waterloopkundig laboratorium
delft hydraulics laboratory

Methods employed to limit saltwater-freshwater exchange in locks

P. A. Kolkman

Delft Hydraulics Communication No. 364

August 1986

Methods employed to limit saltwater-freshwater exchange in locks

Lecture given at Karlsruhe University,
December 1980

P. A. Kolkman

Delft Hydraulics Communication No. 364

August 1986

METHODS EMPLOYED TO LIMIT SALTWATER-FRESHWATER EXCHANGE IN LOCKS.(LECTURE GIVEN AT KARLSRUHE UNIVERSITY, DECEMBER 1980)

dr. P.A. Kolkman, Delft Hydraulics Laboratory

Various methods have been developed from hydraulic theory for limiting the saltwater-freshwater exchange in locks. These methods are considered in two articles.These articles were published (in Dutch language) in PT/Civiele techniek 37 (1982) 2 + 3. This publication contains both articles.
The methods include:
- return pumping the locking volume when lowering the water-level;
- keeping the lock gates open for a short period in combination with an air bubble screen;
- sucking off the saltwater tongue, directly or indirectly;
- exchanging the water in the lock chamber with the gates closed;
- using a freshwater outer chamber which contains a saltwater lift box.

The efficiency of the methods is compared and the relation with saltwater control is showed.

With normal locks it is a requirement that ship passages are made with the minimum loss of water. This loss is equivalent to the locking volume S (the chamber area multiplied by the difference between the upstream and downstream water-levels) and if necessary a similar volume of water can be pumped back to the uppper level. A serious problem occurs with locks leading directly into the sea: saltwater intrusion.Much thought has been given to this problem in the Netherlands. If, with a normal lock operating with a certain difference in water-level the loss of the locking volume is important and the solution using reservoirs expensive then for a lock lying between saltwater and fresh water which requires even more water, the solution can be much more expensive. Every time the lock is operated a quantity of saltwater which is considerably larger than the locking volume penetrates into the freshwater canal. If the saltwater flows out in a thin layer on to the bed of the canal there are many reasons for flushing it back. Figure 1 illustrates this situation. If the sluice is too high (figure 1c) hardly any saltwater is flushed back; if it is too low then the separation surface would have to have a sufficiently steep slope for the underlying salt to flow faster than the average water velocity back into the lock. This is not possible with a thin saltwater layer, the bed friction acting strongly against it when the layer is thin.

Eventually the saltwater layer is broken up by mixing, and is ultimately carried away with water flowing into the lock.
The action of winds and ship movements promote considerable mixing. On what does the volume of saltwater penetrating into the freshwater in fact depend?
As shown in figure 2 saltwater penetrates the canal with the locking volume (on the flood tide only) and with what is referred to as the exchange flow.
When the gates at the canal end of the lock chamber are opened the saline water volume of the chamber flows out forming an underflow with a velocity U_a.
A compensating upper flow with the same velocity, U_a, develops.
After a certain period of time the complete chamber volume, V_k (minus the submerged ship volume, V_s) is exchanged and, together with the locking volume, has entered the canal.
The maximum saltwater load = $V_k + S - V_s$ (1)
It should be noted that exchange flow sometimes produces large cross forces which hinder in coming/outgoing vessels.

Return pumping the locking volume and closing the gates quickly

Two methods for reducing saltwater intrusion come immediately to mind based on the description of how it takes place:

M_1 return pumping the locking volume during level lowering operations;

M_2 opening the lock gate over a short period

M_1 speaks for itself; some explanation is required, however, for M_2. In order to get an indicatation of the duration of the exchange process the situation shortly after the gates have been opened has been considered. This situation is shown in Figure 3.

For similar water-levels the pressure gradient in the saltwater is some what steeper than in the fresh and the resulting shaded pressure difference on the bed is $\Delta p = \Delta\rho g h$, where Δp is the density difference between salt and freshwater. In practice the pressure difference is symmetical and on both the bed and the surface is equal to $\frac{1}{2}\Delta\rho g h$. This situation (figure 3b) develops from the first situation because the excess pressure due to the saltwater causes an (external) translatory wave which has no further effect on the development of a two layer flow. The flow which develops can be caracterized by,what is referred to as, the internal Froude Number.
Using this number an expression can be obtained relating the flow pressure, $\frac{1}{2}\rho v^2$, a quantity which, for example, also occurs in the expression for the resistance of a body in a current, and the above represented pressure

difference of $\frac{1}{2}\ \Delta\rho gh$. The Froude Number F_i, is defined as:

$$F_i = \sqrt{\frac{\text{current pressure}}{\text{pressure difference due to gravity}}}$$

$$= \sqrt{\frac{\frac{1}{2}\rho u^2}{\frac{1}{2}\Delta\rho gh}} = \frac{u}{\sqrt{\Delta gh}} \qquad (2)$$

According to Abraham [1 and 2] the value of F_i, can be calculated by relating the loss in potential energy per unit time (heavier water continually sinks to the bed) to the increase in kinetic energy.
In this situation $F_i = 0.5$ and, thus, $U_a = \frac{1}{2}\sqrt{\Delta gh}$ (3)
A value of F_i 10 % lower is found in practice because of friction on the saltwater/freshwater boundary.
From (3) it follows that the greater the water depth the larger the value of U_a. The exchange process continues as the freshwater tongue reaches the closed gate at the other end of the chamber and the complete saltwater volume is discharged out of the lock.
The exchange discharge per unit width is now:

$$q_a = (\tfrac{1}{2}h)(\tfrac{1}{2}\sqrt{\Delta gh}) \qquad (4)$$

The duration of the exchange process, for a lock chamber of length L is given by:

$$T_a = 2L/U_a = 2L/0.5\sqrt{\Delta gh} = 4L/\sqrt{\Delta gh} \qquad (5)$$

Figure 4 shows the varation in the quantity of saltwater exchanged with time, according to this theory. If we consider a situation which is not too extreme, we find T_a= 15 min, then in order to prevent complete exchange the gates must be opened even over a shorter period.
For ships entering/leaving the lock however this period of time is short, implying that exchange would be complete so that the M_2 approach barely has any effect.
The exchange proces must, therefore, be slowed down.

Application of an air bubble screen

If air is introduced into the chamber via a perforated tube set in the floor, under still water conditions, a zone of air/water develops. Above this zone the water density is less than that of the surroundings. An exchange flow, therefore, develops with a water discharge of q_w which flows sideways. If a simplified flow mechanism is considered in which it is assumed that this sideways flow curves upwards with a constant speed then the air-water mixture forms with a lower density, see Figure 5a. A more comprehensive description of this mechanism is given in [3]. The density difference, $\Delta\rho$, can be defined in this situation by:

$$\Delta = \Delta\rho/_{\rho water} = (q_1/q_w)\ [U_w/(U_w + U_{st})] \qquad (6)$$

The second term, $[U_w/(U_w + U_{st})]$ arises because the time in wich the air is in the water is reduced by U_{st} where U_{st} is the rising velocity of the air bubbles relative to the water. If we now substitute in

$$q_w = \tfrac{1}{2}\, h.U_w = \tfrac{1}{2}h\ (\tfrac{1}{2}\sqrt{\Delta gh}), \qquad (7)$$

in which water flows from both left and right sides it can be shown by calculation that, by approximation, the following relationship is valid

$$U_w \pm \sqrt[3]{q_\ell g} \qquad (8)$$

The variation in the term $(\{U_w/\ (U_w + U_{st})\}^{1/3}$ can be neglected by approximation because it is only important for small air descharges. Although application
of Equation(4) (found for a starting exchange flow), is a toss-up for a permanent steady flow, it appears that the relationship(8) can also be found in practice. The water discharge in fact only occurs in the upper $\tfrac{1}{4}$ of the depth.

It is possible to use the air bubble screen as a saltwater barrier: if there is freshwater on one side and saltwater on the other, see figure 5b, and air can be mixed with the saltwater giving a mixture (density $\rho_o - \Delta\rho$)

If the density of the mixture is similar to that of the freshwater no exchange flow takes place. There is, however then a density difference and, thus, an

$$\Delta = (q_\ell / q_w) \left(\frac{U_w}{U_w + U_{st}}\right) \qquad (9)$$

in which we find:

$$q_{\ell o} = \tfrac{1}{4}\, h \sqrt{\Delta gh} \sqrt{\Delta gh}\, (1 + 2\, U_{st} / \sqrt{\Delta gh}) \qquad (10)$$

The results from a series of full-size tests for different locks with various air discharges which has been adapted from [2] are shown in Figure 6.
The air discharges are expressed in the figure in terms of the water velocity produced by the bubble screen. The water velocities are then related to the velocities which must be formed to resist the salt.
This gives a parameter $\sqrt[3]{q_1 / q_{1o}}$ which by approximation appears to be lineair with the extent to which the salt tongue is held back. For large values, of the order of 0.8 to 1, the effect of the bubble screen does not increase because there is so much mixing that this forms a new source of salt load.
The conclusion from Figure 6 is that the air bubble screen is effective for increasing the exchange period so that it becomes possible to close the gates before the complete chamber volume is exchanged. The following points should be taken into account when considering air bubble screen operation:

- an air bubble screen should be operated at both sets of gates, there is always mixed water in the chamber, so that $\Delta\rho$ across a screen is less than that wich occurs between fresh water and saltwater.
- gate closure, even with a screen, should be as rapid as possible.
- the locking volume, which is in effect unaltered by the screen(s) still increases the salt load.
- ships passing through the screen push the water aside, a process which is unaffected by the screen.

In practice, see Figure 7:

- hawser forces due to the exchange flow are strongly reduced,
- small ships have a problem with the disturbance in the water,
- air tends to enter the engine cooling system, and the ship's toilet, producing flow inwards.
- the combination of air and saltwater produces considerable corrosssion.
- the energy required for the air bubble system is expensive.

One adventage of the system is that it can be fitted into existing locks.

The Terneuzen System: sucking of the salt tongue, Method M_3

It is possible to flush or pump the penetrating saltflow on the bed directly back, see Figure 8a, or to use a receiving basin set in the canal bed, Figure 8b. With direct back pumping it is possible to prevent almost all the salt getting into the canal, provided that $q_{sluice}=1.25...1.5q_a$ where q_a is defined by Equation (4) and there are no ships in the lock.
If ships are entering or leaving the chamber, however, the exchange flow varies considerably so that, in practice, $q_{pumping}$ must be 1.5..1.8 q_a. This discharge must be maintained for the whole exchange period (T_a) because this time is so short that the gates cannot be closed early. The factor 1.5...1.8 is, therefore also an indication of the relationship between the sluiced volume needed to hold back the salt and the volume of the chamber. From the numerical example given in Figure 8a, it appears that the exchange discharge is large implying that the pumping discharge to counter the salt tongue directly must be very large. By using a receiving basin set in the bed of the canal the return discharge can be spread over the entire emptying locking cycle. The basin can be located directly outside the lock gates or aside in order to reduce the mixing effect caused by ships. In order to prevent the salt tongue being diluted excessively the receiving basin should always be partly filled with saltwater.
In addition a full receiving basin promotes selective flushing of its contents. With this system it must be assumed that the volume to be back-flushed must be 1.5-1.8 times the volume of saltwater coming in. The amount of flow exchanged is unaffected by the system. Because of the large difference in velocity, $2U_a$, between flow at the surface and at the bed, however, the freshwater in the upper layers does become fairly polluted with salt. Since this water flows into the chamber the effect is not noticed in the freshwater canal until a ship enters the chamber forcing freshwater out, causing a salt load in the canal.
A plan view of the Terneuzen sea lock is shown in Figure 10. Here the intake for the return flushing system with its mouth immediately outside the lock gates is incorporated in the filling and emptying system. A description of the construction of the system is given in [4]. Experience with this lock has not been so good since during construction it was decided to deepen the canal but not the receiving basin or the mouth of the flushing system. As a result the volume of the basin is too small and the intake is too high relative to the

bed of the canal. In addition the amount of freshwater available is too small for back-flushing. Air bubble screens are also used in the Terneuzen lock in combination with the salt removal system. The screens are positioned at the gates at both ends of the lock. The air bubble screens certainly reduce the exchange flow but, at the same time, cause some mixing. This increases the volume of saltwater to be flushed back and also makes it difficult to remove out selectively the mixed zone which develops above the saltwater in the receiving basin. It appears that the air bubble screens are very effective for reducing hawser forces (because the depth is large, U_a is also large,and sea going vessels have, in comparision only small allowable hawser forces). Direct sucking of the salt tongue, using a large discharge, has not been applied at the Terneuzen lock because with inflow discharges larger than q_a, extra flows develop towards the lock and, ships entering the lock will experience loss of sterage. Investigations still have to be carried out into the allowable inflow discharge in relation to ship in manoeuvrability.

In the foregoing, measures used to prevent salt intrusion are treated in which, in principle, the exchange flow when the gates on the freshwater side are opened is stopped using an air bubble screen or is sucked off directly or indirectly (Terneuzen system). A combination of both methods can also be used. These methods have little effect on locking time, because vessels can enter or leave as soon as the gates are opened.

Air bubble screens can inprove locking operations since they tend to weaken the exchange flows which hinder ship manoeuvres. There is, however an increase in the volume of salt water to be flushed back.

The second part of this article discusses measures which are related to exchanging saltwater in the chamber for freshwater before the doors at the freshwater side are opened.

The Duinkerken / Kreekkrak / Philipsdam System

The article on measures limiting the salt-freshwater exchange at locks is continued here with a discussion of measures in which saltwater in the lock is exchanged more or less completely with freshwater before the gates on the freshwater canal side are opened. In the early sixties Sogréah developed a new system [5] known in the Netherlands as the Duinkerken system after the place where it was first applied. The principle of the system involves draining the chamber through its perforated floor, and filling with freshwater through wall apertures at about the water-level while the gates are still closed.
Since ships must not be allowed to stand dry and in order to save time and to obtain a lower discharge head for the pump, emptying and filling are carried out simultaneously and ships stay in their position. This process is referred to as saltwater-freshwater exchange.
The system can also be used in reverse, freshwater in the chamber being exchanged for salt, the freshwater draining back into the freshwater canal via the wall apertures. This process is referred to as freshwater recovery. It is very important that large scale mixing is not caused by the process. This can be prevented by correctly shaping the chamber and by using only small discharges at times which are critical for mixing. From the photograph of a laboraty test, reproduced in Figure 11, it appears that a layered situation develops in the process, in which there is, however, some mixing and , in which saltwater flows out at the bed as freshwater enters the lock chamber.
The advantage of the system is that saltwater is prevented from entering the canal with little loss of freshwater.
Disadvantages are that extra time is needed for locking, ships are affected by cross-flows, and a considerable volume of water has to be pumped. Some of the time lost is recovered because, with a bottom filling system, the levelling process can be speeded up without large cross-forces acting on vessels moored in the chamber.
With the Sogréah solution, Figure 12a, there is a freshwater system along each side of the chamber. When the saltwater in the chamber is higher than the freshwater outside it is pumped back into the saltwater approaches. When the level is down to that of the freshwater canal sluices are opened and the freshwater sewer system is linked up with the freshwater canal. In the Netherlands variant, Figure 12b, wall sluices are used along the whole length of the chamber on both sides, water from the freshwater canal surrounding the

chamber on both sides. This variant was applied for the first time in the Kreekrak lock in the Antwerp/Rhine link canal and is described further in [6]
A saltwater-seal was introduced in the Sogréah solution to ensure that the freshwater sewer system remains fresh when the water in the chamber is salt.(see Figure 13)
This operates on the principle that the boundery layer between the saltwater and freshwater is only stable when there is horizontal stratification in which the heavier water is below.
To achieve this the saltwater in the chamber must first partly enter the sewer system to be pushed out again later on when the chamber content has to be exchanged to the fresh situation. Mixing occurs during this operation. Mixing also occurs when ships enter or leave the freshwater chamber and a presssure wave develops in front of the ship. Flow then takes place in the sewer system and salt is carried from the chamber into the sewers.
This is prevented in the Netherlands variant by using chamber wall apertures which can be closed. Another problem develops however. Level control sluices are used between the wall sluices and the chamber, see Figure 14a, to ensure that, with different water levels in the surrounding freshwater, freshwater can still be brought into the chamber at the level of the water surface.
When the lock gates at the salt end of the chamber are open the chamber will be completely filled with saltwater. The freshwater pocket which develops immediately between the closed wall sluices and the levelling sluices then rises and the space is filled with saltwater.
The freshwater in the system is, as a result, lost. If freshwater subsequently flows again from the surrounding water then it must first displace the saltwater which then contaminates the freshwater. This saltwater volume is 2 to 3% of the volume of the chamber. An improvement is shown in Figure 15. This has been applied in the Krammer locks of the Philipsdam. In this case the levelling sluices also have a closure function so that virtually no water is lost near the wall sluices.

Causes of mixing

The M_4 system for preventing saltwater/freshwater intrusion through locks is based on the replacement of water in the chamber with freshwater and vice versa while maintaining statification. Mixing must, therefore, be prevented as much as possible. With saltwater-freshwater exchanges are carried out care must be taken to ensure that the speed of the incoming freshwater is as slow as possible, otherwise the freshwater jet through the wall apertures will suck a considerable amount of saltwater with it or a kind of internal hydraulic jump will develop, see Figure 16a. The speed, however, should not be so low that saltwater gets into the apertures, see also Figure 11. This requirement can be specified theoretically as $F_i = 1$, see Figure 16b, where F_i is as defined in Equation (2). It has also been shown to be this value in tests . If a ship is lying in front of the apertures there is much less mixing since the space between the ship and the wall quickly fills with freshwater and there is hardly any velocity difference between the upper and lower layers. If the ship lies asymmetrically across the chamber a problem arises because the space between the ship and the wall fills much more quickly with fresh water than that on the other side of the ship. This freshwater flows under the ship to rise to the surface on the other side, through the saltwater, see Figure 16c causing mixing. With rising level exchanges salt can penetrade into the wall apertures because a freshwater pocket persists for some time under the ship. This has to flow around the ship and a flow situation develops which is comparable to a free flow condition on a weir which restricts the discharge. Because the freshwater stays behind in the pocket under the ship the saltwater level alongside the ship rises sharply and thus care should be taken to ensure that not too much "fresh" water is recovered and this not too quickly, otherwise saltwater will be carried out into the canal, see Figure 17a. Mixing also occurs with a perforated floor and to prevent jet effects, see Figure 17b, the discharge through the floor must not be larger than that which can flow away sideways, Figure 17c. This requirement can also be expressed in terms of the internal Froude Number. When the freshwater/saltwater boundery is at the level of critical points in the chamber, which could cause mixing, the discharge should be reduced temporarily.

A ship lying asymmetrically in the chamber

The assymmetry of the boundery between freshwater and salt near to a ship lying across the chamber gives rise to problems during filling and emptying. The rate at which the boundery layer rises or falls should be fairly low, of the order of 1 cm/s, and the hydraulic resistance of the flow should be determined for the wall apertures where the velocity is considerably higher, Figure 18. Initially the flow out is symmetrical and

$$\Delta h = Sq^2 \qquad (11)$$

where S = the resistance per unit length of wall apertures,

q = the discharge per unit length of the apertures.

In this case the head drop across the right hand chamber wall equals that across the left, that is:

$$\Delta h_R = \Delta h_L \tag{12}$$

and, therefore,

$$q_R = q_L \tag{13}$$

When the boundary layer reaches the underside of the ship the rate of rise of the boundary layer becomes asymmetric, which can become an equilibrium situation in which the rate of rise to the left is similar to that to the right. This does not occur, however, in all situations.

Because of the difference in level of the boundery layer of z and because the saltwater pressure is the same on both sides there is a difference in freshwater level given by, see Figure 19:

$$z = \Delta h_R - \Delta h_L = \Delta Z \tag{14}$$

since for a simular rate of rise on both sides

$$q_L = q \frac{a}{a+b}, \tag{15a}$$

and therefore

$$q_R = q \frac{b}{a+b} \tag{15b}$$

Δh_L can be calculated from:

$$\Delta h_L = Sq^2 \frac{a^2}{(a+b)^2} \quad \text{and} \quad \Delta h_R = Sq^2 \frac{b^2}{(a+b)^2} \tag{16}$$

thus

$$z = \frac{Sq^2}{\Delta} \frac{b^2-a^2}{(a+b)} = \frac{Sq^2}{\Delta} \frac{b-a}{b+a} \tag{17}$$

From this appears that the effect of asymmetry can be by reducing the discharge q, through the floor, by aligning the ship more symmetrically and what is also important, by lowering the resistance of the wall apertures (although it should be remembered that this resistance naturally helps to distribute the flow uniformly over the length of the basin). The value $\Delta h_R - \Delta h_L$ should ideally be small in view of the transverse forces which can develop on the ship. In the Netherlands variant saltwater should not be allowed to penetrate the wall apertures since it would ultimately be able to get from there into the freshwater canal. Normaly, therefore, freshwater recovery is stopped when the boundery layer approaches the underside of the ship with the largest draught. This means that there is a loss of freshwater equivalent to 0.3 to 0.4 times the chamber volume. It is possible to recover further on at extra low speed.

With the Sogréah solution somewhat higher boundary layer positions are accepted because salt, in the first instance, enters the freshwater sewer, from which it is pushed out without too much mixing during the emptying phase, see Figure 20.

Large pump discharges are needed with large push-tow locks in order to be able to exchange water in a reasonable locking time. Sometimes it is recommended that this discharge is spread out over the whole locking cycle by using auxilliary reservoires. Two auxilliary saltwater reservoirs are needed for the Philipsdam locks because the salt seawater is sometimes higher and sometimes lower than the level in the freshwater canal, see Figure 21a. The result is a complex sewer system, Figure 21b.

A pump station is located in the connection between the low and high level reservoirs; Figure 22 shows an oblique view of the lock complex. The floor construction of such a lock, in this case the Kreekrak locks in the Scheldt-Rhine link canal, is shown in Figure 23.

The lock at Duinkerken, the Sogréah solution, funtions as designed[7]. The Netherlands variants, however, have not yet been put into operation because the saltwater-freshwater delta compartimentation works are not ready yet. (Are planned to be put in operation in 1987)

Salt lift lock system

When a somewhat small lock, the Bergsche Dieplock near Bergen op Zoom, had to be built near to oyster breeding beds it was necessery to provide an installation in which the freshwater load in the saltwater area seaward of the lock was kept to a minimum. The various lock systems were re-evaluated and a number of new ideas were proposed. The idea of pumping the chamber completely dry was also considered afresh. In the system selected the ships are not allowed to set dry; a saltwater box is provided in what would be the normal floor of the chamber. Saltwater and freshwater are pumped in and out of the chamber via apertures located low down in the chamber walls at the level of the lock gate tresholds. Discussions were held with nautical engineers and experts to determine whether or not smaller ships and pleasure craft could be allowed to set dry. The following idea was developed from these discussions. (It concerns a meeting with mr. R.E.P Vallenduuk of the ANWB (Organisation of Dutch Tourists)) see Figure 24. The lock chamber is constructed to double its normal height and with a permanent low level dividing wall across the middle. When freshwater is pumped into the lock the ship is lifted above the saltwater, the saltwater behind the dividing wall remaining relatively undiluted.
When the ship is moved over the dividing wall it can be lowered by draining out the freshwater back into the freshwater canal.
Some alternatives considered for improving the basic design are shown in Figure 25. The first alternative, Figure 25a, involved extending the sidewalls over which the freshwater flows into the chamber. One of the disadvantages of this alternative was that the large volume of freshwater had to be pumped while the head could be some metres. The next alternative to be considered involved a low level saltwater basin provided with a lift system, reffered to as a lift box. Such a system conserves energy and the ship need not be moved during the operation, Figure 25b. It is possible to use this system when water levels at the ends of the lock are different, Figure 25c. In this situation, however there is a complication since the saltwater basin box and the lift system must be able to take fairly large water pressure differences. These results from the differences in level between the freshwater and saltwater approaches to the lock.
The system ultimately selected has a fixed concrete outer chamber in which the freshwater outside of the box can be filled up to the level of the freshwater

canal (this is in fact the levelling process) so that large pressures cannot develop across the lift box.

Figure 26 shows how a concrete lock, with a large additional depth, remains filled up with fresh water, levels are equalized by pumping water from the freshwater approaches or by gravity. Inside the permament concrete lock there is a steel box, filled with saltwater which can be sunk from under the ship. Ultimately the choice was for a lift box with open sides which slides along the end walls of the outer chamber. The rubber sealing strips are provided with pressure relief systems. Figure 27 shows the sequence of locking operations. In the figure the ship is sailing from the saltwater approaches into the basin which contains saltwater because the lift box is raised. The lock gates are then closed and the lift box containing saltwater is lowered. At the same time the freshwater content of the chamber is adapted to the level of the freshwater approaches. The gates are opened and the ship then sails into the canal. This system causes little mixing because freshwater is introduced effectively along the full length of both sides of the chamber. Only a small difference, z, in the boundery layer develops across a ship lying asymmetrically because the resistance S, caused, by the wall sluices is now low, see Figure 19 and relationship 17, and is similar on each side of the chamber.

With a lift lock very low saltwater loads, of the order of 5% maximum of the volume of the lift box, are expected. The freshwater loss will be about 10% of the volume of the lift box. Two aspects have to be taken into consideration.

- The volume of saltwater required in the box varies with the water displaced by ships in the box and this must be adjusted for using saltwater from the saltwater approaches using a flexible pipework system such as those used by the dredging industry.
- mixing and internal waves develop because ships above the boundery layer sail into and out off the freshwater approach. Internal wave crests should be below the level of the sides of the lift box.

These aspects have been tested in a scale model. Figure 28 shows two cross-sections of the lock chamber, one filling and one emptying.

Figure 29 shows plan, side and end views of such a lock.

Method effectivity analysis

A comparison of the various systems for minimising salt and freshwater exchange, discussed in these articles is given in Figure 30. If the effect of the locking volume is neglected (or if method M_1 is applied) and also if the underwater volume of the ship is ignored, the whole chamber volume (≈ M_o) will be exchanged unless special measures are taken. If such an exchange occurs the volume of water in the freshwater canal, will remain unchanged but the quality will be reduced. If the freshwater is now used to flush clean the freshwater canal, many times the volume, M_o, will be required. M_o, is somewhat less than 100 % of the chamber volume, because the gates are never allowed to remain open infinitely long and the rate at which the exchange takes place is a little less than the theoretical value, see Figure 6. With the air bubble system (M_2) the situation is the same but the exchange volume rate is limited, depending on the air discharge. When the salt tongue is sucked off, directly or indirectly, (M_3), about 1.5 to 1.8 times more freshwater is used than the reduction in the saltwater load on the canal. At the same time freshwater in the canal is contaminated when ships enter and leave the lock. M_2 and M_3 can be apllied in combination. In the Sogréah solution, M_4, the amount of freshwater used is greatly reduced but mixing occurs when freshwater is pumped into the chamber and when saltwater is forced in and out of the freshwater sewers. This effect is reduced in the Netherlands version of M_4 but less freshwater can be recovered (in case less freshwater is used the salt load on the freshwater component is increased). This problem can be reduced a little, if filling exchanges are carried out more slowly when there are fewer ships in the lock . It appears that generally M_4 works more effectively if a lower discharge is used during exchanges. As stated above very low salt loading can be expected with solution M_5, the lift box, even with a small loss of freshwater.This is also shown in Figure 30. The amount of freshwater used in system M_4 depends on whether freshwater recovering is chosen or not and if so, to what extent. In M_5, freshwater is lost if the saltwater volume in the lift box is adjusted to the ship's volume. The choice of a particular system depend on freshwater availability, while the way of operation can depend on the season.

Is the effect worthwhile?

In general it is difficult to say which particular system should be applied to combat salt intrusion in a particular situation. What is certain is that the quality of agriculture, drinking water, industrial water, the environment, and living conditions are all strongly related the amount of salt in the freshwater system. In the densely populated Netherlands a considerable effort has to be made in this respect. In order to illustrate how the results of figure 30 can be applied a situation with a canal, at the end of which there is a lock and a water intake requiring a certain water quality, see Figure 31, is considered. The lock, filled with a salt combating system, uses a freshwater discharge of Q and, at the same time depending on how good the salt combating system is, also uses saltwater discharge, averaged over the locking period, Q_a (the resulting exchange flow). The freshwater discharge of the lock, Q is equivalent to the flushing discharge of the canal. The larger the value of the canal discharge (larger Q available) the larger Q_a can be, while maintaining the required quality of the canal water at the inlet of the flushing discharge. This process is repesented graphically in Figure 31 by the "freshwater needed" line. The lock characteristics given in Figure 30 are superimposed on Figure 31, the point of intersection giving the discharge quantity of freshwater needed to flush the canal.
It is obvious that a small improvement in the "lock characteristic" will have an important effect on the quantity of freshwater needed. Since the freshwater availability varies over the year the position of the lock characteristic curve greatly influence the duration of the period in the year when the intake quality requirement can be satisfied. In addition the results of Figure 30 should be especially assessed for the quantity of freshwater used in relation to the volume of water exchanged (Volume A)

Closing remarks

From this review it can be concluded that in the last 20 years important developments have been made in the Netherlands in combating salt intrusion at locks located on the fresh/saltwater boundary. The results of efforts to reduce the loss of freshwater are even more obvious. If no salt/freshwater intrusion prevention measures are taken there will be exchange of almost 100% of the chamber volume with every locking operation. These losses can be halved

using an air bubble screen. The application of reservoirs in the freshwater area, in which saltwater is stored initially to be returned to the saltwater area, is an important step in the prevention of saltwater intrusion. Because of the mixing which takes place during locking in fact about two times the chambers volume must be return pumped. This system, therefore, requires a considerable amount of freshwater. Systems have been developed recently in an attempt to reduce both salt and freshwater losses. These can be important in two situations: when freshwater is required (for other purposes) and when freshwater cannot be allowed in a seawater area.
Of the developments outlined in the article the lift lock seems to be the most succesful (appears to be the most promising)
The Netherlands Ministry of Public Works and Transport is now seeking the maximum possible reduction in freshwater/saltwater losses with lift locks.*
In 1 This is because positive decisions have to be taken about the application of these locks in the Oesterdam at Bergen op Zoom in connection with the oyster beds in the area.
Since Duinkerken no developments have been published by foreign organizations related to systems used for preventing salt/freshwater intrusion at locks. The developments outlined above are very Dutch and can be seen as a very important contribution by the Netherlands hydraulic engineering sector in this field. It will be obvious to the reader that the more effective a system is in reducing salt/freshwater intrusion the greater will be investments in the system. Given allowable fresh/saltwater losses for a particular project it is now possible for the designer to choose from various systms. It appears also that the "internal Froude number" plays an important role. From this it follows that the speed at which water flows into or out of the chamber is also important. Efficient lock mangement is, therefore, essential, for the succesful operation of a salt/freshwater separation system and for this reason the relationship between salt/freshwater losses, schematized in Figure 30, should only be seen as indicative of the efficiency of particular systems.

Remark: In 1982 the decision was taken to build a very small lock instead of the lift lock.

References

1 Abraham, G., v.d. Burgh, P.:
"Reduction of Saltwater Intrusion through Locks by Pneumatic Barriers"
Publ.28. Delft Hydraulics Laboratory, 1962.
shorted also in Proc. ASCE(90) 1964, HYI paper 3759.

2 Abraham, G.,van der Brugh, P. de Vos, P.:
"Pneumatic Barriers to Reduce Salt Intrusion through Locks".
Rijkswaterstaat Communications 1973 nr.17.
Also W.L. Publ. 126.

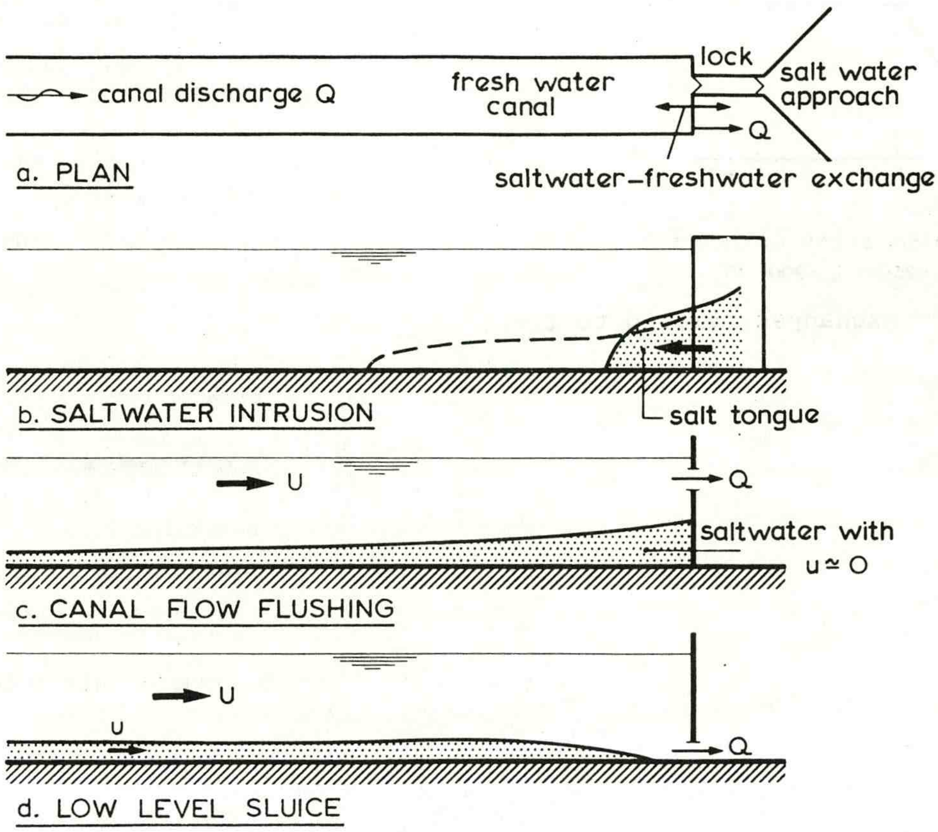
3 Abraham, G.:"Theoretische beschouwingen over zoutbestrijding bij
schutsluizen door luchtbellengordijnen.
De Ingenieur (84) maart 1972, no.2, Also W.L. Publ.nr.138N.

4 Jonker, L.A. and Barentsen, W.H.: "De nieuwe zeevaartsluis te Terneuzen"
5th Internat. Haven Congres. Antwerpen juni 1968, paper 2.12

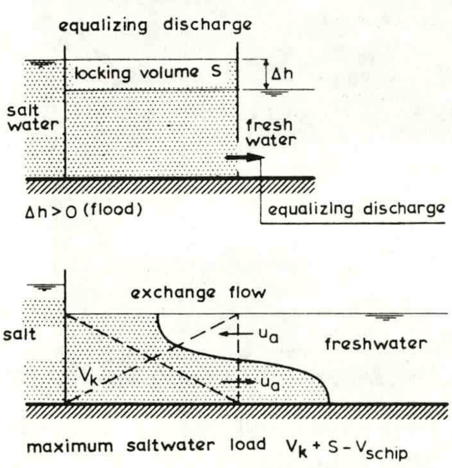
5 Ribes, G. and Blanchet, CH.: "Les courants de densité et le projet de
l'écluse de Mardyck á Dunkerque' La Houille Blanche 1965 no.1.

6 Kolkman, P.A. and Slagter, J.C.: "The Kreekrak Locks on the Scheldt-Rhine
Connection". Rijkswaterstaat Communications nr.24, 1976.

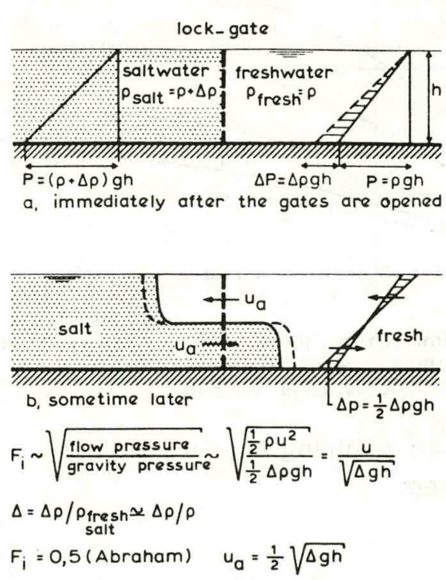
7 Quetin, B.: "l'écluse de Mardyck (près de Dunkerque) limite la pénétration
d'eau de mer dans le canal à grand Gabarit".
La Houille Blanche, (27) 1972 no.2/3.



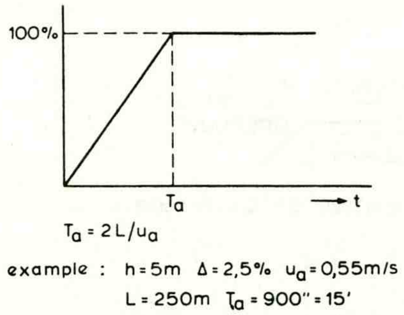
1. Situation with a normal salt intrusion



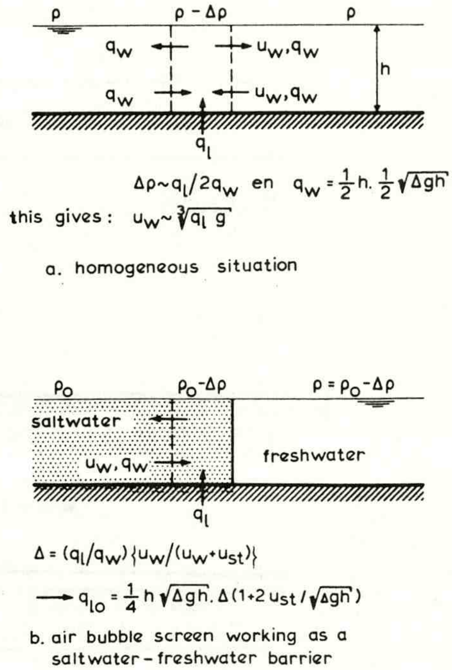
2. Factors which determine the salt load



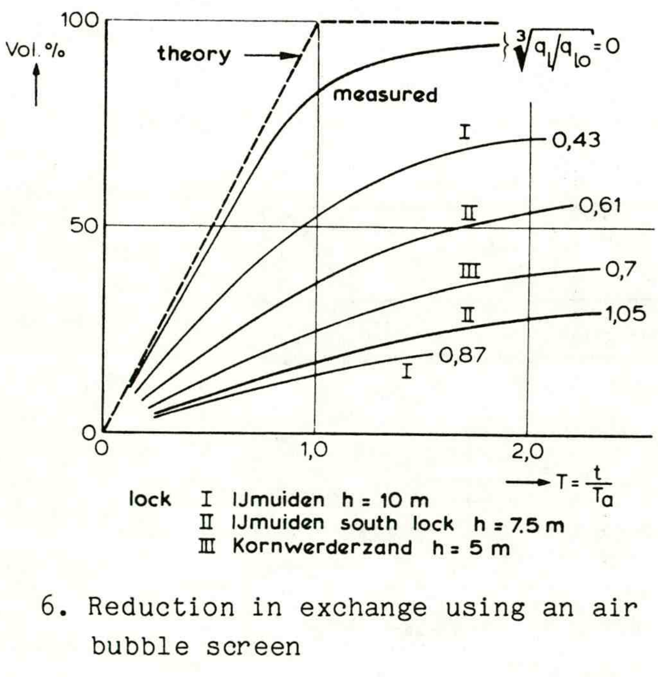
3. Saltwater-freshwater exchange shortly after the gates have been opened



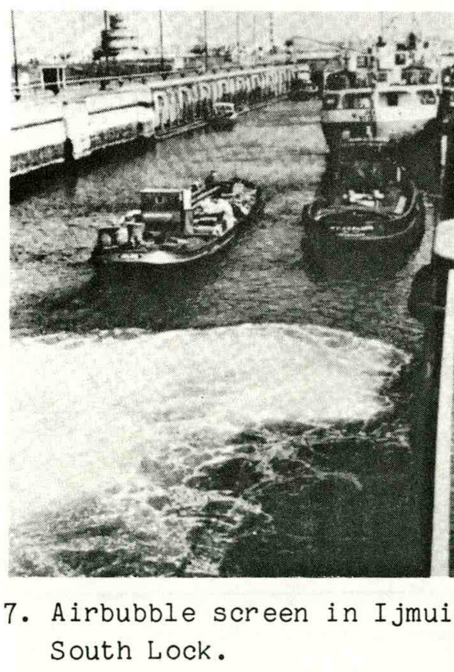
4. Volume exchanged related to time



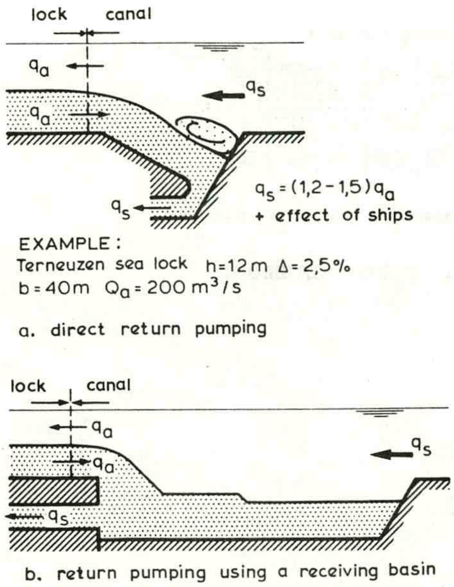
5. How an air bubble screen works



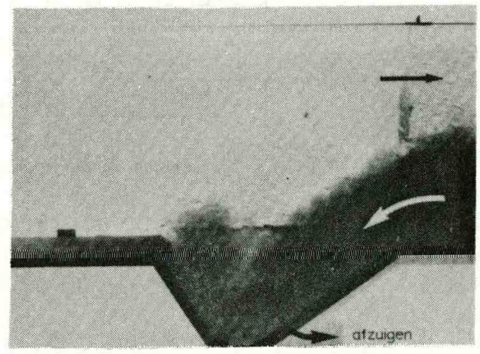
6. Reduction in exchange using an air bubble screen



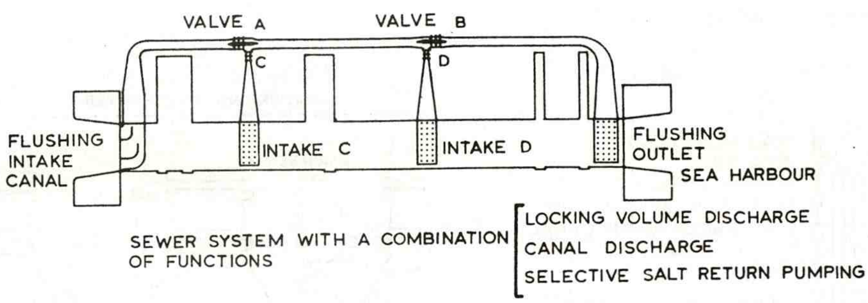
7. Airbubble screen in Ijmuiden South Lock.



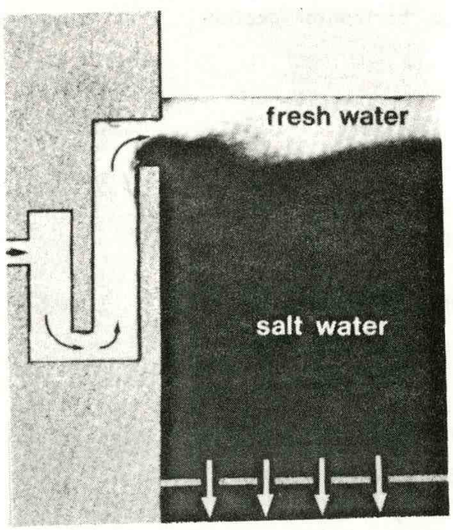
8. Method M3: pumping back (return pumping) the salt tongue



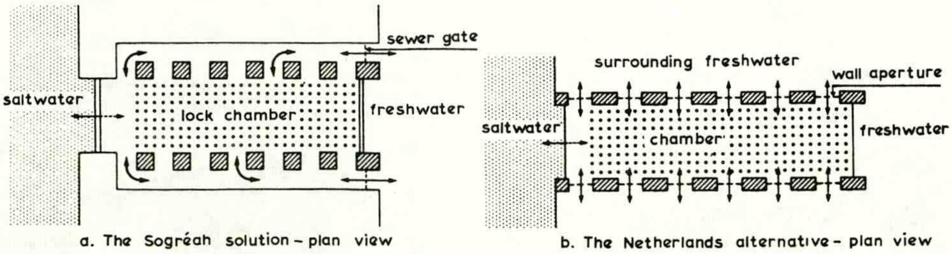
9. The salt (coloured) underflow being return pumped directly.



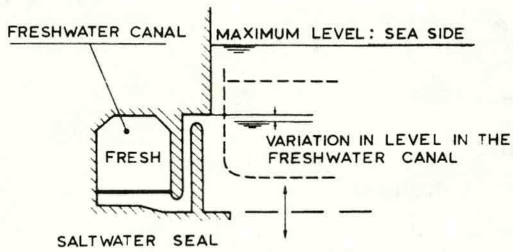
10 Plan view of the Terneuzen sea lock



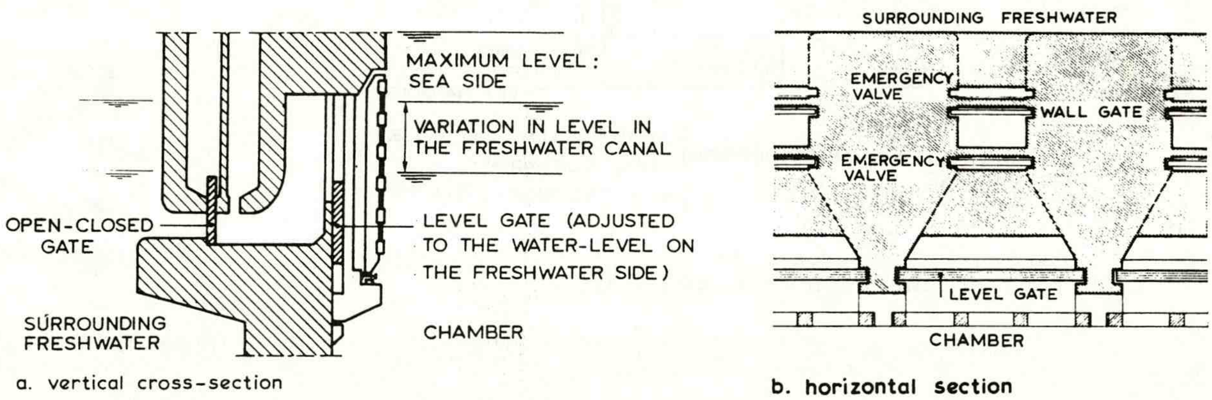
11.Test introducing freshwater into the lock chamber which is full of saltwater.



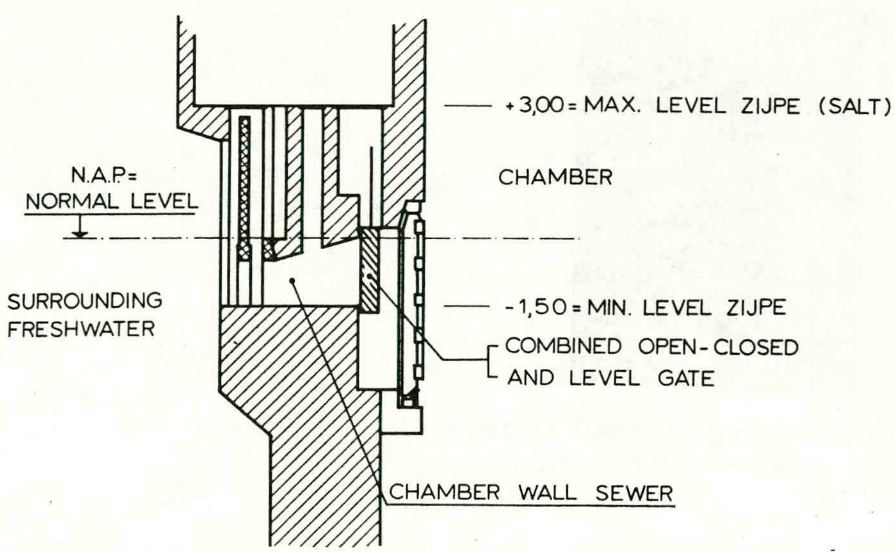
12. Preventing salt intrusion by exchanging the chamber contents with the lock



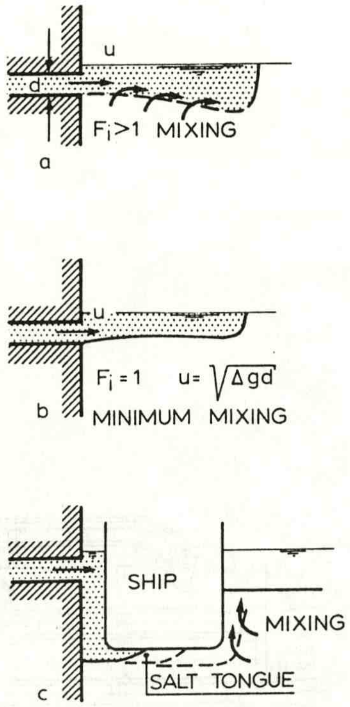
13. The lock system used at Duinkerken - cross section



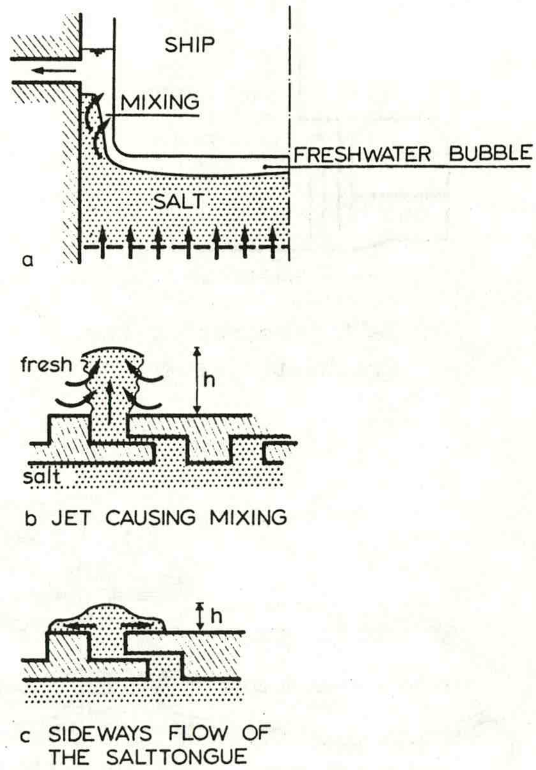
14. The Kreekrak chamber wall



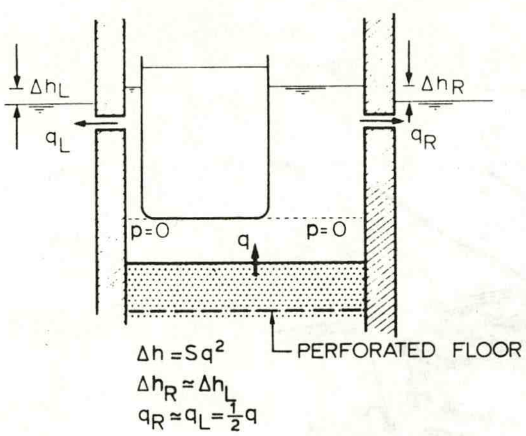
15. The Philipsdam lock chamber wall sewer system, cross section



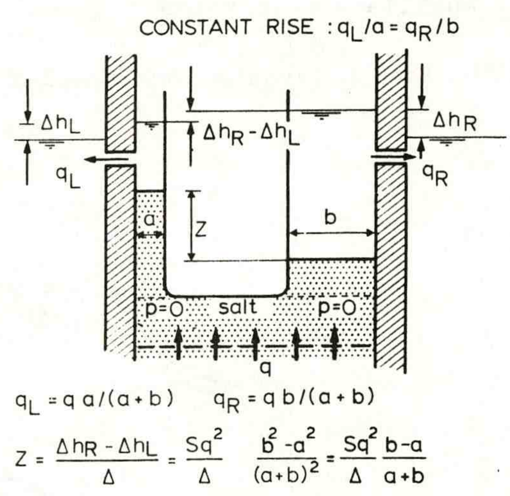
16. The causes of mixing during saltwater-freshwater exchange



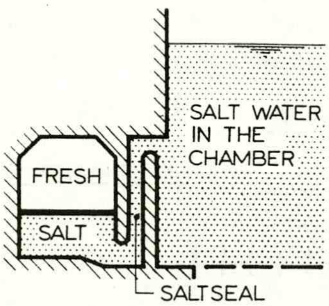
17. The causes of mixing and saltwater loss during freshwater recovery



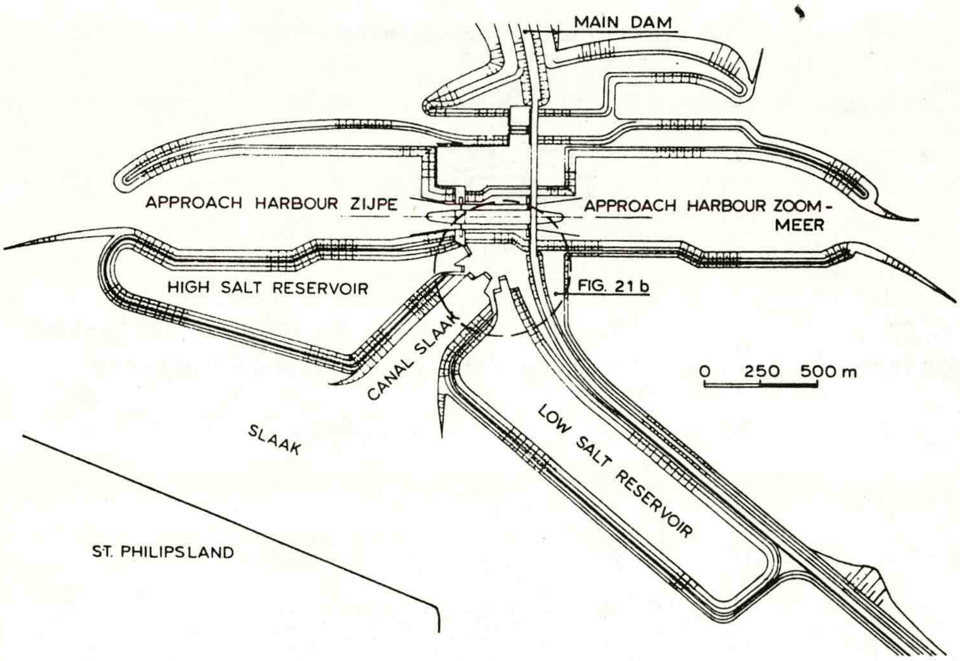
18. The effect of wall aperture resistance when the chamber still contains freshwater



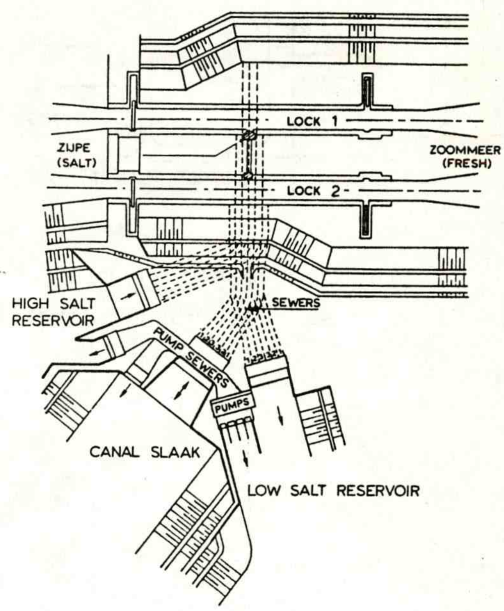
19. The situation when the rate of rise of the boundery layer is the same on both sides of the ship.



20. Salt penetrating the freshwater sewer

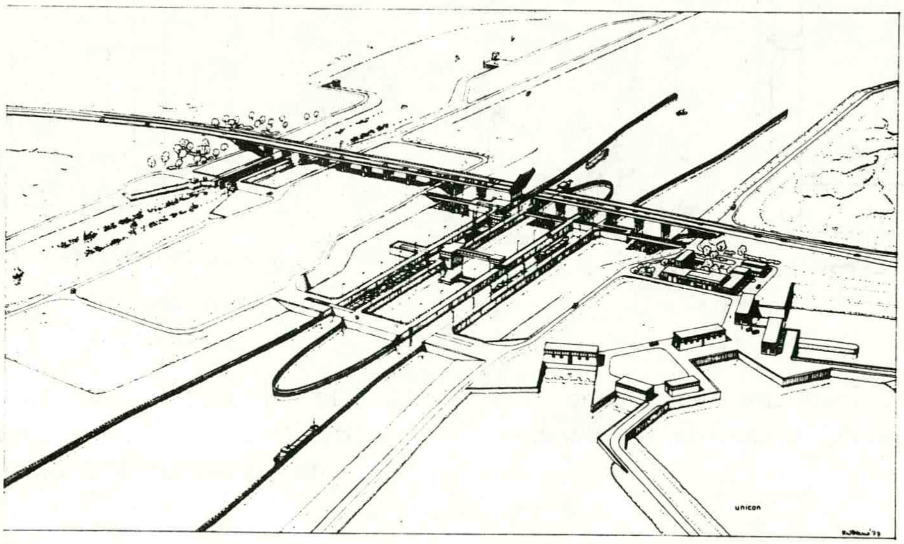


a. Plan view of the two push-tow locks with auxiliary reservoirs

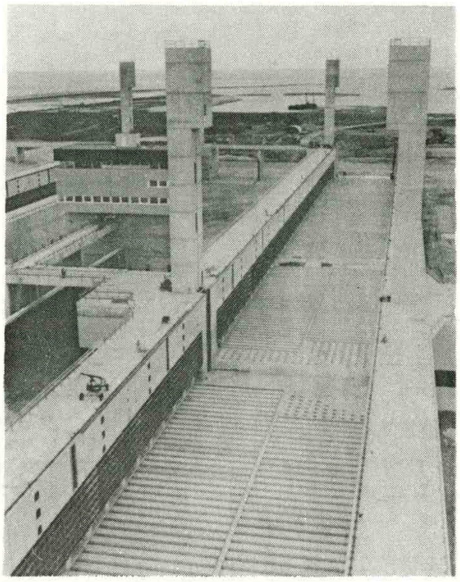


b The sewer system

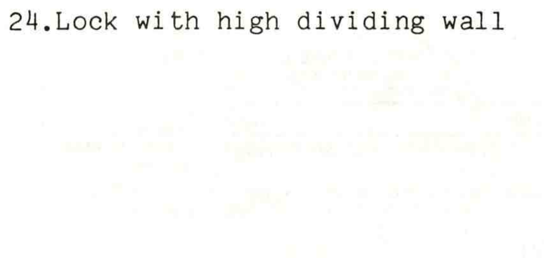
21. The philipsdam lock complex - plan view



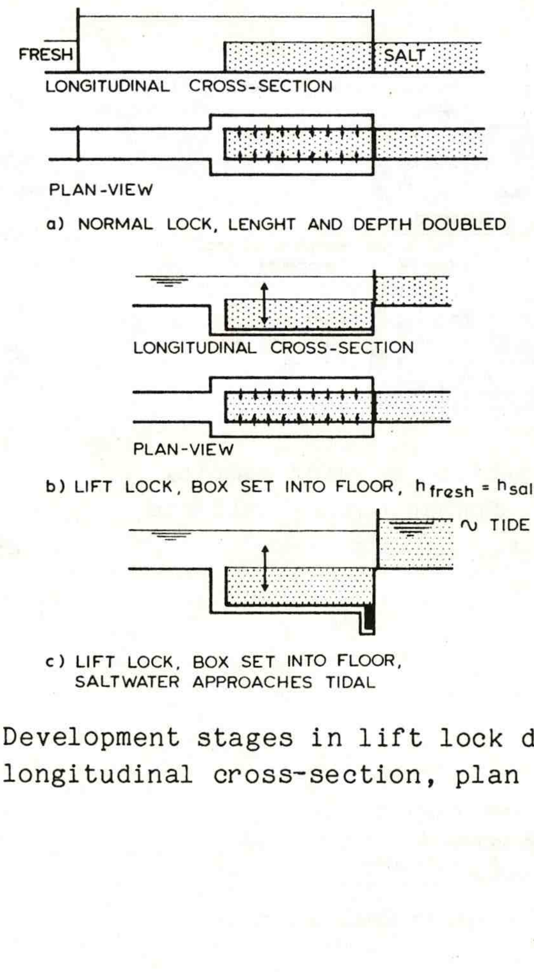
22.Push - tow locks at Philipsdam with freshwater in the foreground which runs alongside the locks.



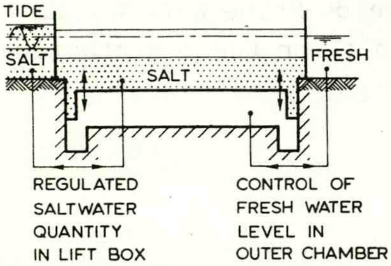
23.The Kreekrak locks in the Scheldt-Rhine Link Canal constructed with a perforated floor for distributing the saltwater inflow and outflow.



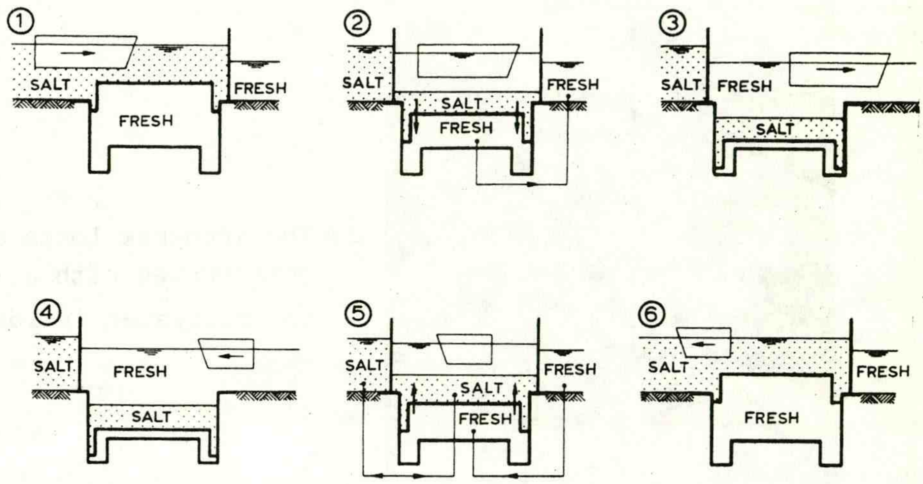
24.Lock with high dividing wall



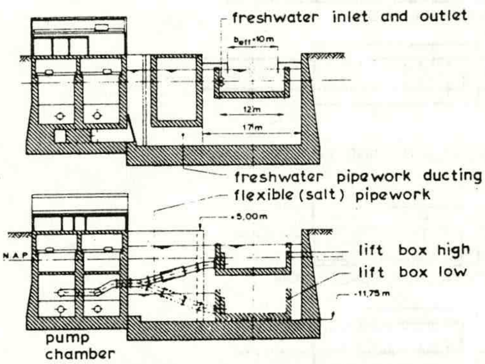
25.Development stages in lift lock design, longitudinal cross-section, plan view



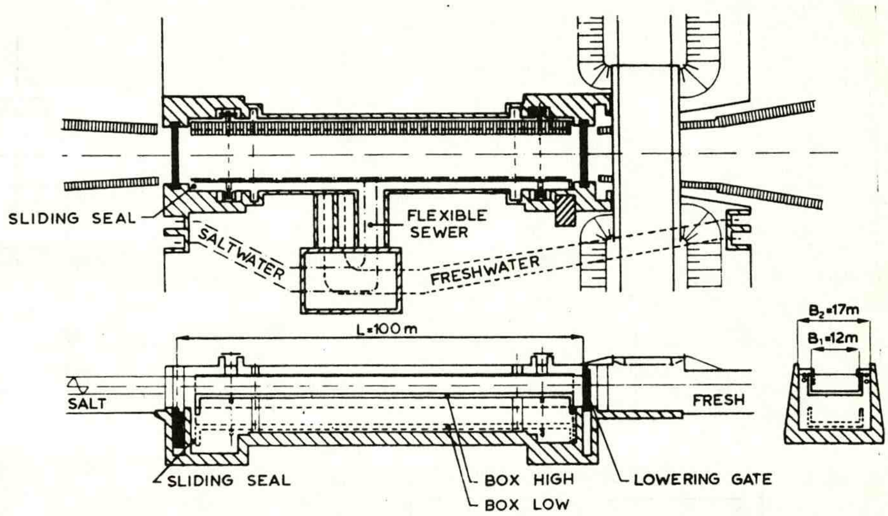
26.The lift lock principle



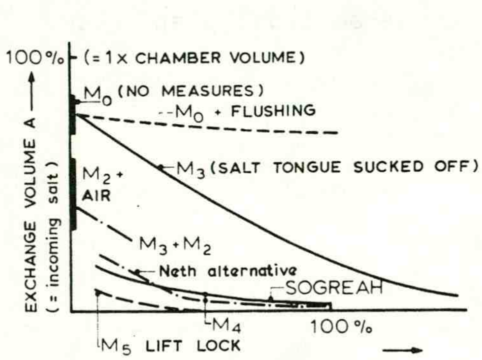
27.Locking operations with a lift lock



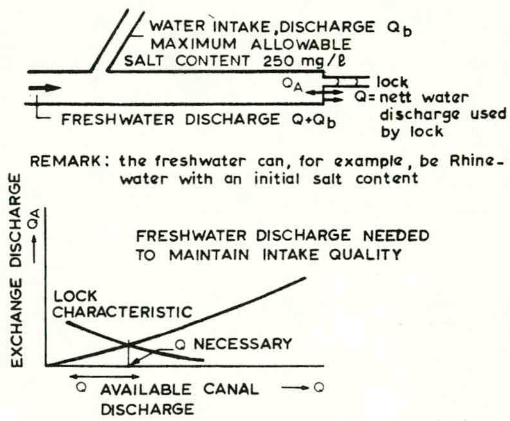
28.Cross-section showing pumping systems for adjusting salt and freshwater levels.



29.Lift lock - plan view and cross - section



30.Exchange volume A(= incoming salt)



31.The situation of a lock with a freshwater intake in the canal.

p.o. box 177 2600 mh delft the netherlands