the system is used as follows: the evacuation rate is taken roughly as Q for the period during which the natural drop is high enough to achieve

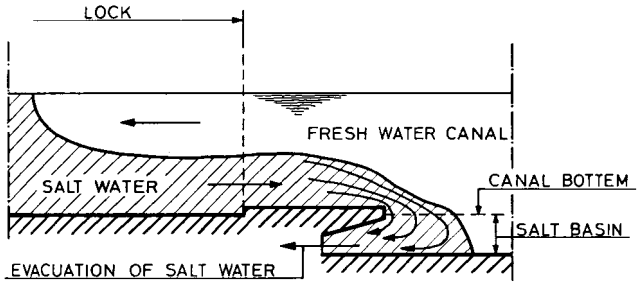


Figure 6. The Terneuzen system: selective withdrawal of salt water intruded in the fresh water canal.

this discharge rate. Behind the lock a deepened collecting basin is used as a reserve in which the excess salt can be stored. The salt can be evacuated selectively at low velocity from this sump located at depth. By positioning the inlet at the lock gate low, below the sill, the same aperture can be used for evacuating the salt intrusion as well as emptying the basin. With this system virtually the entire contents V of the lock chamber are discharged if the gates are left open for a fair length of time. Since the contents are taken from the canal and are not compensated this volume of water, plus the amount required to evacuate the basin, is therefore the fresh-water loss. The fresh-water loss travels up the salt canal pound just as the lock gates on that side are opened and a natural exchange is created. The system has been extensively studied in a physical model at the Delft Hydraulics Laboratory. If the Terneuzen system were used for the Kreekrak locks it should be possible to achieve a reduction in fresh-water loss by forcing back the fresh chamber water to the fresh side of the canal before the gates are opened on the salt canal side. This could be done by pumping salt water along the bottom into the bottom of the chamber and withdrawing the fresh from the surface by means of the gate or high-positioned parallel conduits. Whether this is an attractive proposition depends inter alia on the quality of fresh water recovered; when the salt intrusion is evacuated a salt residue may be left in the chamber.

1.3.4 *System of complete lock-chamber exchange with the chamber sealed off (Dunkirk system)*

The cardinal feature of this system is that the lock gates on the fresh-water side of the canal must be opened until there is no salt water left in the chamber. All the salt water is therefore first discharged or pumped out. In order to keep the vessels afloat, fresh water is brought in at the same time. Steps must be taken to keep the layers of water stable (salt below, fresh above) so as to reduce the amount of mixing that occurs, and the fresh water must be introduced in such a way that no turbulence or jet effect results. Furthermore, the entire process must take place fairly evenly along the entire length of the chamber, since otherwise wave effects would be produced at the interface, preventing all the salt water from being evacuated at the same moment by which also fresh water will be taken away, with moreover the result that the exchange process would take too long.

This gives a system in which the salt water is withdrawn from the chamber floor through perforations along its entire length and the fresh water is introduced as high as possible (yet below the free water level) by means of fresh water conduits along the entire chamber wall (figure 7).

The amount of water returned to the salt pound through the floor, and consequently the amount withdrawn simultaneously from the fresh pound, is at least equivalent to the entire chamber volume; also the locking water has to be pumped back to the salt pound if it is on a higher level. Additional fresh water has to be brought in if

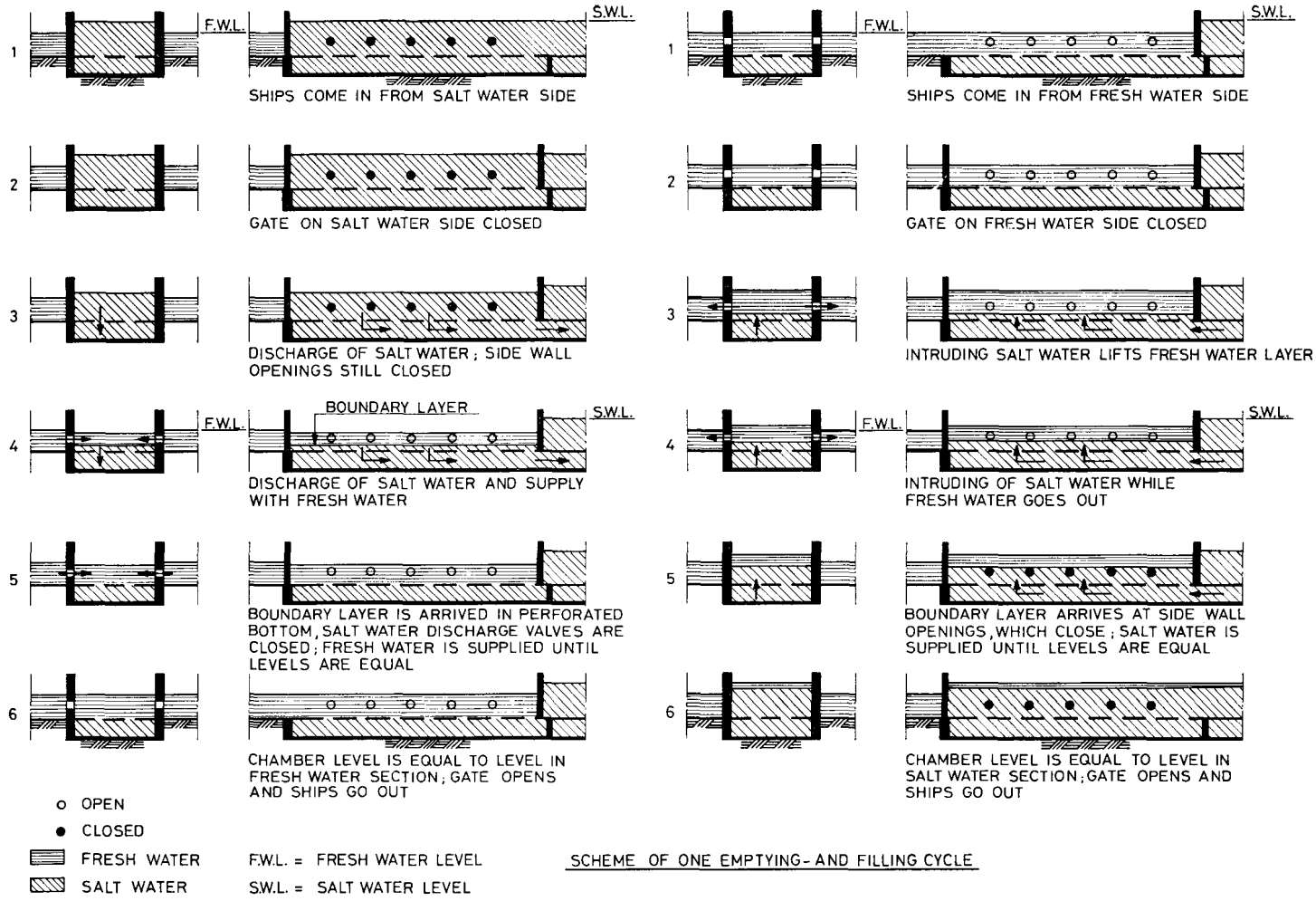


Figure 7. System of complete exchange of closed lock chamber.

during the process there is so much mixing that the mixture has to be removed to the salt pound.
Vessels can enter and leave without currents being present. Unless precautions are taken in locking vessels back to the salt pound, there is a fresh-water loss equivalnet to the chamber capacity, as in the Terneuzen system.
In order to limit the loss the same procedure as described in the Terneuzen system could be used here, i.e. salt water is brought into the bottom with the gates closed. while fresh water is simultaneously removed from above through the walls.
For this purpose the already existing system with a performated floor and high-positioned fresh-water inlets along the entire length of the chamber wall can be used (figure 7). In this case also the effectiveness of fresh-water recovery is determined by its quality, i.e. whether too much salt will be let in into the fresh pound as a result of mixing.
The drawback to navigation is the loss of time due to the need to exchange not only the locking water but also the entire chamber before the gates can open.
The system was first used for a lock at Dunkirk, the design being supplied by the SOGREAH Laboratory in Grenoble, where a detailed model investigation was also conducted [2]. We were able to make use of the complete research report and engineering drawings supplied by SOGREAH and Ponts et Chaussées in evaluating the various systems.
Figure 8 illustrates the engineering of the lock at Dunkirk.

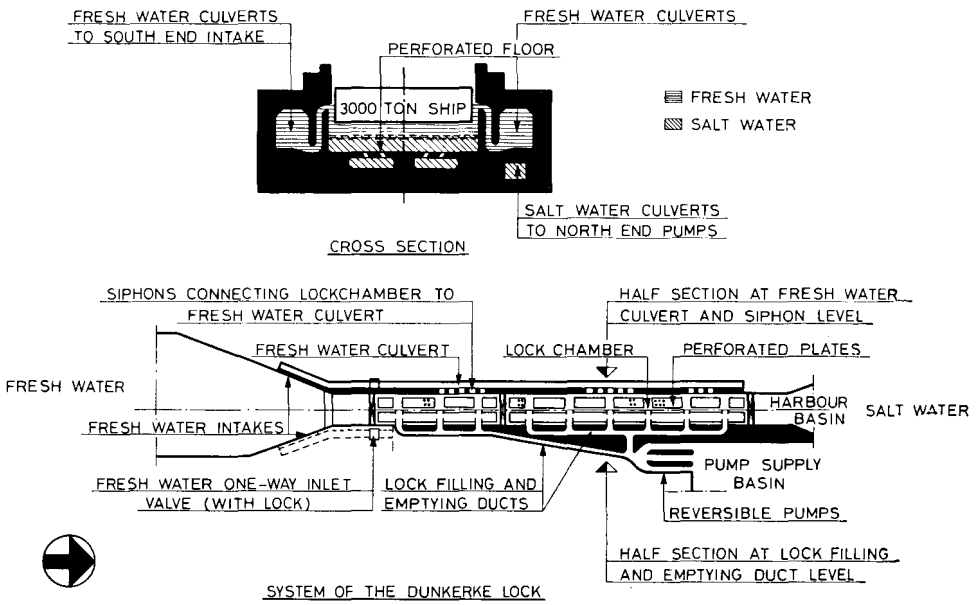


Figure 8. The Dunkirk lock system.

Table I. *Comparison of alternative methods of salinization prevention*

per locking cycle (i.e. up and down)	no action taken	air-bubble flow	Terneuzen (constant-rate removal programme and fresh-water recovery)	Dunkirk
salinization	1.0 V	0.5 V	0 except when vessels pass	0
fresh-water loss	0.8 V	0.5 V	1.4 to 1.8 V	0.4 V
volume of water pumped	—	0.2 V (locking water)	1.9 to 2.3 V	1.0 V
effect of vessels on mixing due to change	—	return current from vessels passing	largely due to vessels passing — can be helped by adjusting waiting time	largely due to vessels berthing in the lock chamber
time for equalization + exchange	15 min.	15 min.	18 min.	approx. 24 min.
waiting time due to vessels passing	0	0	0 (if vessels do not exit at once the quality of water recovered improves)	unnecessary
overall time (equalization, exchange and waiting time)	15 min.	15 min.	18 min.	approx. 24 min.
safety	fixed programme	fixed programme	flow rate dependent on density difference. Any reduction in salt-water loss and salinization due to vessel movement by means of programming is undesirable on safety grounds	fixed programme adapt to circumstances
additional hindrance to navigation	exchange current when sailing	exchange + bubble current when sailing	exchange currents when sailing	transverse forces on berthed vessels

V = Volume of chamber between Antwerp Canal level and Zeeland Lake sill level.

Since know-how was available in the Netherlands on air-bubble screens as well as the Terneuzen system, and the results of the DUNKIRK model investigation were likewise available, the systems could be compared overall with each other. In addition, further tests were conducted at the Hydraulics Laboratory in Delft for both systems on very approximate physical models.

Table I gives the various factors which enter into the projected construction of the Kreekrak locks. Conditions are such that the salt pound is always higher than the fresh, so that when salt water is removed from the chamber, pumping must be resorted to when this water is brought back into the salt canal. All the data available at the time the system was selected were used in compiling the table. These inclused a preliminary investigation of the Dunkirk system with a view to possible application for a small lock on the Voorn Canal near Rotterdam.

A separate investigation was carried out for the overall evaluation of the Terneuzen system to supplement the already available data on the Terneuzen sealock itself, and to determine where mixing occurs between the layers and whether the amount of mixing is low enough to make the recovery of the fresh chamber water just feasible. When the figures are compared it should be observed that the quantitative estimates are very approximate, and that fresh-water losses in the Terneuzen system are very large, since the discharge rates in the tests were not adjusted for the effect of vessels passing through, but an excess was allowed for such that, even with ships passing through, no salt water would get into the fresh-water canal.

The table shows that the Dunkirk system is the more economical one as far as water is concerned. Capital expenditure is the same as for the Terneuzen system. No adequate answer has yet been found to the question as to whether in the case of these large locks the entire process of filling and emptying and the exchange between salt and fresh water and vice versa could be achieved in a reasonable time with the Dunkirk system. On the basis of the preliminary investigation carried out it was decided to conduct a systematic investigation on a model reproducing the design of the entire lock and enabling complete programming of the valves and vessels using the system. The model was based on a design using the closed-gate exchange system (Dunkirk system), but also included facilities for implementing the Terneuzen system in order to determine whether, by selecting a discharge-rate programme more suited to vessel movements, much better results could be achieved than those shown in Table I.

2 Design and hydraulic investigations

2.1 Design of the Kreekrak locks (Dunkirk system)

The Kreekrak locks were designed in close conjunction with the model investigation. Design and investigation exercised a clear influence on each other, with the participation of various departments of the Netherlands ministry of water control (Rijkswaterstaat), the Delft Hydraulics Laboratory and, in view of the international liaison involved, three Belgian engineers.
The Kreekrak locks, constructed in accordance with a salt and fresh-water exchange system with gates closed, differ in many respects from a conventional lock design. Essentially these differences boil down to the following:
a. The locks are double-bottomed. Under each lock there is a culvert for salt-water supply and removal. The lock is separated from the culvert by a perforated floor; the floor is designed to ensure proper distribution of the flow.
b. The salt-water culvert under the lock is connected by means of supply conduits with an intake on the Antwerp canal for the purpose of filling the lock.
c. For emptying purposes the salt-water culvert is connected by means of discharge conduits with an outlet to the storage basin.
d. A storage basin has to be constructed to accommodate the salt water removed, the alternative of direct pumping appeared to be uneconomic due to the high peak discharges. The water level in the basin must be kept lower than the level on the Eastern Basin.
e. In order to maintain the water level in the storage basin a pumping station has to be constructed to return the salt water to the canal.
f. Wall openings which are vertically adjustable and can be sealed off must be provided along the entire length of the chamber for the supply and removal of fresh water from the Eastern Basin.

These apertures, which are positioned near the top, must be vertically adjustable owing to the variations in water level on the Zeeland Lake, whereas the locks are not similarly constructed; the basins outside the locks are in open connection with the Eastern Basin and constitute the surrounding fresh water (photo 1).

The locks have a basically trough-shaped section and steel foundations.
The deep floor and walls are largely constructed of reinforced concrete.
In order to secure proper distribution of the vertical salt-water movement along the entire lock bottom, use was made of an intermediate floor having a high pressure resistance between the lock chamber and the salt water floor drain. This drain for the

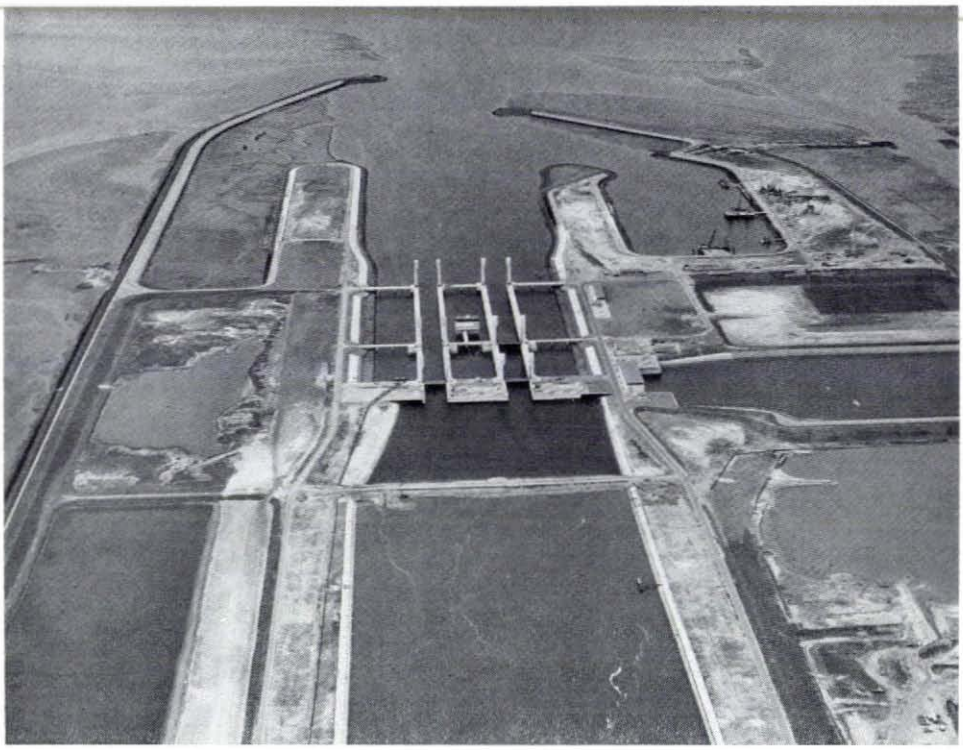


Photo 1. The Kreekrak locks with the surrounding fresh-water Eastern Basin.

supply and removal of salt water was laid under the lock chamber proper in order to obtain the shallowest possible foundation level. The nature of the ground is locally such that a load-bearing layer suitable for building on without piles is not found above N.A.P. —14 m (figure 9). This level was achieved by means of the construction method described above.

The intermediate floor between the drain and the chamber has only 1.3% apertures; the resultant high resistance provides good flow distribution along the entire floor surface in both directions. A draw-back of this device is the high current velocity during exchange produced by the big drop; unless precautions are taken, too much fresh water is entrained in consequence to the floor drain, while salt water is left behind in the chamber.

Conversely, the entrained fresh water is never returned, while the vertically rising jet of salt water produces too much mixing.

These problems can be prevented by fitting baffles under as well as above the floor perforations (figure 10).

The alternative shown at the top of figure 11 was the one originally intended for the design, but a much simpler design (illustrated at the bottom of figure 10) was put into practice: the shape of a prestressed concrete girder provides the requisite baffle on

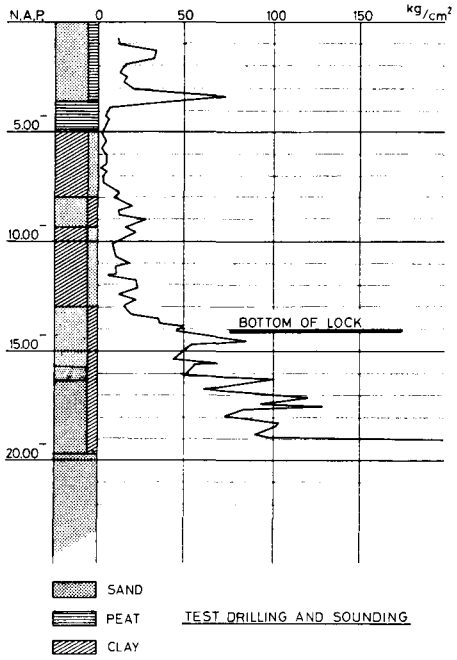


Figure 9. Results of test drilling.

both sides of the holes in the floor beams, while the design height is kept very low. The shaped beams were prefabricated. Every beam was prestressed with high-tensile steel and manufactured in accordance with the bench system. The prestressing is 200 tons for each beam. The intermediate floor was constructed by assembling the beams and sealing the joints with rubber strip (figures 10, 11, 12 and photo's 2 and 4).

The bottom culverts, divided into two parts by the intermediate gate to serve the two lock parts, are supplied by means of amply dimensioned conduits from the Antwerp Canal. These enable the contents of the chamber to be exchanged in a very short filling time whatever the circumstances, using the natural drop between the canal level and the Eastern Basin.

The flow rate is controlled by means of a set of three valves per lock at the intake (photo 5).

The valves are designed in such a manner as to provide the maximum possible tightness in order to prevent salinization (figure 13).

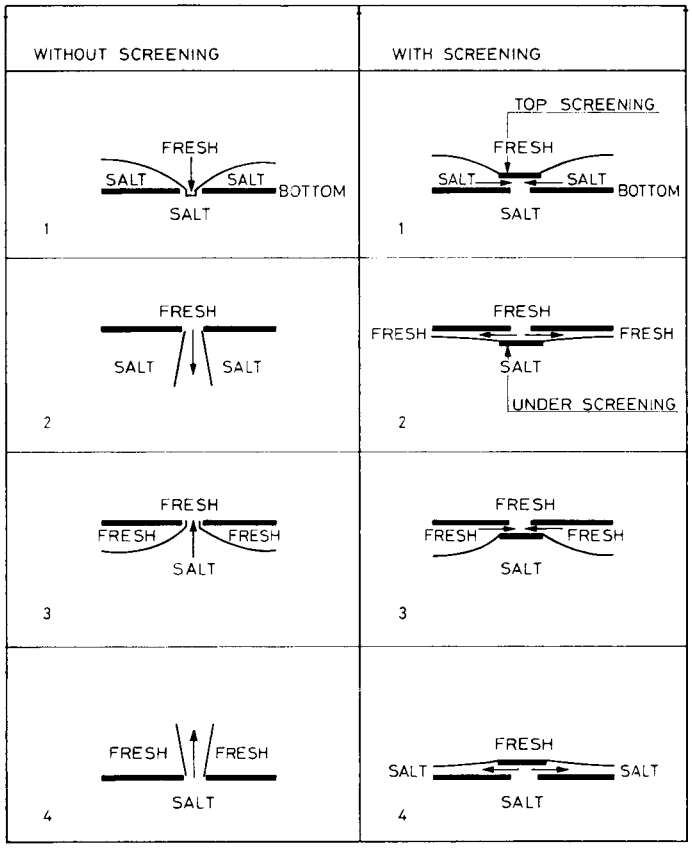
The salt water is evacuated from the chamber using the drop as well; the water is discharged into a 40-hectare storage basin whose level is kept sufficiently low by means of a pumping station (see figure 3). Here too three conduits per lock are available.

The flow rates are likewise controlled by means of valves. These valves are installed in the sluiceway. Here again great care has been taken to ensure a watertight seal. The outlet conduits for a future third lock have to be constructed already at this stage as far as the section below the lock system under construction is concerned.

Figure 14 and photo 6 and 7 illustrate the conduit system and sluiceway.

Discharge into the storage basin referred to above is essential to avoid the necessity of pumping the very large amounts of water discharged from the lock straight into the Antwerp Canal. The discharge rate is about 100 m^3/s per lock.

The locks discharge abruptly into the basin within a short time, and then the water is returned to the Antwerp Canal by the pumping station operating almost continuously at a maximum throughput of about 40 m^3/s when traffic is heavy. Stoppage of the pumping station can be made good for several hours by keeping the level of the basin fairly low.



1 Edge plane down, sucking off remaining salt water
2 Edge plane down, first fresh water passes bottom
3 Edge plane upwards, sucking off remaining fresh water
4 Edge plane upwards, first salt water passes bottom

Figure 10. Floor perforations with and without baffles.

Owing to the cross-current on the canal caused by the pumping station, a detailed model investigation was required to find a satisfactory solution for navigation.
The investigation also embraced current movement in front of the inlet system. Here too safe conditions for navigation were created by adaptation of the protective frame.
Fresh-water supply and removal has been achieved without conduits.
Both locks are completely surrounded by the fresh-water Eastern Basin; this has resulted in „short-circuiting" between the chamber and the fresh-water basin being prevented only by the chamber walls (photo 1). For a proper distribution of fresh-water supply and removal an elongated aperture had to be provided on the outside of the lock on a level with the Eastern Basin (figure 15). The aperture had to be made

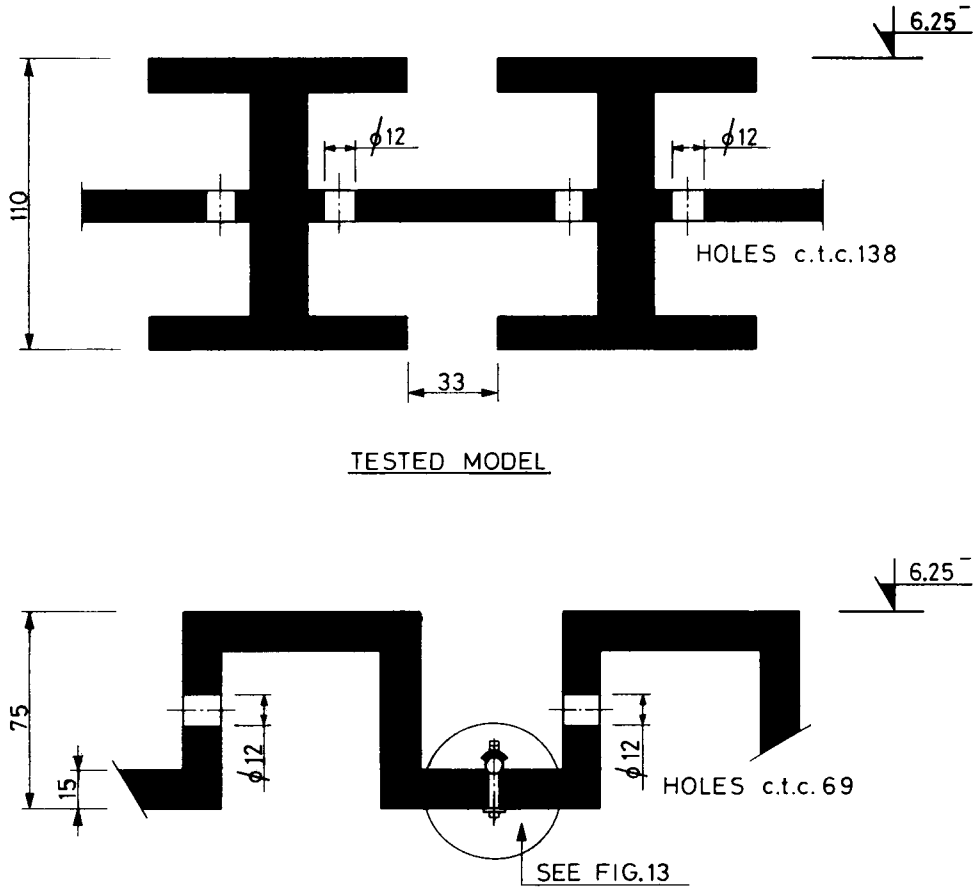


Figure 11. Alternative type of chamber floor with the version selected.

with as few interruptions as possible on both sides of the chamber at a level of 0.75 m directly below the surface of the water (photo 8).

The entire system is mounted above platforms along the walls. On the outside of the lock there are valves which provide the requisite aperture depth of 0.75 m, for on account of the variation in the level of the Zeeland Lake the overflow edge must be adjustable. The wall aperture recedes very considerably at the back in order to make the chamber valves as small as possible (figure 16), thus necessitating heavy columns between the apertures in order to support the superstructure.

Each wall aperture has two operating valves which act as standby to each other. By the use of emergency valves the valve rails can be drained and inspected. In the design of the valve system a great deal of precast concrete was used for the stops and

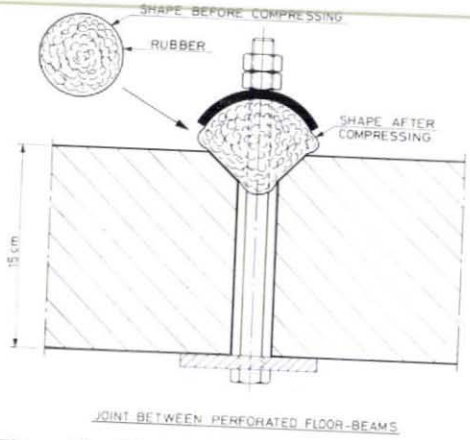


Figure 12. The joint between two beams.

valve rails (photo's 9, 10 and 11). This was necessary in order to produce the particularly complicated shape of this part of the walls.

At the same time a better quality of concrete was achieved by the use of such material for a number of important components. An engine house recess was constructed to accommodate the lock-operating machinery, while the wall apertures on the chamberside are protected against damage by vessels by means of a heavy wooden frame.

The structure, which is built in sections, can if necessary be quickly replaced (figure 17 and photo 4). The top of the engine house recess forms part of a carriageway covered with non-skid material and fitted with a robust guard rail to prevent cars etc. going into the water.

Since the navigation clearance is limited to 9.10 (the same as on the Rhine) lifting steel gates were selected as a locking device because they allow vehicular traffic to

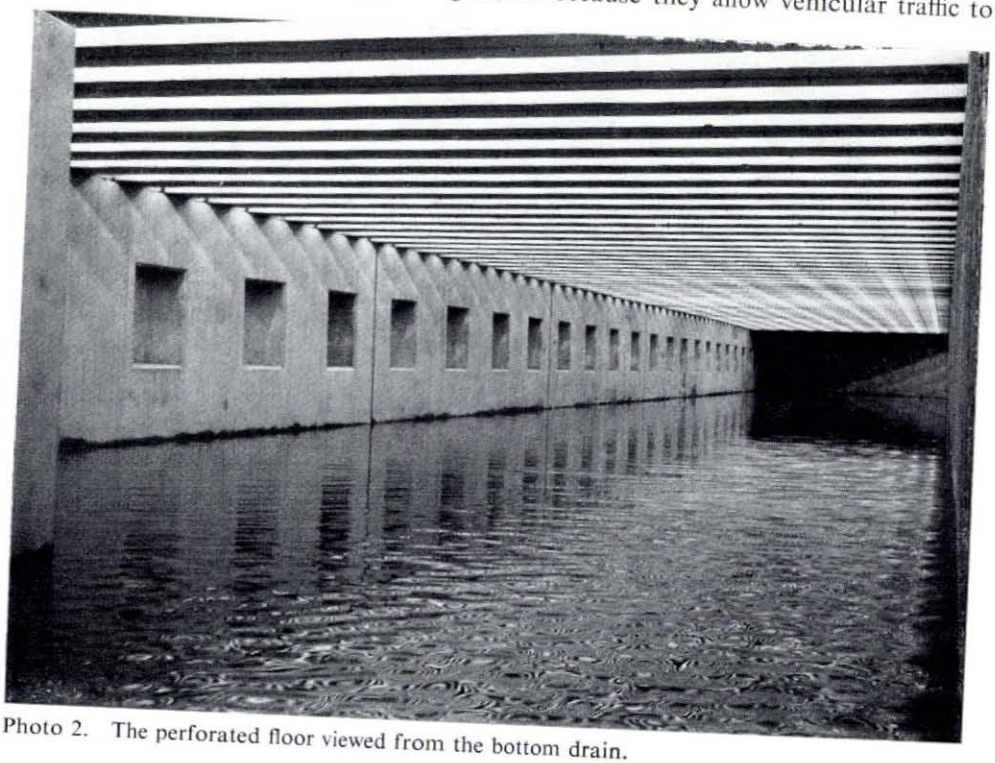


Photo 2. The perforated floor viewed from the bottom drain.



Photo 3. Detail of floor beam.

cross; furthermore, in relation to the effective locking length specified, the lock chamber was made as small as possible, thus keeping the contents of the chamber and the associated salt contamination and fresh-water losses to a minimum.

Despite the gantries, the cost of these gates is also lower. They are cheaper than mitre gates, since owing to the reversal of the drop — as long as the compartment dams still have to be closed and the lake is a tidal salt water area — two sets of mitre gates would be required at each entrance.

„Dripping" is a drawback of lifting gates, which attempts will be made to prevent by means of guttering.

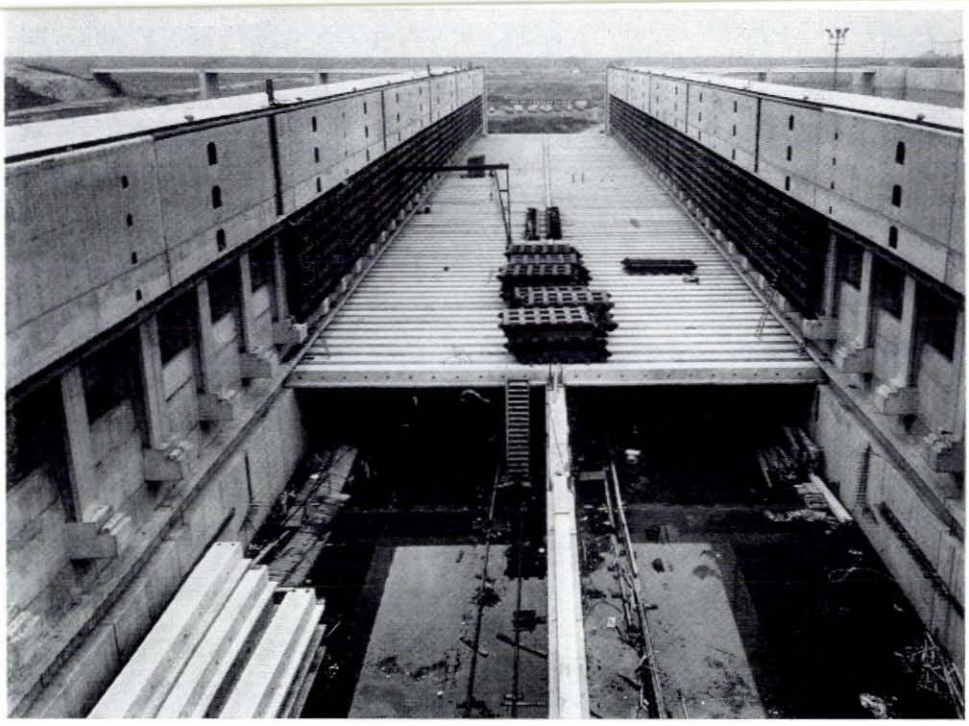


Photo 4. The perforated floor under construction. The figure also clearly illustrates the design of the guide frame in the lock wall.

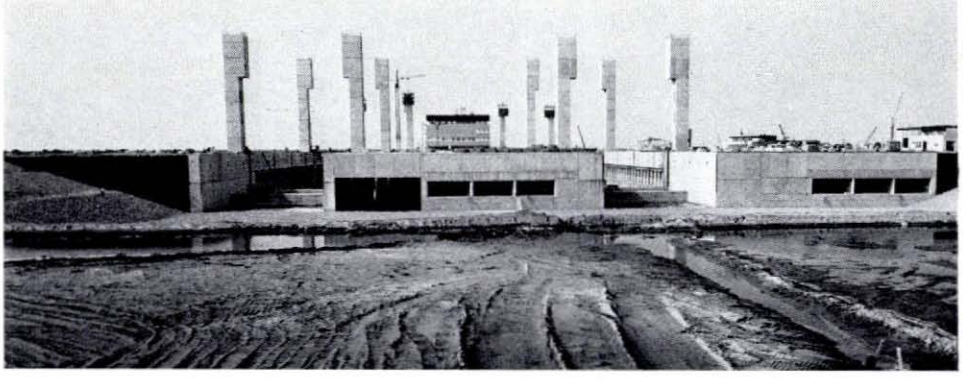


Photo 5. The two inlets on the Antwerp Canal side.

The longitudinal section given in figure 18 shows that the lock chamber is divided by means of an intermediary gate positioned asymetrically into two chambers, one about 210 m and the other about 105 m long. Both chambers can be filled separately

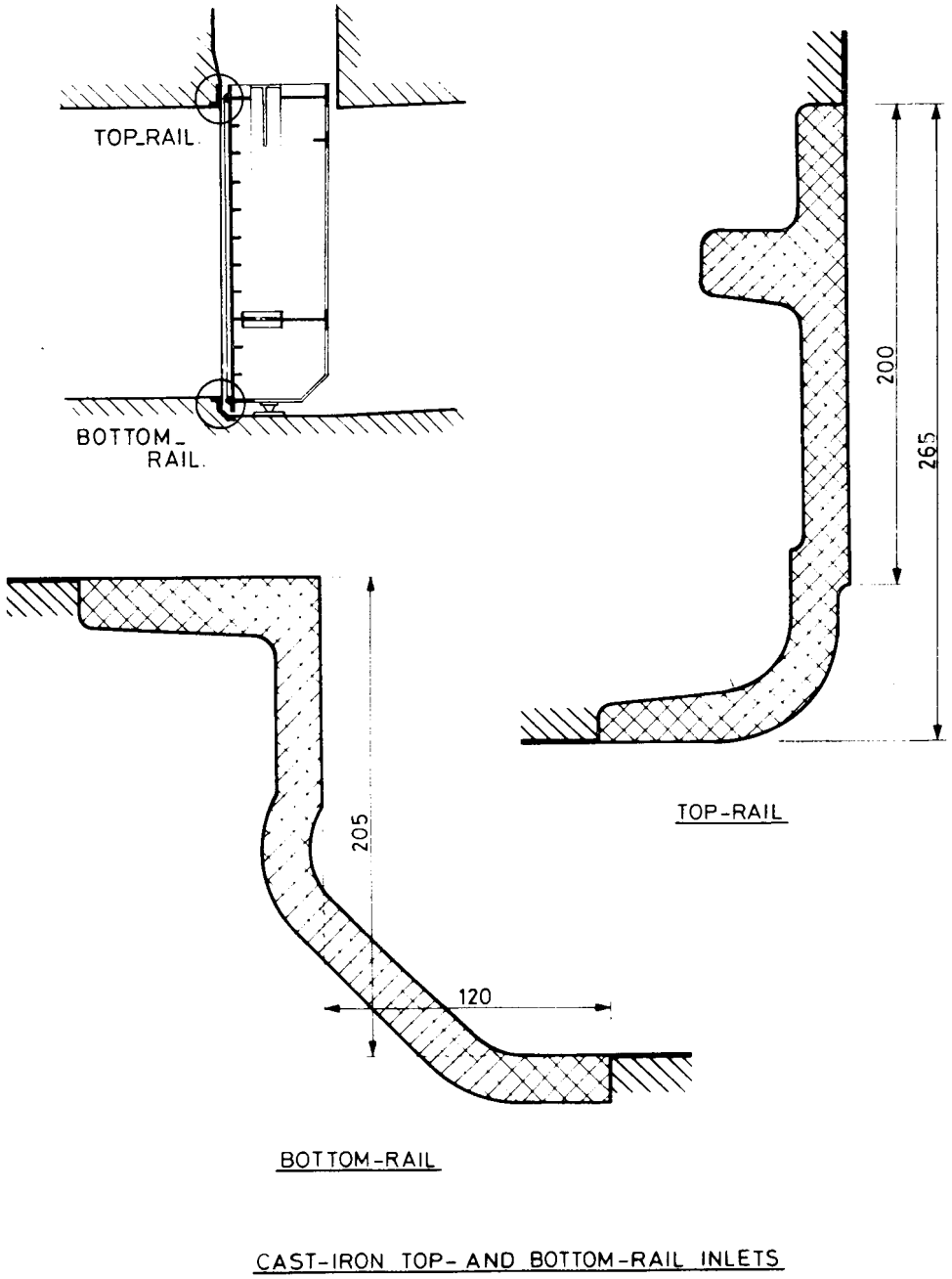


Figure 13. Design of the inlet valve.

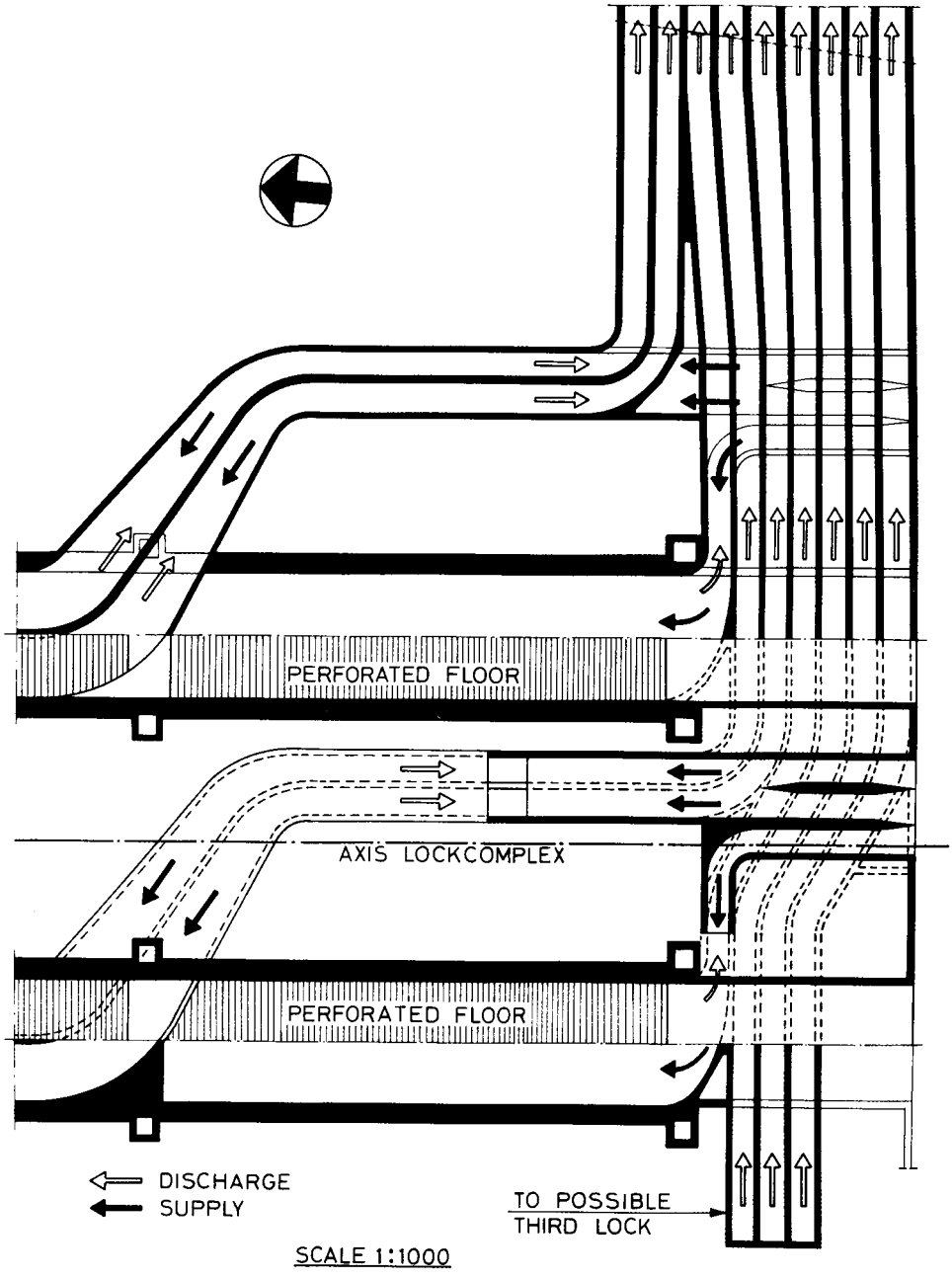


Figure 14. The conduit system of the Kreekrak locks.

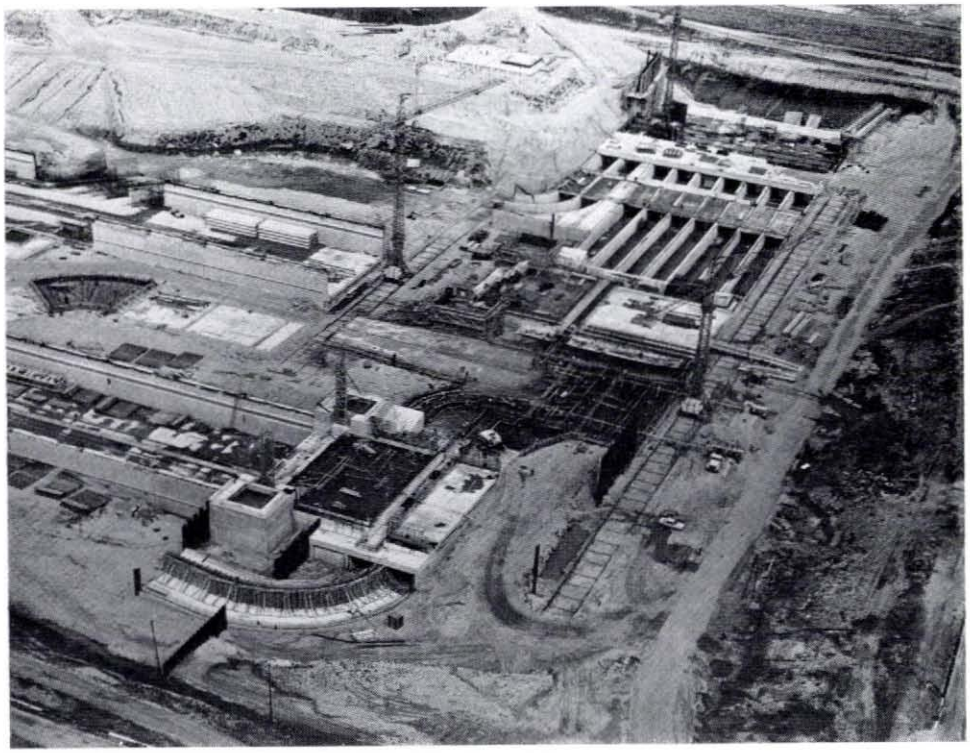


Photo 6. The conduit system under construction.

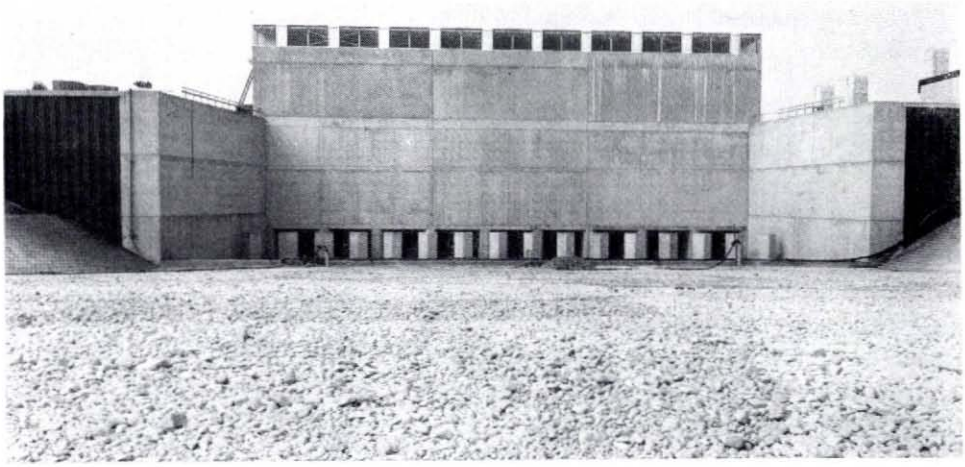


Photo 7. The sluiceway viewed from the storage basin.

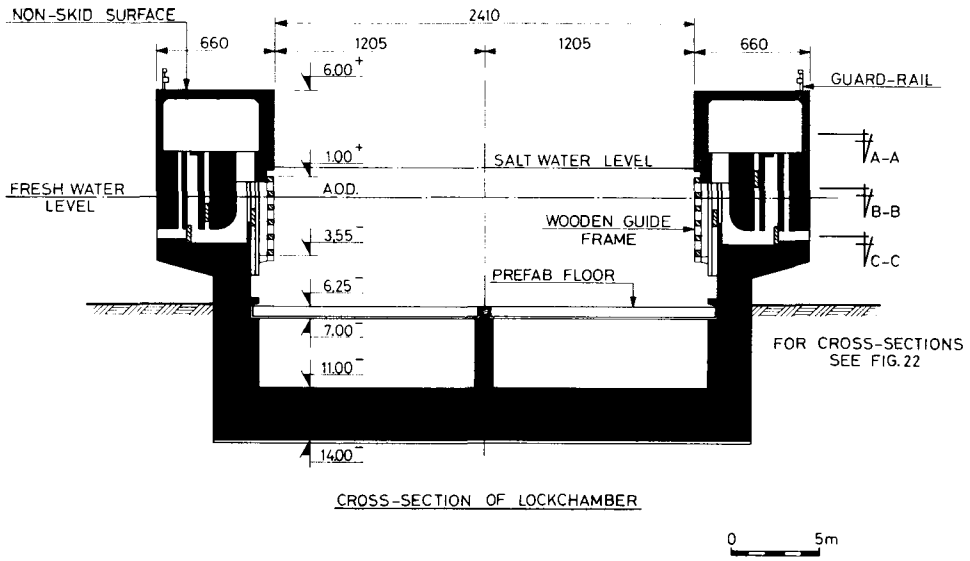


Figure 15. Cross-section of lock chamber.

by means of conduits. This makes it possible to use the complete system also when traffic is light.

This asymmetrical arrangement was adopted to enable the lock to aecommodate a pushed train of four barges in the long section of the chamber.

By the location of the locks northwards, out in Eastern Scheldt so to speak, they have been kept away from the bridges that are to be built for rail and road traffic between Bergen op Zoom and Flushing (figure 2).

This has saved an appreciable amount of construction time, and no valuable agricultural land had to be purchased for the system.

A number of non-residential buildings will be located at the locks to accommodate the administrative and maintenance staff as well as the State police and customs (figure 19).

The locks are centrally operated. A detailed operational investigation has been carried out for this purpose.

The central operations building is located on the water in the centre of the system. The location of the operations room at about N.A.P. + 20 m provides the operations staff with a good vantage point.

A convenient operating console has been designed, partly as a result of research on the physiology of the sense organs (photo 12). A great deal of attention has been paid to accessibility. Despite the water surrounding the locks, both sides of the chambers and the central operations building are accessible by car: a sensible arrangement from the safety point of view, as the fire brigade and ambulance must not be forgotten.

Outside the locks waiting berths and guidingstructures are planned on either side. Years of experience are available on such installations.

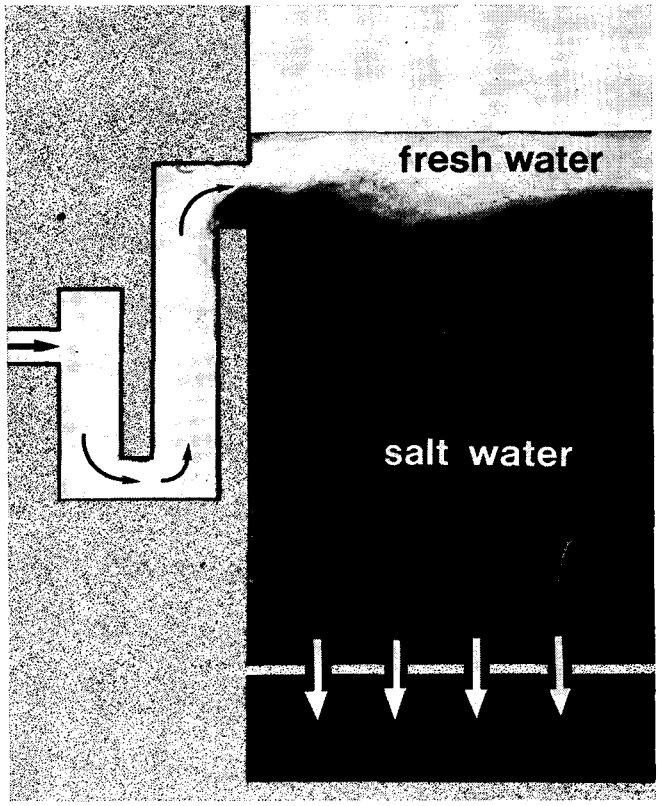


Photo 8. Change-over from salt to fresh water in a cross-section model.

A recent investigation showed the optimum lay-out for waiting berths as illustrated in figure 19.
By widening the channel between the waiting berths on either side of the centre line of the locks as the distance from the lock increases, the nuisance to waiting vessels caused by ships sailing out is diminished. The nuisance is greater if the ships start to sail faster, which ought to be possible in order to get the maximum locking capacity. The increasing nuisance due to vessels picking up speed is neutralized as the distance gets greater.

About 250.000 m^3 of reinforced concrete and more than 5.000 m^3 of prestressed concrete is required for the construction of the locks.
From the designers point of vue the locks are attractive particularly because of the combinations of prestressed, reinforced and precast concrete.
Photo's 13 and 14 give a general view of the lock system just before flooding. The concrete work is finished.

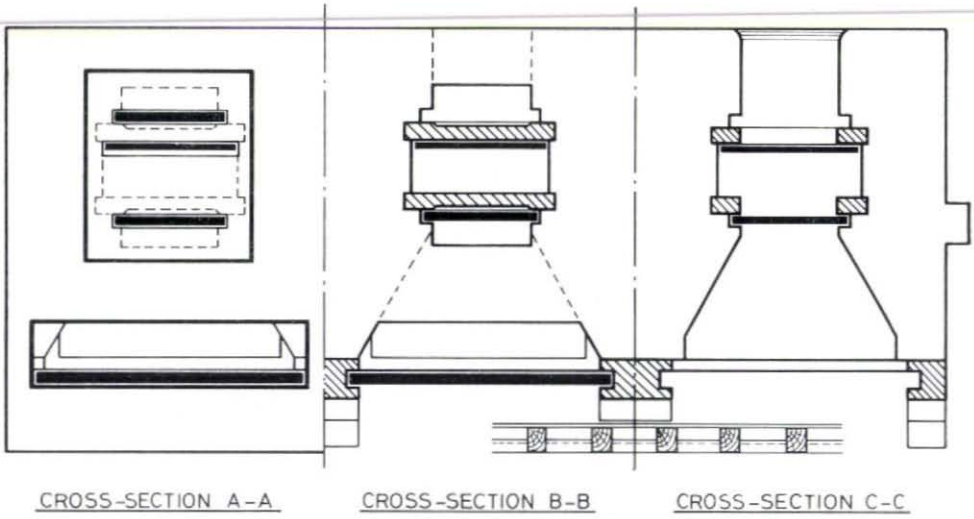


Figure 16. Cross-section of apertures in the lock chamber wall.

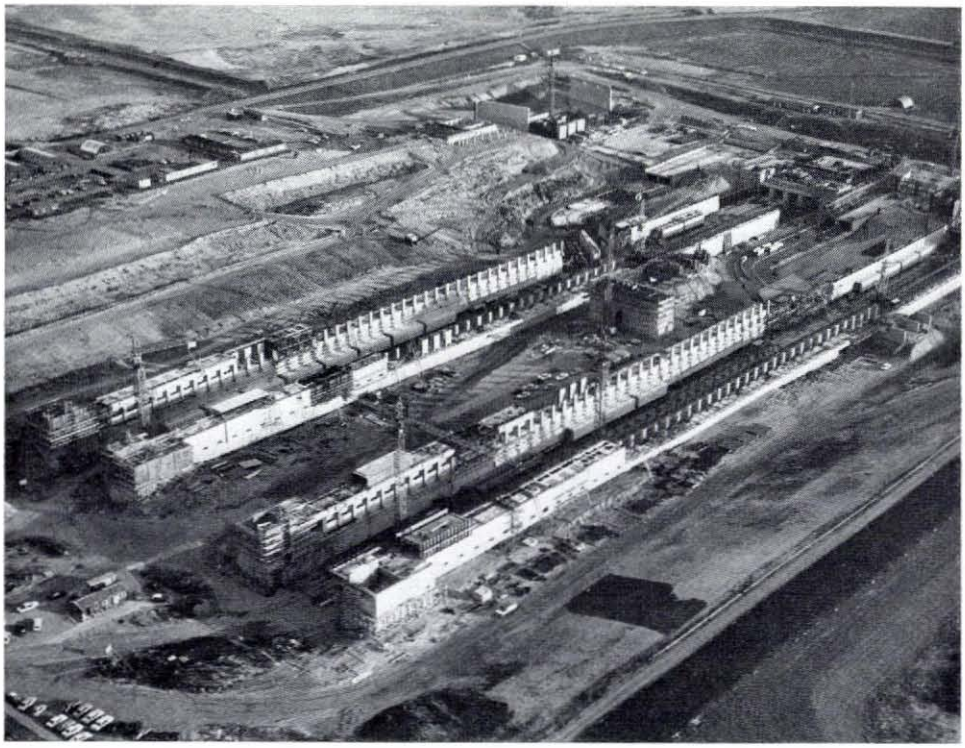


Photo 9. A stage in the construction of the lock system, illustrating mainly the wall structure.

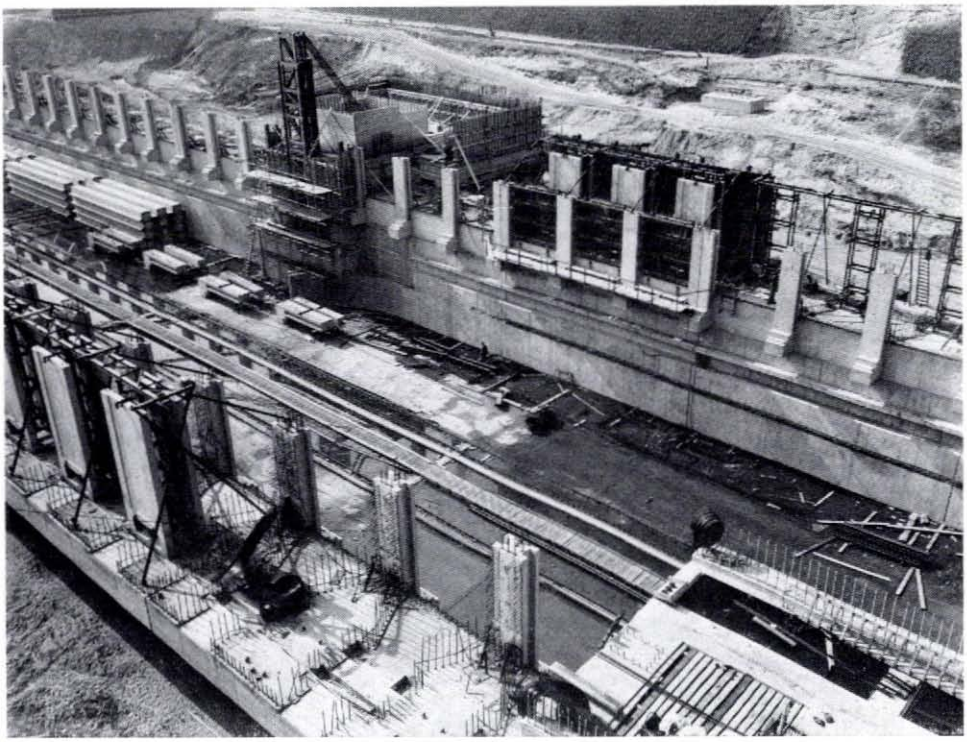


Photo 10. Wall construction using precast concrete components.

2.2 Hydraulic investigations on the Dunkirk system

A particularly large number of design and operational details had to be resolved in designing the locks in accordance with the system of exchange with gates closed. As already stated in Chapter 2.1, a team was engaged on these problems throughout the entire design and investigation phase.

The entire project was investigated at the Delft Hydraulics Laboratory using a model (scale 1:30) of a single lock with about 1 km of canal section on the fresh-water side and about 0.5 km on the salt-water side. The model reproduced in detail the lock design, valve operation and vessel movement (with propeller effect).
The storage basin was not reproduced in the model, although the conduits and valves connecting immediately with the basin were fully incorporated. Use was made of existing rules of scale enabling the model results for homogeneous as well as stratified (and mixed) salt-fresh flow to be translated into actual values. Virtually all kinds of test were carried out in the model, including the appropriate vessel movements with propellers rotating so as to involve all the mixing factors as completely as possible in the investigation. Photo's 15 to 18 inclusive convey an impression of the lay-out

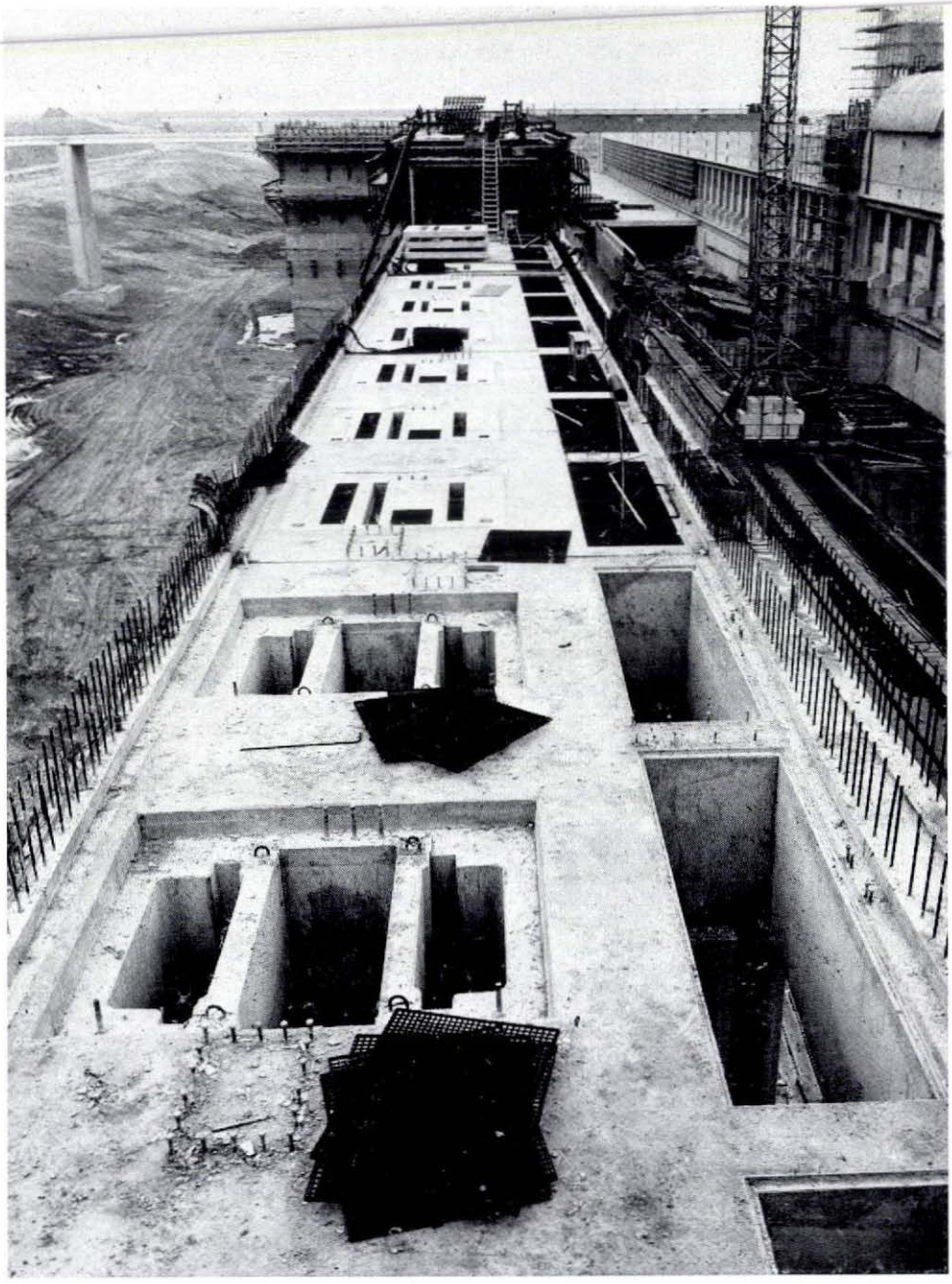


Photo 11. The lock wall illustrating the recessed engine house. The valve slots are clearly visible on the floor.

of the model, the salt-gauging equipment, the valve-programme control and the arrangements for measuring the berthing stresses.
A series of approximate models was also used to determine separately the smallest permissible scale.
Since the model described above was very complicated, and since furthermore components such as the culvert capacity, the design of the perforated floor, the walls etc. were troublesome to alter, a large number of detail study models were built and

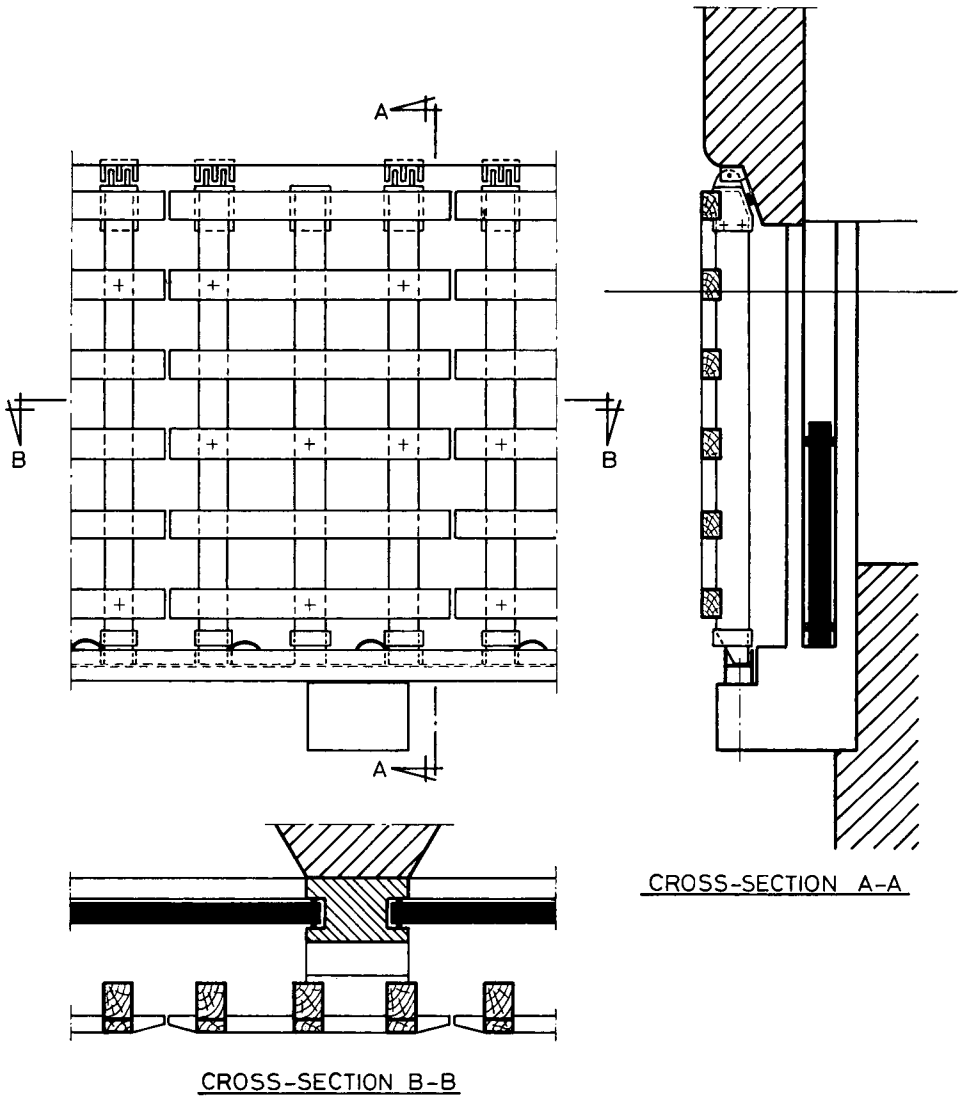


Figure 17. Design of the wooden guide frame.

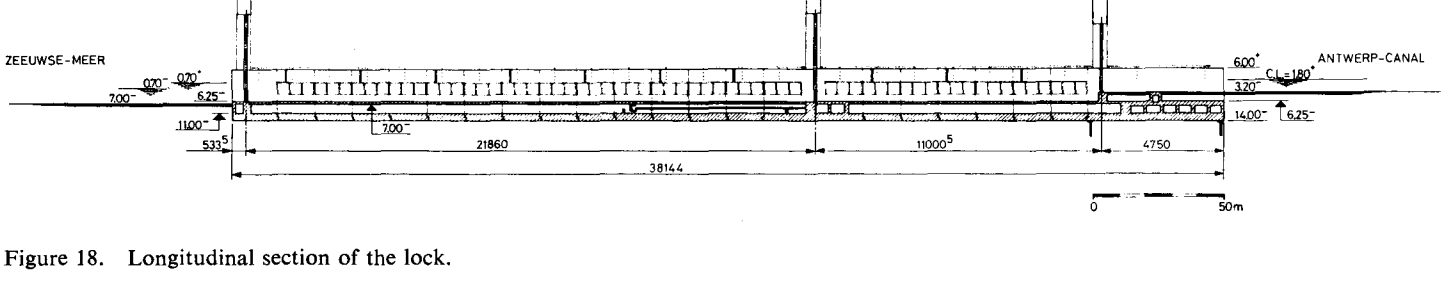


Figure 18. Longitudinal section of the lock.

Figure 19. General lay-out of the Kreekrak lock system showing buildings and waiting berths.



Photo 12. Control panel.

calculations made in order to ensure that from the design point of view the overall model was the best possible, and that it would mainly be used to study the optimum operation of the lock and the efficiency attainable.

DETAIL STUDY

The maindetails to be technically studied were as follows:

a. The way in which an even flow-rate distribution is achieved along the chamber when salt water is supplied and removed through the floor as well as when fresh water enters and leaves through the wall. A separate model (scale 1:10) was used to determine the rate of removal through floor perforations with longitudinal flow in the bottom culvert, and the pressure distribution along the culvert can be computed for the case where water is drawn off and supplied at the sides. As already stated in chapter 2.1, this study resulted in a chamber floor having uniformly distributed perforations equivalent to 1.3% of the floor surface, and a (modified) system of fresh-water supply: large open culverts which produced the feature of fresh-water enclosing the locks.

b. The walls and floor must be designed in such a way that when the chamber is exchanged from salt to fresh water and vice versa as little mixing as possible occurs, even when vessels are present.

Mixing occurs especially where water is brought in. A jet effect was created which initially shot through the salt-fresh interface (actually there is no definite stratification in the initial stage).
The jet effect is aggravated by the desirability, in order to achieve the uniform flow distribution referred to in a., of small apertures having locally high velocities. Mixing due to the jet effect can be inhibited by first directing the jet against a wall; a great deal of kinetic energy is then absorbed and the water is dispersed over a larger section.

This principle was applied in the case of the floor as well as the walls, although an adjustable valve was also fitted to the wall in order to supply or remove water as far up as possible in a selective manner owing to the variable level of the Eastern Basin. It was found that the presence of berthed vessels also reduces mixing at the wall, although the flow distribution along the wall from one end of the chamber to the other becomes less uniform. These phenomena were studied in models (scale 1:30)

of a short chamber section and also a larger-scale model (1:5) using a single floor perforation.

c. The design of the culvert and wall valves must be such that when closed they afford maximum tightness yet the valves must be easy to operate and very reliable. Sliding valves were used as wall valves; they are operated when the water levels are virtually the same in order to eliminate current forces.
Wheel-mounted valves were used in the conduits in order to reduce the lifting effort required under full water pressure. In order to provide a proper seal a continuous rubber ring was fitted on the frontal plate of the valve to rest on the conduit seat. Before it is raised the valve is first released from the seat (against the direction of flow) in order to prevent damage to the ring as it is being raised (figure 13). Theoretical calculations showed that a valve of this kind was liable to vibrate, and a separate model (scale 1:15) was constructed for the purpose of developing the optimum valve design (photo 19). It was found that for the design and rigidity selected the valve must be disengaged at least 15 mm (excluding flexure) in order to prevent violent vibration.



Photo 13. General view of the Kreekrak lock system just before the flooding of the construction site. The concrete work has been completed. The forebays are being dredged to the requisite depth.

The discharge characteristics of the valve were also determined accurately from the same model. These were used in turn in the calculation of the valve-opening programmes.

d. The design of the sluiceway of the emptying conduits into the storage basin (photo 7); the weight of the protection layer on top of the soil must be optimalized in relation to the grille fitted downstreams of the sluice valves. This was studied in a feature model (scale 1:50).

e. „Overtravel" can occur in a lock having long conduits. This means that when the lock fills when there is a natural drop the upper pound — conduit — chamber become a system of communicating vessels where surging to and fro is possible. In that case the gates must not be opened. The extent to which the culvert valves must kept closed to damp out the oscillation in order to limit overtravel has been determined from calculations.

f. The design at the outlet of the pumping station was studied on a model of the Antwerp Canal to a scale of 1:25, although at a much later stage than the other investigations discussed.

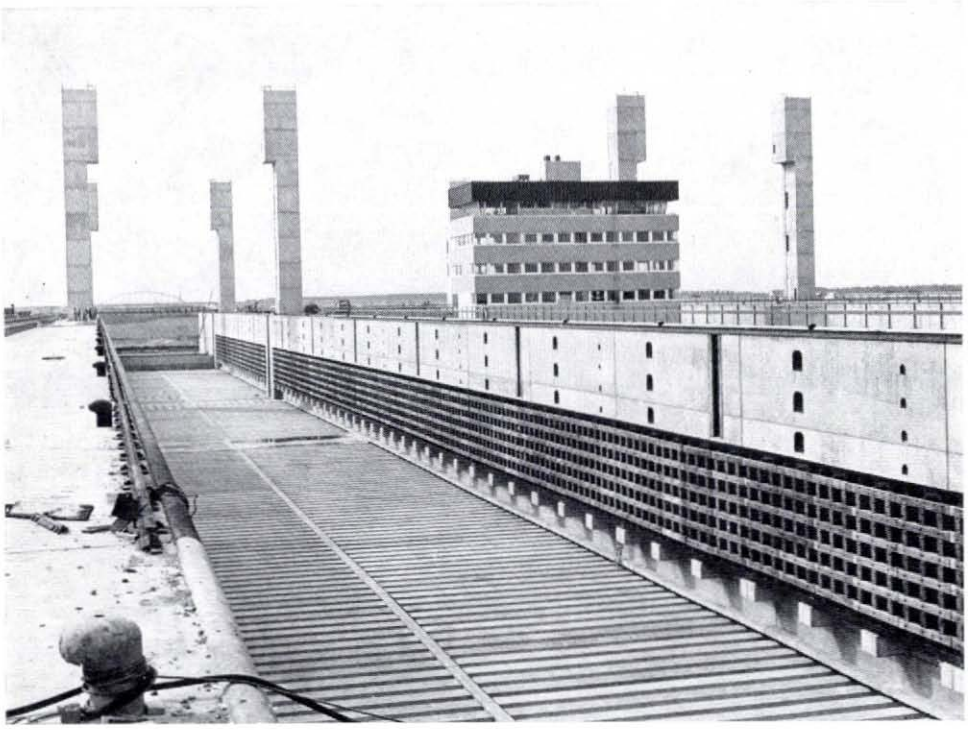


Photo 14. The lock chamber completed.

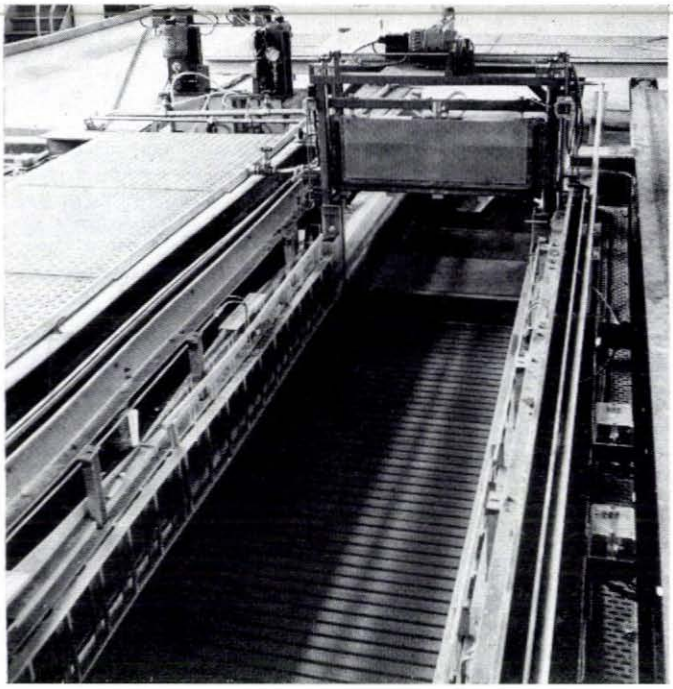


Photo 15. Overall model to a scale of 1:30, showing the perforated floor, the wall valves and the lifting gate.

The overall model was completed in the meantime, after many of these points had been solved in principles, and a start was made on the determination of the optimum operating programme and the efficiency of the salinization prevention system.

OPTIMALIZATION OF THE OPERATING PROGRAMME

A vast range of options is available for determinating the optimum operating programme.

1. A constant flow rate can be used in the salt to fresh-water exchange phase, or the flow rate can be restricted when the intake of fresh water commences, as this is the most critical moment as far as mixing is concerned. At all events, a reduction in flow rate at a particular moment implies that in order to maintain the same duration of the locking cycle the flow rate is increased for the remainder of the time, while rapid fluctuations in the flow rate can produce translation waves detrimental to navigation as well as undulation at the interface.
It was found that there was really nothing to be gained by „programming" the flow rate.

2. Ultimately the efficiency of the salinization prevention system must be determined in terms of the quantity of salt water entering the fresh-water section related to the amount of fresh water withdrawn therefrom. The loss of fresh water serves to evacuate the mixed layer in the change-over from salt to fresh and to compensate the top layer of fresh water which can not be recovered in the change-over from fresh to salt, since in that case too much salt would be entrained. The greater the quantity of fresh water that can be withdrawn from the fresh section, the more effective salinization prevention will be.
Fresh-water losses can be limited in the following ways:

a. By pulling the salt layer further than usual through the perforated floor, which gradually improves the quality of the fresh chamber water so that when the gates are opened not much salt gets into the pound. Furthermore, ships entering and leaving will stir up less salt from the bottom drain.

b. By stopping fresh-water recovery sooner so as not to recover water of too poor a quality. In assessing this we must remember that if smaller quantities of water are pumped in the time available, the flow rates, and consequently mixing as well, will be reduced.

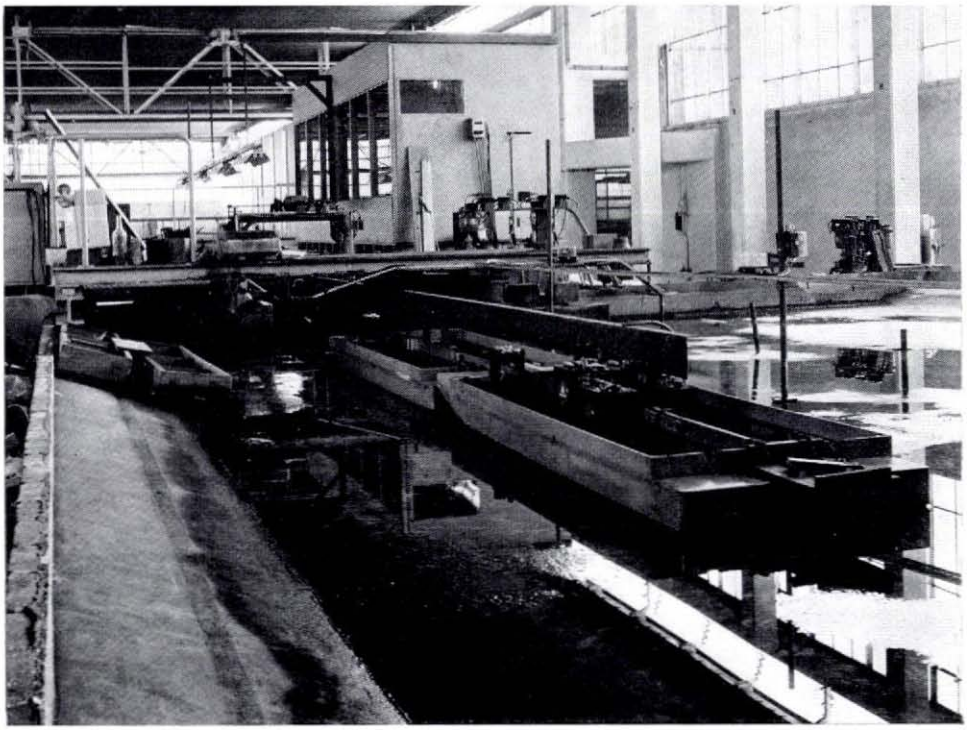


Photo 16. Overall model; vessel(s) entering the chamber.

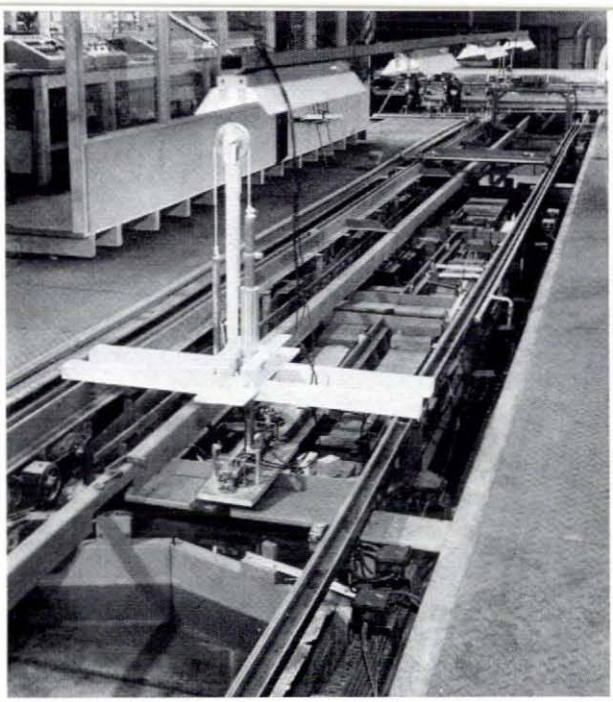


Photo 17. Overall model; gauging the forces acting on a vessel in a pushed-barge train.

The alternative which ultimately proved to be best for all conditions, both with and without vessels and for the likely variable salt content in the Antwerp Canal (the difference in density between salt and fresh water in the tests ranged from 3 to $12^{0}/_{00}$ of the density of fresh water; for the sake of comparison, the sea water in the North Sea is $30^{0}/_{00}$ denser), showed that the best course is to remove the theoretical salt limit as far as the perforated floor, and in fresh-water recovery not to exceed the limit compatible with the available fresh-water supply. In any case recovery is found to be possible only until the interface reaches the bottom of the vessel with the deepest draught; immediate thereafter salt water is entrained from under the vessel.
The amount exchanged when the chamber changes over from salt to fresh is therefore smaller than in the reverse process; since the flow rates are also lower, the locking times differ to some extent in opposite directions.

3. The optimum position of the valves which, rising and falling with variations in the level of the Eastern Basin, ensure that the fresh water is supplied or withdrawn as far up as possible, is found to be 0.75 to 1 m below the surface.

4. The operating regime of the conduit valves must be determined in relation to the permissible stresses of the vessels berthed in the chamber. The maximum permissible opening rate for the filling valves was found to be 15 mm/s.

The emptying valves, which are somewhat narrower and higher, can be operated at 20 mm/s. When the emptying valves are closed the wall apertures must be open in order to reduce translation waves; this will frequently be the case anyhow.

Ultimately the efficiency of salinization prevention can be summarized in figure 20, where the salt intrusion (expressed as the percentage of undiluted salt water in the contents of the chamber between the perforated floor and the Antwerp Canal level) is plotted against the fresh-water loss. Although the results in the case of small density differences show an appreciably larger salt intrusion, expressed in terms of salt water volume, the amount of salt intrusion is in fact appreciably smaller. It was to be expected that the quantity in terms of volume would be greater, since the entire system depends on stratification of salt and fresh water; as the density differences decrease this tends to be less and less the case, and turbulence and other factors which cause mixing will predominate increasingly.

2.3 Comparison of the Dunkirk and Terneuzen systems

As already stated, the overall model to a scale of 1:30 of the Dunkirk lock system incorporated facilities for a detailed study of the Terneuzen system. The design of the tunnel inlet used (photo 20) was selected on the basis of a comparative investigation



Photo 18. Overall model; the flow-gauging device and programming panel for valve operation.

among ten or so alternative types. In order to determine the requisite discharge rate the quantity of salt water which travels up the canal in a given unit of time was gauged first. It was found to be somewhat less than the theoretical value given in Chapter 2. Subsequently the quantity of salt water that could be removed through the suction tunnel at various flow rates was examined in conjunction with the programmed entry and exit of a pushed-barge train (4 barges, 10.000 tons) and several self-propelled vessels.
After the vessel movements the quantity of salt water left behind in the chamber was gauged, so that the remainder had entered the fresh canal pound.

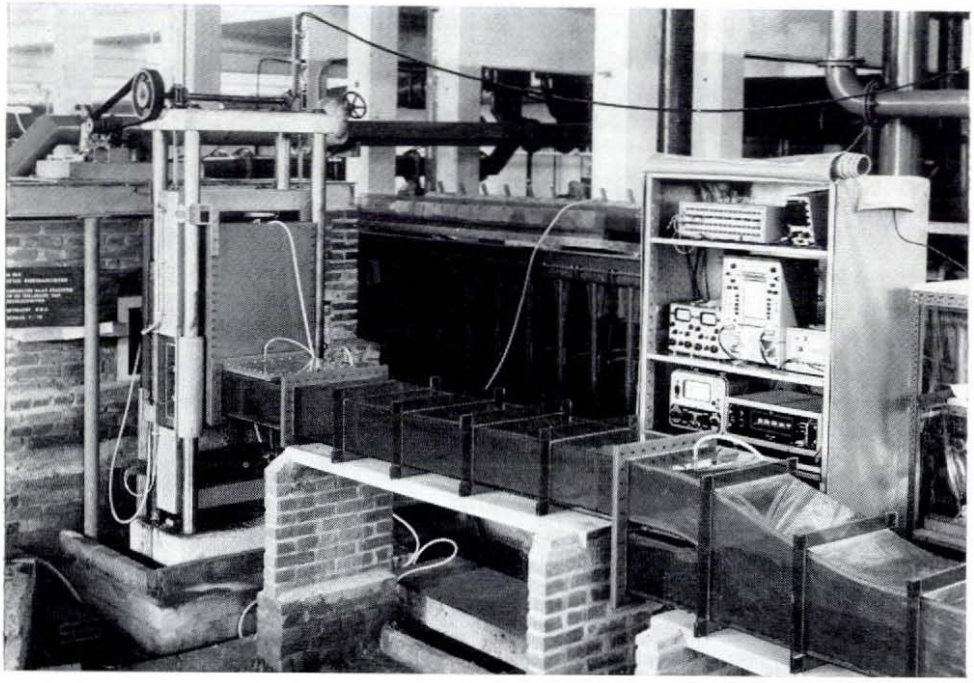


Photo 19. 1:15 scale model for valve investigation purposes.

2.4 Conclusions

a. From the salt content of the water discharged it is not possible to find a reliable indication on which to base the discharge rate programme in relation to vessels entering and leaving; although an adjusted program can be established in the case of a pushed-barge train if the speed and load factor are at all available.

b. The quantity of salt water left behind in the chamber after the doors are closed is so large and distributed vertically to such an extent that there can scarcely be any

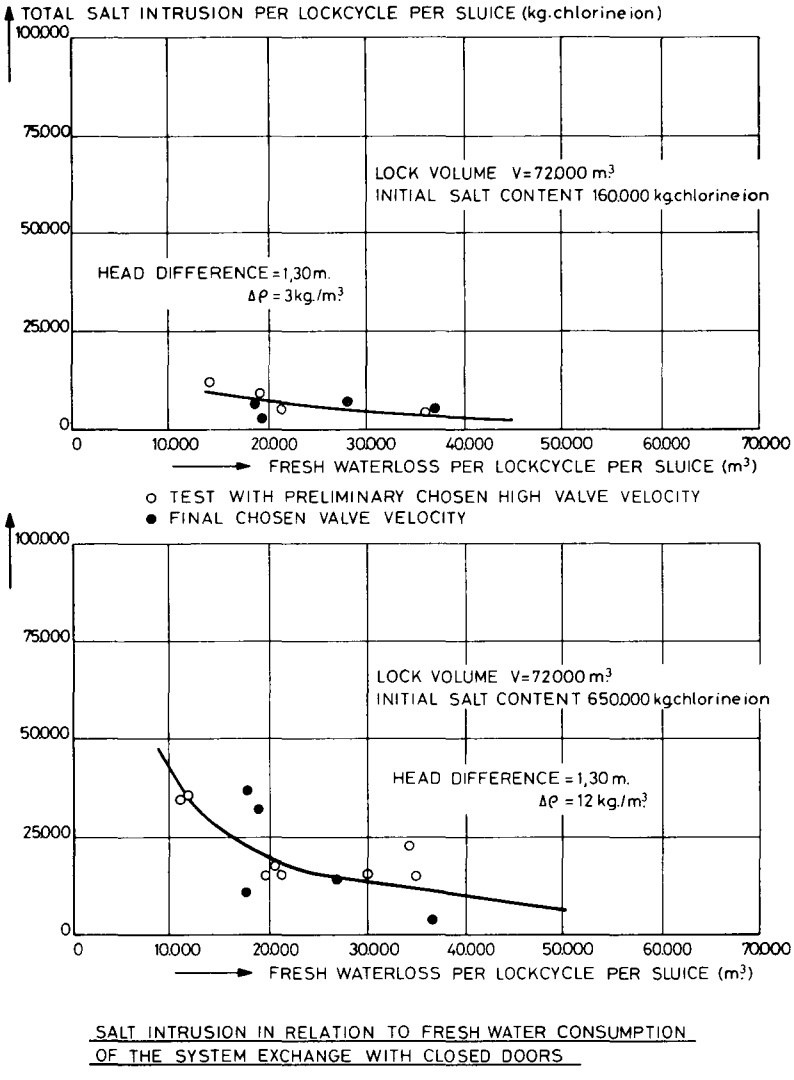
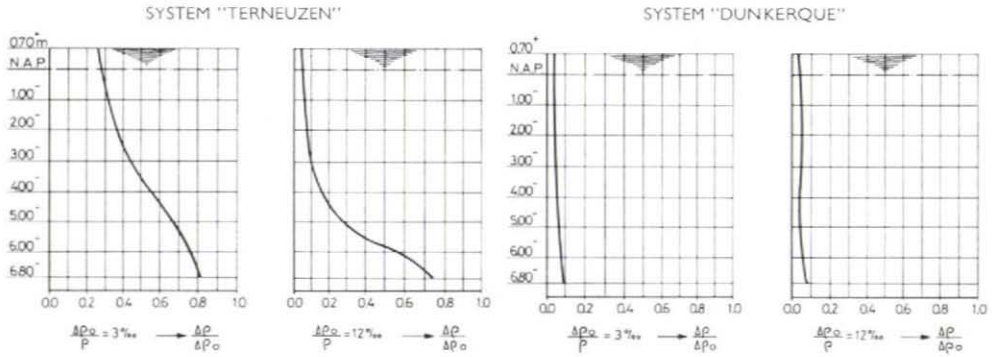


Figure 20. Salinization in relation to fresh-water loss in the closed-gate exchange system.

question of fresh-water recovery; figure 21 gives a comparison of similar situations for optimum operating conditions in the Dunkirk and Terneuzen systems.

c. For a small difference in density ($3^0/_{00}$) the natural exchange discharge is lower, and the removal rate can be made somewhat higher without excessive loss of water; in this situation we find that the Terneuzen system is similar to the Dunkirk System as long as sufficient fresh water is available to obviate the need for the recovery of fresh chamber water in the Dunkirk system as well.

In all other cases, greater relative density differences and/or economical fresh-water management, the Dunkirk system is found to be more effective in preventing salinization, with the result that this was the system definitively selected.



Salt contamination of the lockwater which can be regained at system „Terneuzen" and system „Dunkerque" (situation after the closing of the doors).

Figure 21. Comparison of the Terneuzen and Dunkirk systems.

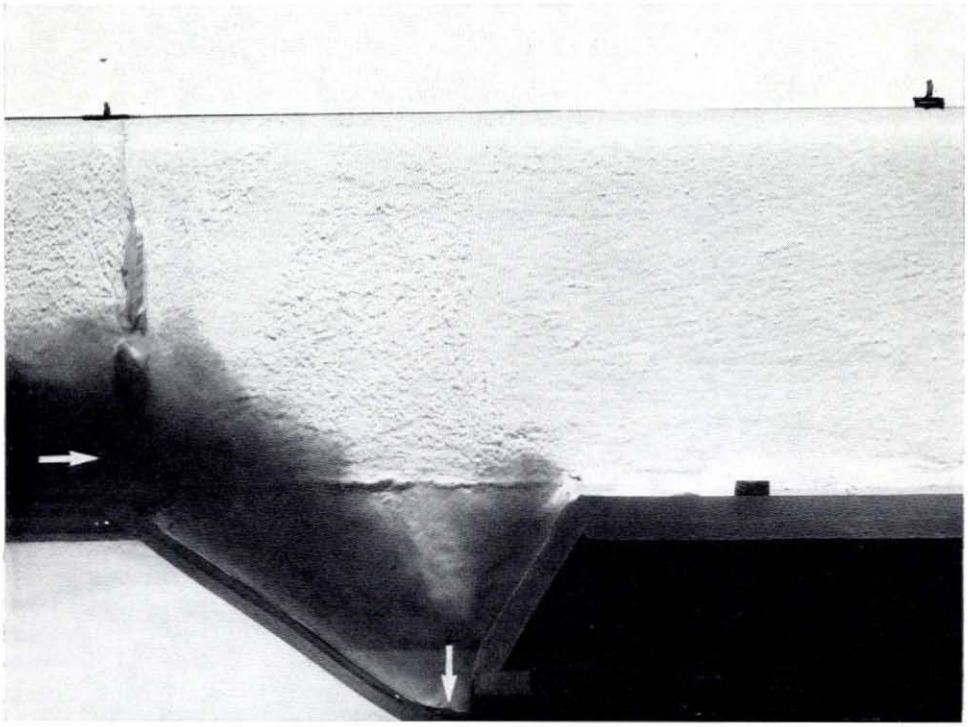


Photo 20. Optimum design of the salt-water suction tunnel in the Terneuzen system.

3 Programming of the lock

The main requirements for the programming of lock operation have already been referred to in the preceding part. All the operations involved in locking traffic from the Antwerp Canal to the Eastern Basin and vice versa are described below in chronological order.

The assumptions on which the programming is based are as follows:

- The correct speeds for the raising and lowering of the conduit valves have been definitively selected.

- The adjustable chamber-wall valves that ensure selective fresh-water supply and removal are adjusted, relayed to the level of the Eastern Basin (e.g. are checked once a day).

- The storage basin is sufficiently below the level of the Eastern Basin (the fresh water basin), to ensure a minimum drop of 50 cm to the storage basin when salt water is being removed.

3.1 Locking from the Antwerp Canal

(FOR DISCHARGE PROGRAMME SEE TOP OF FIGURE 22 AND LEFT-HAND SIDE OF FIGURE 7)

I. Vessels from Antwerp enter, berth in the usual manner, and the lock gates are closed, just as in any other lock, although the propellers have to be stopped.

II. The valves in the sluiceways running into the storage basin are opened; as soon as the valve movement stops the discharge rate slackens off, since the chamber level falls, and the basin rises a bit. Once the chamber level falls to the Eastern Basin level the wall valves open and within a short time the rate of entry through the wall valves is the same as the rate of exit at the bottom; the chamber is somewhat lower than the Eastern Basin.

Comment: The flow rate used in changing over is made as low as possible in order to limit mixing. If more fresh water is available, there is, for instance, no need to recover fresh water, thus leaving more time for the change over from salt to fresh and allowing a lower flow rate to be used. The flow rate during the change-over is

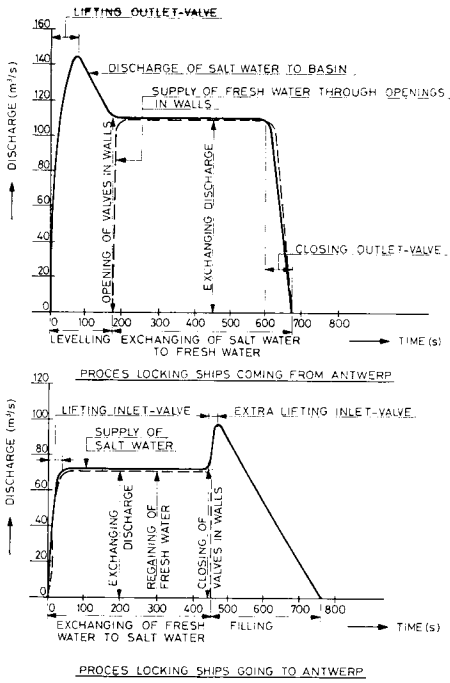


Figure 22. Locking procedure in the Kreekrak locks.

produced by the natural drop between the chamber (which is somewhat lower than the Eastern Basin) and the storage basin, and the extent to which the valves in the emptying conduits in Phase II is determined from a calculation made in advance on the basis of the water levels and allowing for the possibility of certain valves being unserviceable.

III. In the change-over from salt to fresh the chamber level remains virtually constant, and the basin level rises somewhat because the chamber discharge rate is higher than the pumping rate. The drop and consequently the discharge rate fall a bit, but so little that the level is felt to be constant. Long vessels experience a transverse thrust away from the wall because the space between the vessel and the wall is the first to fill with fresh water; at the bottom of the vessel the fresh and salt-water pressure is the same, and so at the top the fresh-water level is somewhat higher. The transverse thrust disappears when the top chamber layer becomes fresh as far down as the vessel's draught.

IV. The sluiceway valves at the basin are closed, the moment of closing being calculated in advance in such a way that when the valve is closed the interface has just been drained down to the perforated floor. The wall valves are left open, perhaps because in the rising phase fresh water is recovered, but in any case to attenuate translation waves.
After the valves are closed the gates can be opened at once; owing to the slackening flow rate the chamber level equalizes with the level of the Eastern Basin.

V. Vessels exit and enter; if the entire lock chamber has been used in locking vessels from the Antwerp Canal, and if afterwards only the section of the lock chamber on the Antwerp side is used to lock vessels in the opposite direction, it may be advisable to fill the space under the perforated floor of the lock section which is out of use with fresh water in order to limit salinization. To reach this a low evacuation rate has to be used in order to maintain a stable interface under the floor, although vessels may enter and leave in the meantime.

3.2 Locking from the Eastern Basin

(FLOW RATE PROGRAMME AT THE BOTTOM OF FIGURE 22 AND ON THE RIGHT-HAND SIDE OF FIGURE 7)

I. Vessels enter, berth in the usual manner, and the gates are closed. If fresh water is recovered the propellers have to be stopped.

II. The inlet valves are opened until the requisite exchange flow rate is attained. Although the vessels are inclined to move to one side these forces are very slight. The flow rate remains constant until the salt water reaches the bottom of the vessels with the deepest draught, and then the wall valves are closed.
This moment is computed in advance (according to the estimated draught).

III. The water level rises; as far as the salt-fresh interface is concerned it would be possible to open the inlet valves fully. But they have to be kept about 25% open, otherwise the rising chamber level would go too far above the Antwerp Canal level due to the overtravel phenomena.
The gates may not be opened until the difference in water level on either side is slight. For this purpose the permissible limit was taken as 10 cm; if it is greater, excessive translation waves result when the gates are opened. Consequently, the gates can be opened when the chamber level is within 10 cm of the canal level.

IV. Vessels exit and enter; since a fresh-water residue is left in the chamber when the gates are opened it will flow into the Antwerp Canal after the canal is opened. The vessels will not be greatly affected as a result.

As far as possible the operation of the locks is to be automatically controlled, with the facility of processing data such as waterlevels, traffic density etc. on a control computer.

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