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THE CLOSURE OF TIDAL BASINS

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ABSTRACT

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The closing of tidal basins generally serves a combination of various purposes, such as land reclamation, protection against floods, creation of fresh-water reservoirs, etc. Closure works in tidal areas will change the tidal conditions on the sea side of the closure, while desalination will be the main problem in the enclosed area. A comparison between some closure methods is given. A distinction is made between sudden and gradual closure methods, the latter being subdivided into vertical, horizontal and combined methods.

Some attention is paid also to the seabed protection, which is needed in order to reduce the risk of instability of the closure dam during construction. As an illustration of a large-scale closure operation, a case study has been worked out briefly. From a comparison between a vertical and a combined horizontal and vertical closure method, the latter appears to be less appropriate in the case of large-scale closure works.

INTRODUCTION

Closures of tidal basins have been carried out around the world for many centuries. Before the twentieth century, they were mostly of a limited scale, using simple techniques mainly based on experience; this experience was built up by trial and error. Methods to determine the expected velocities in the different stages of the closure and the effect of these velocities on stone stability, scouring etc, were not available.

People involved in this type of closure experienced many disappointments. Partly completed dams were often destroyed by the combined action of currents and waves. The introduction of proper methods of seabed protection. e.g. by using wooden or reed mattresses, diminished scouring problems, thus enabling the execution of larger closures.

Real scale enlargement, however, was not attained before the beginning of this century. Two basic features started this new era; improved insight into tidal hydrodynamics and the development of larger, mostly steam-propelled (floating) equipment. More modern dredging techniques played an important role in furthering this development.

In The Netherlands two events led to the political willingness to undertake larger closure operations. During the first world war (1914—1918), the Netherlands remained neutral and suffered food shortages because of the disturbance of supply lines. This situation called for additional agricultural land, to be reclaimed from the sea. Secondly, a flood disaster induced by a storm surge occurred in 1916. The result of these two events was the closure of the Zuiderzee in 1932, followed by land reclamation in the enclosed lake (see Figs. 1 and 2). Two purposes were served by this closure; increased safety against both storm surges and food shortages.

The southwestern part of the Netherlands was partly inundated by the flood disaster of 1953 in which some 1850 people were killed. The "Deltaplan", whose main purpose was to shorten the coastline and thereby to prevent similar disasters in the future, was subsequently carried out. The main layout of the Deltaplan and the closure dams constructed within its scope, are indicated in Fig. 2. Improved water management of the main river infrastructure was a secondary goal of the Deltaplan, but land reclamation was not one of the purposes of this project. The principle underlying the Delta project was to start small and then to proceed to more ambitions schemes.

In the Republic of Korea, the need for additional agricultural land became more pressing during the last decades. This need was triggered by the very

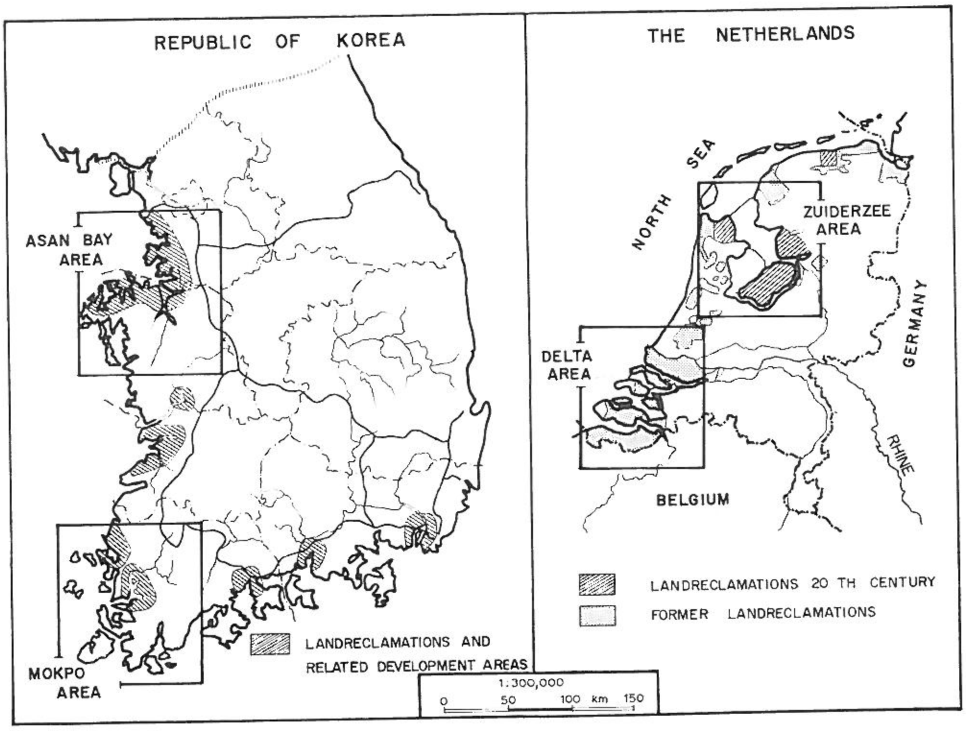


Fig. 1. Land reclamation in the Republic of Korea and The Netherlands.

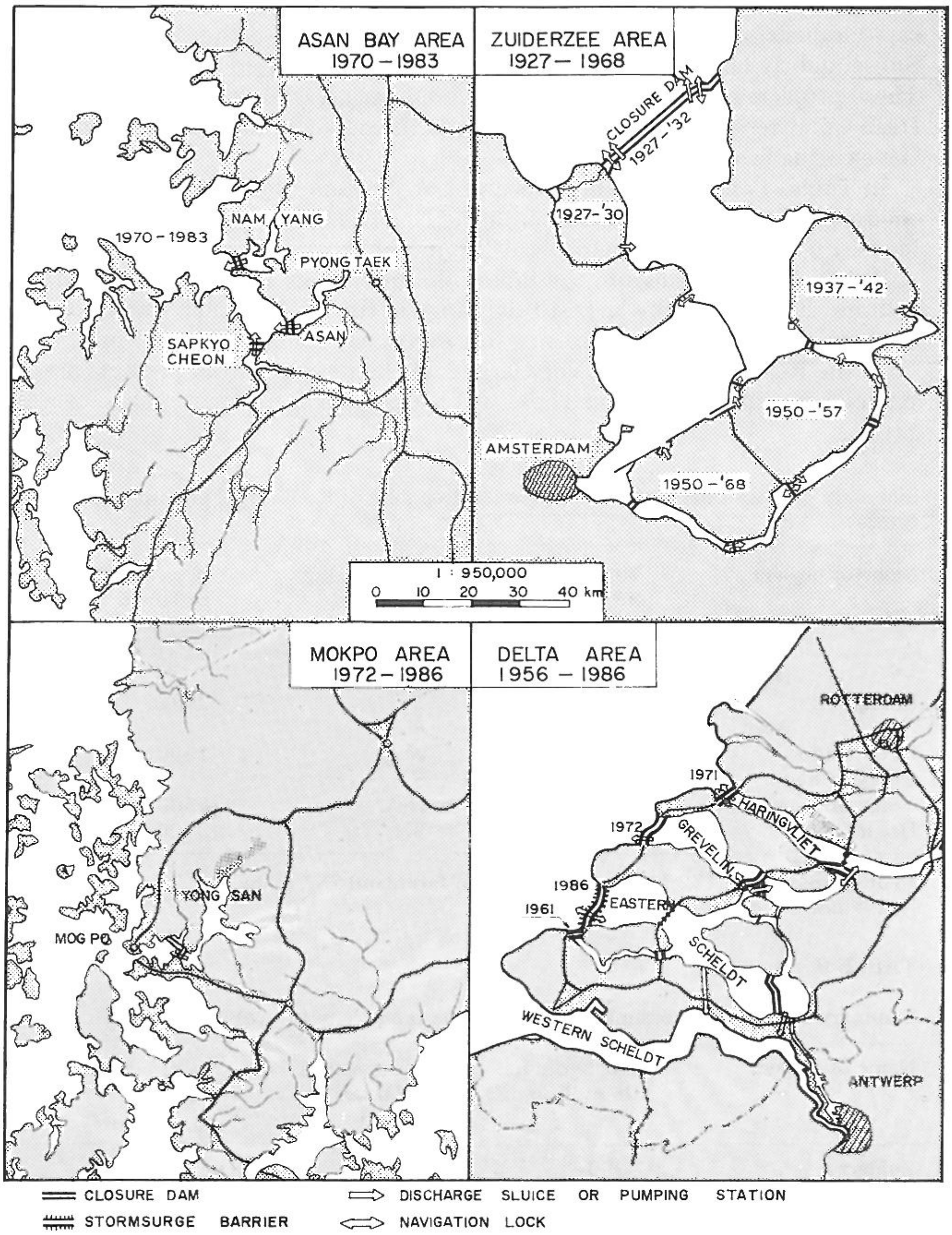


Fig. 2. Tidal basin closures and related land reclamation in the Republic of Korea and The Netherlands.

rapid industrial development that required large parts of the "old" land. Subsequently large land reclamation projects were carried out. (see Fig. 1.) These projects required the closure of tidal basins, enabling the creation of fresh-water reservoirs for water supply to the newly reclaimed areas and to the existing farm land (see Fig. 2).

In Tables I and II a summary is given of the main tidal-basin closures and the related land reclamation in both the Republic of Korea and the Netherlands. Figures 1 and 2 illustrate this summary.

As can be observed from the tables, the tidal range in the Asan Bay area is more than double.the largest tidal range in the Netherlands. However, during construction-phase storms, this range may increase up to 6 m.

In the Republic of Korea very large-scale land-reclamation projects are planned for the near future. These will necessitate even larger-scale closures,

TABLE I

Summary of main tidal basin closures in the Republic of Korea (Past and immediate future)

Name of project	Tidal volume (in million m³)	Mean spring tidal range (in m)	Area of land reclamed (in ha*)
Namyang	80	8	
Pyongtaek			2682
Asan	180	8	
Gyew Hado	N.A.	N.A.	7500
Sapkyo Cheon	145	8	—
Yong san gang	N.A.	N.A.	5500
Dae ho area	N.A.	8	3700

*Total project area 172,115 ha, expansion of farm land 28,732 ha.
N.A. = not available.

TABLE II

Summary of main tidal basin closures (past and immediate future) in The Netherlands*

Name of project	Tidal volume (in million m³)	Mean spring tidal range (in m)	Area of land reclamed
Zuiderzee	300	1.0	165,000
Veerse gat	80	3.5	—
Haringvliet	250	2.5	—
Brouwershavense gat	360	3.0	—
Lauwerszee	120	2.4	5 000
Eastern Scheldt**	1100	3.5	—

* Only 20th century closures and land reclamation indicated.
** Storm surge barrier under construction.

than those carried out in the last decade. Some techniques and experience obtained with similar scale enlargements in the Netherlands are presented in this paper.

THE PURPOSE OF TIDAL BASIN CLOSURES AND THEIR EFFECT ON THE ADJACENT AREAS

In general, the closing of tidal basins serves a combination of the purposes mentioned below:

(a) Land reclamation.
(b) Protection against floods from the sea.
(c) Creation of fresh-water reservoirs (water supply).
(d) Production of tidal energy.
(e) Closed sea harbours (behind locks).
(f) Closure in relation to the construction of docks, locks, sluices etc.

As already mentioned in the introduction, the closure of the Zuiderzee in the Netherlands served the first three of these purposes. The Delta project in the Netherlands is aimed at flood protection and the creation of fresh-water reservoirs. The closure of the Rance in France is an example of the production of tidal energy.

In the Republic of Korea, land reclamation in combination with the creation of fresh-water reservoirs is the main purpose of the tidal basin closures carried out in the last decade. The closure of Asan Bay is a potential example of an enclosed sea harbour behind locks. There are of course many more examples in the world.

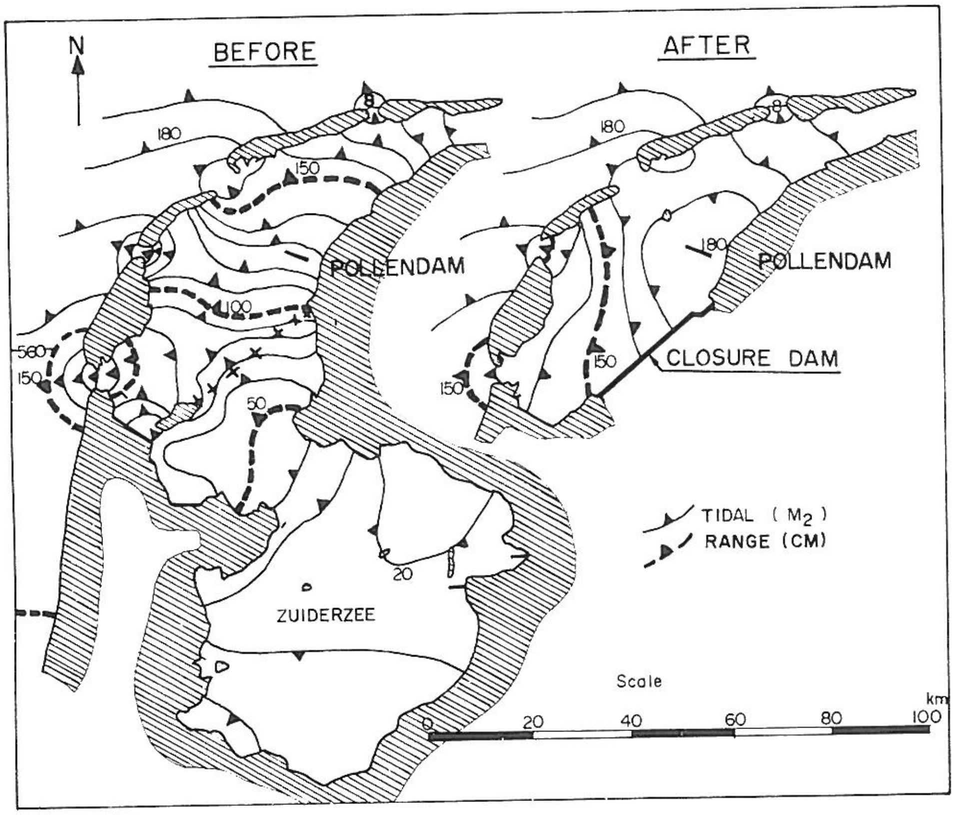
Before discussing the technical aspects of closure operations, it is worthwhile to pay some attention to the effect of completed closure operations on the areas adjacent to the closure dam. These can be subdivided into effects on the remaining tidal estuary and on the enclosed lake.

Effects on the remaining tidal estuary

The primary effect of a closure dam on the remaining estuary is a change of the tidal conditions in this estuary. This effect has to be forecast in order to prevent undesirable changes of this tidal regime. Mathematical tidal models are available and have been succesfully used to assess the characteristics of the new tidal regime.

An example of the changes in the tidal conditions after the construction of the Zuiderzee closure is presented in Fig. 3. From Fig. 3A it may be observed that near the "Pollendam", the tidal difference of the lunar semidiurnal tide (M_2) increased from 1.3 m before to 1.8 m after the closure.

The maximum ratio of the tidal current velocities after and before closure amounts to 1.25 as can be seen in Fig. 3B. A change of the tidal regime will induce morphological changes; tidal gullies will shift, whilst the depths will change as well. These morphological changes will in their turn influence the



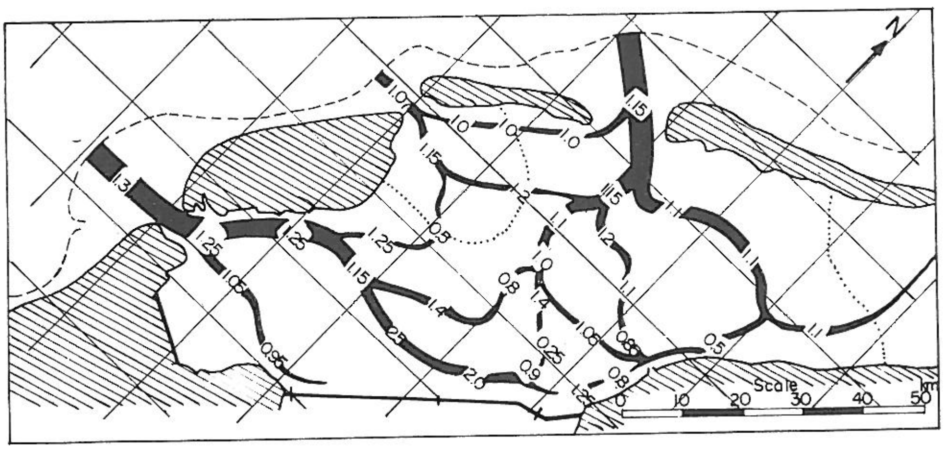


Fig. 3. The influence of the Zuiderzee closure (1932) on the tidal regime in the remaining estuary. A. Tidal range before and after closing. B. Current velocity ratio between situations after and before closing.

tidal regime and so onwards, showing the strong interaction between the two.

Three main aspects, which will be influenced by the above-mentioned effects, can be distinguished: (a) the accessibility of harbours; (b) the storm surge levels; and (c) the environment.

After the enclosure of a tidel basin, sedimentation will occur in a zone near the closure dam and may occur at other locations in the remaining estuary. The depth of harbours and shipping channels may decrease, necessitating maintenance dredging. The changed current pattern may influence the nautical behaviour of ships. The latter can lead to a necessary reconstruction of shipping channels and the installation of (additional) navigational aids. The above-mentioned effects will be strongly influenced by the alignment of the closure dam. Again tidal models will enable the prediction of the changes. If the effects are undesirable, closure dam alignments can be adapted. An example of such a reconsideration of the closure dam alignment is the closure dam of the Zuiderzee. As can be observed in Fig. 3A, the chosen alignment of this dam is not the shortest connection between the two shorelines. Tidal computation for a situation with a more southern alignment showed an unacceptable increase in the amplitude of both the tidal currents and the vertical tide. Consequently the alignment was shifted in a northerly direction.

An increase in tidal difference may also lead to an increase of storm surge levels, necessitating a reconstruction of existing sea defences.

Environmental changes in the remaining tidal estuary may occur due to changes in location and area of tidal wetlands. These changes may affect the biological production of these areas. Ecological effects, not necessarily negative, may result. Water quality aspects will, under certain circumstances, play a role in the choice of the closure dam alignment. A change of the current velocities may result in different dilution patterns of the discharge of sewage and other effluents and the water quality of the remaining estuary may be affected thereby.

Effects on the enclosed lake

The closure dam alignment determines the shape and extent of the enclosed lake. Vital for the functioning of such an enclosed lake as a source of water is a sufficient influx of fresh water enabling (among other things) a proper desalination. The replacement of the brackish water in the enclosed basin by fresh water from rivers is brought about by a mixing process, whereby excess water is evacuated via sluice gates to the sea.

The time of desalination will depend upon a number of parameters, of which the fresh water inflow is one of the most important. The equilibrium salinity level reached in the reservoir will be influenced by the supply of salt from various sources such as:

(a) Leakage of sluice gates.
(b) Sea water intrusion during locking operations of ships.
(c) Saline seepage underneath the closure dam.

(d) Brackish effluent from (polder) areas draining into the reservoir
(e) Diffusion of salt from the river bed.
(f) Inflow of river water with a certain salinity.
(g) Inflow of brackish ground water.

Before a proper reservoir design can be accomplished, it is necessary to obtain an insight into the presence and magnitude of the above-mentioned sources of salt supply. Based on this information and the water balance, a salt balance can be drawn up. In this way failures can be avoided. If the outcome of the above-mentioned study is negative, a revised, feasability plan can be drafted.

If the above-mentioned considerations lead to such a revision of plans, this may well include a change of the closure dam alignment. The geometry of the enclosed lake, in relation to the location of fresh-water inflow is also an important aspect for both the desalination process and the equilibrium salinity level of the reservoir.

The success of land reclamation is not only determined by a sufficient quantitative and qualitative supply of water. A proper drainage system, vital to desalinate the soil and to prevent the occurrence of too saline ground water after the initial desalination, has to be installed. Drainage techniques are well developed in the Netherlands, especially in relation to the large land-reclamation projects (165,000 ha) in the Zuiderzee region (see Fig. 2).

A subject not yet discussed is the water quality in the reservoirs. Main aspects determining this quality are the dissolved oxygen content in relation to sewage disposal and the prevention of algal bloom. The possibility of maintaining a proper water quality is to a large extent influenced by the availability of a sufficient discharge to flush the reservoir through the discharge sluice. Reservoir salinity level and water quality are of course strongly interrelated as both depend on the above-mentioned discharge.

Concluding, it can be remarked that the closure of tidal basins in general and the alignment of the closure dam in particular, have an impact on both the remaining estuary and the newly created lake. The success of a project will therefore not only depend upon the technical accomplishment of the closure operation, but to a very large extent on a proper analysis into all the aspects which determine the quality level, with which the ultimate goal, mostly land reclamation, is reached.

STARTING POINTS OF CLOSURE OPERATIONS

General

When preparing the construction of a closure dam, a number of essential decisions have to be made, of which the most important are:

(a) The alignment of the closure dam, some aspects of which have been discussed in the previous section.
(b) The location and design of structures in the dam (e.g. locks and sluices).
(c) The closure method.

The *alignment* of the closure dam determines the cross-section and therefore the shape of the gap to be closed. The alignment also determines the tidal basin area to be closed. Together with the tidal difference and the closure method, the alignment therefore determines the current velocities in the different stages of the closure operation.

The *locks and sluices* in the dam alignment have to be built on the tidal flats, inside a construction dock. After completion of the structures, the construction dock can be dredged away.

Various *closure methods* are available and have been successfully used. The Deltaplan in the Netherlands is an example of scale enlargement in closure operations.

In the next section closure methods and the factors determining the choice between them will be discussed.

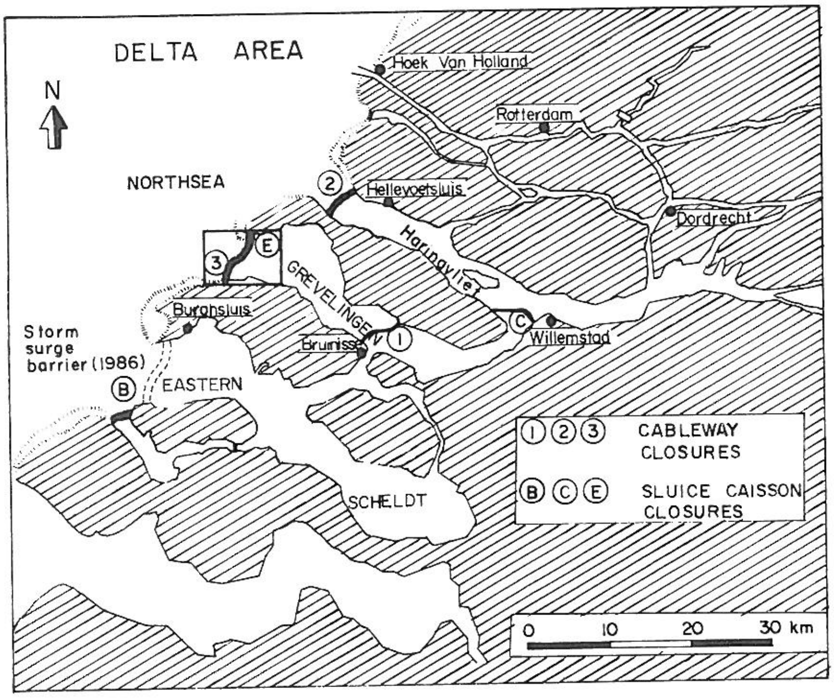
CLOSURE METHODS

General

When a closure dam is built, the in and outflow of water through the gap, that is gradually narrowed during the closure, will be hampered. This results in a decrease in the tidal range in the basin. As the tidal characteristics outside the basin remain mostly unchanged, the water level differences across the gap increase. Consequently the tidal current velocities through the gap will increase as well. The scouring effect of these larger, turbulent velocities, will endanger the stability of the seabed adjacent to the dam and thus the foundation of the closure dam. This implies, that the seabed, when it consists of easily erodable material, has to be protected by current-resisting constructions. In general, prior to the start of a closure operation, a seabed protection has therefore to be laid to ensure a stable foundation of the closure dam.

The materials (rock, concrete blocks, stiff clay, or concrete caissons) used for the closure operation should resist the current velocities occurring. Independent of the closure method, coarser materials are necessary in the subsequent stages of a closure operation. From the above it will be clear that knowledge of expected current velocities is necessary to determine material sizes, and to predict scourhole dimensions. Mathematical and physical tidal models can be used for this purpose and are in fact indispensable tools. An example in Fig. 5 illustrates the computed and observed vertical tide and discharge through the Brouwershavense gat (for location see Fig. 4). As can be observed, the computed curves very closely match those observed. In the same Fig. 5, the computed water-level differences during the final closure stage are also shown.

In the first stage of a closure operation, the gap can be narrowed by building out from the sides. For the closing of the final gap two groups of closure methods can be distinguished: (a) the gradual closures; and (b) the sudden closures.



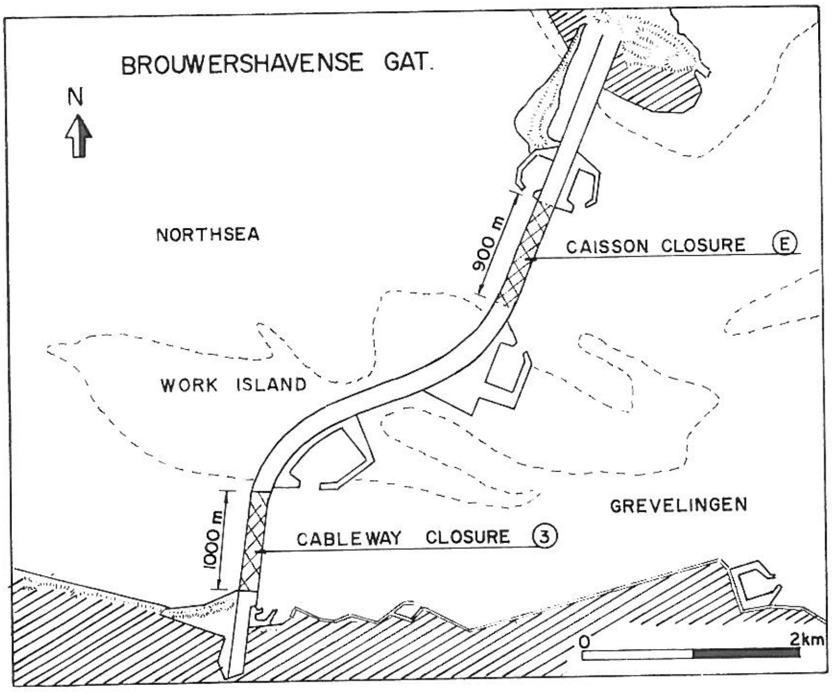


Fig. 4. Various tidal basin closures in the Delta area.

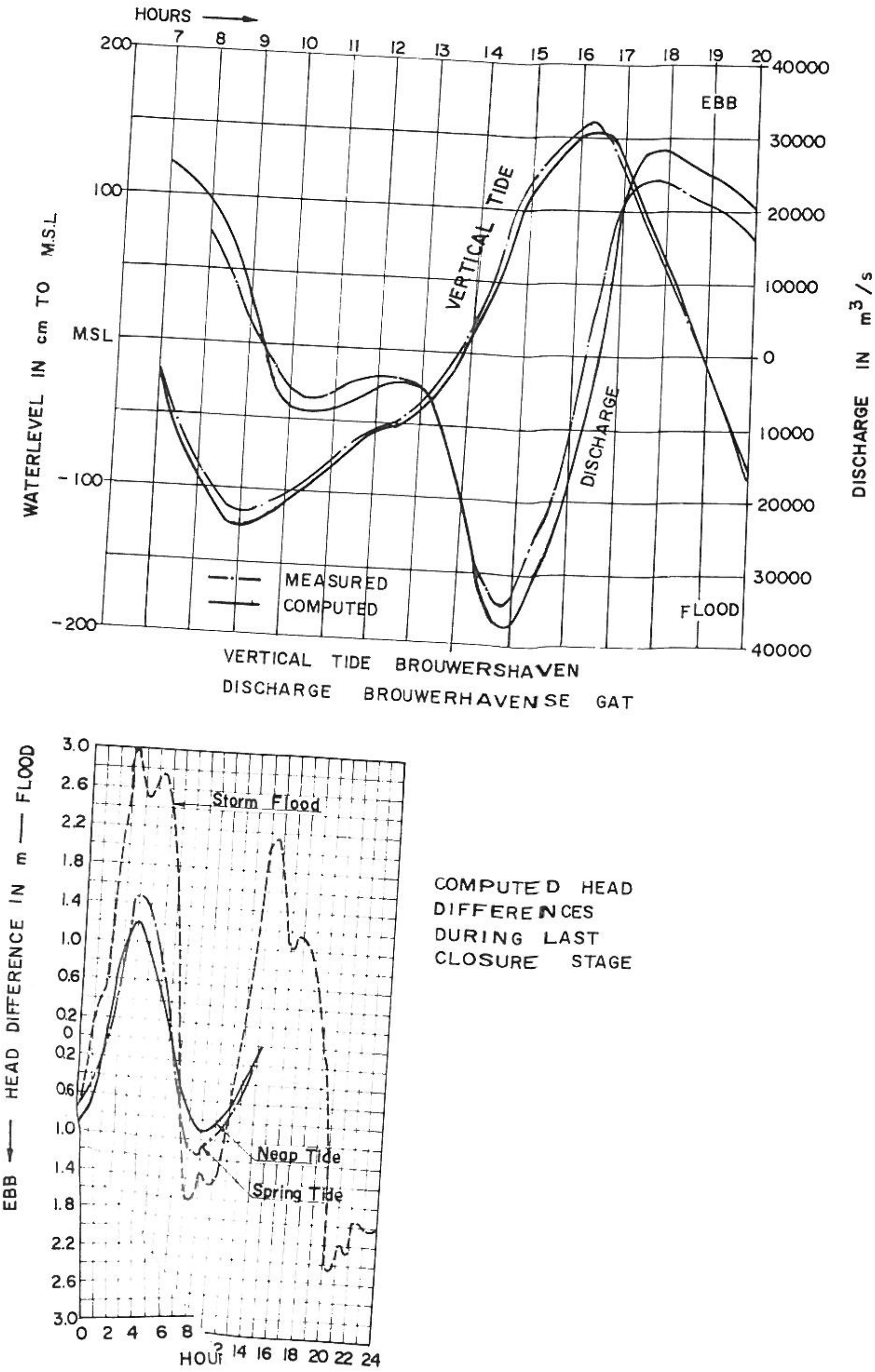


Fig. 5. Tidal computati... Brouwershavense Gat.

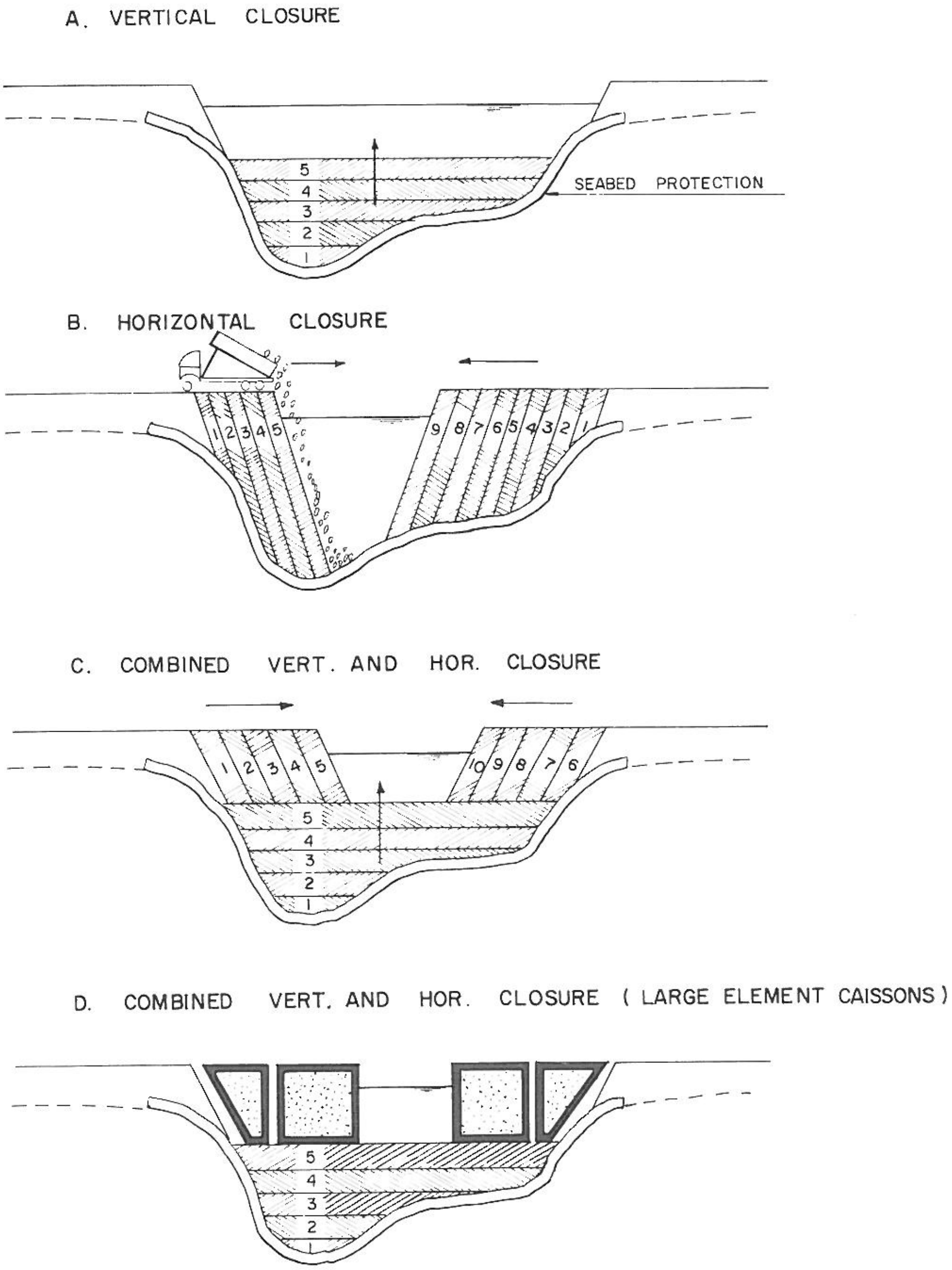


Fig. 6. Gradual closing methods.

The gradual closure

The gradual closure methods can be subdivided into horizontal and vertical closures. A combination of the horizontal and vertical method is one of the possibilities. Figure 6 illustrates the main principles of these closure methods.

Vertical closure methods

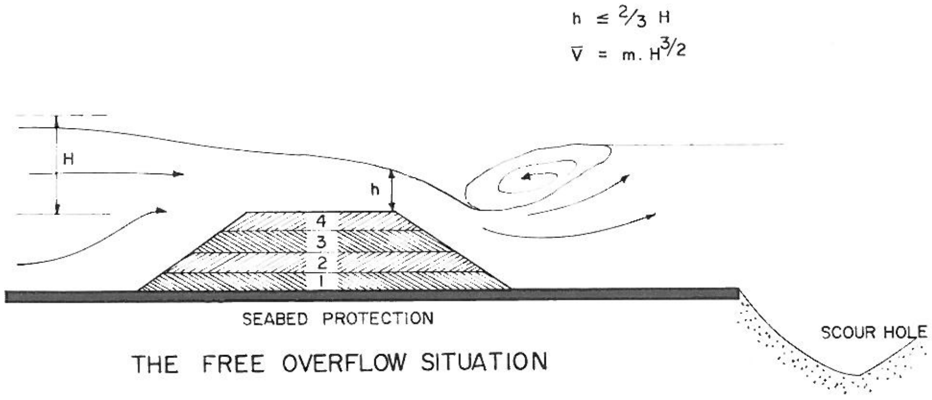
The great advantage of a vertical closure operation is the fact that a situation of free overflow is reached after which the current velocities do not further increase. Such a free overflow situation and the relation between current velocity and remaining gap profile is illustrated in Fig. 7.

In a vertical closure operation two stages can be generally distinguished. The first stage will consist of the dumping of stone of gradually increasing sizes with the help of floating equipment. In the Netherlands split barges and specially designed stone-dumping vessels are employed in this stage. This operation can be carried out until either the available depth becomes too low or the current velocities become too high during the tidal cycle (larger than 2—2.5 m/sec). In both cases the production decreases to such an extent that other methods become more feasible. For the second stage of the closure operation, various methods are available such as cableways, helicopters or the use of a bridge. In some cases floating cranes can be used in the second stage.

Three major closure operations were carried out with the help of cableways in the Netherlands, as is illustrated in Fig. 8. The cableway closure system had been used once before in the UK but cableways had been extensively used all over the world for transporting persons and material from one place to another and could, with minor changes, be adapted for the use intended in the Netherlands. Because the operations required only a short time a self-propelled cable car was chosen instead of cable cars, which were hoisted or moved along a continuous looped carrier cable and moved, all of them simultaneously, by a second cable. The disadvantage of the self-propelled cabins is the greater weight but this was easily offset by the greater flexibility of the system and the economics.

The payload and dumping capacity of the cableways used are illustrated in Table III.

As can be observed, concrete blocks of 2.5 tons were used in the last two mentioned closure operations. The block sizes were not only determined by the current velocities in the last closure stage, but also by wave attack after closure and before completion of the (sand) dams. The reasons for using concrete blocks instead of, for instance, rubble are the following: (a) rubble has to be imported in the Netherlands, involving high transportation costs; and (b) concrete blocks are easy to produce, to stack and to handle. By dumping concrete blocks, a closure dam with a large initial permeability is constructed. The voids between the blocks have to be filled in and several succesful methods (e.g. using sand asphalt) have been used.



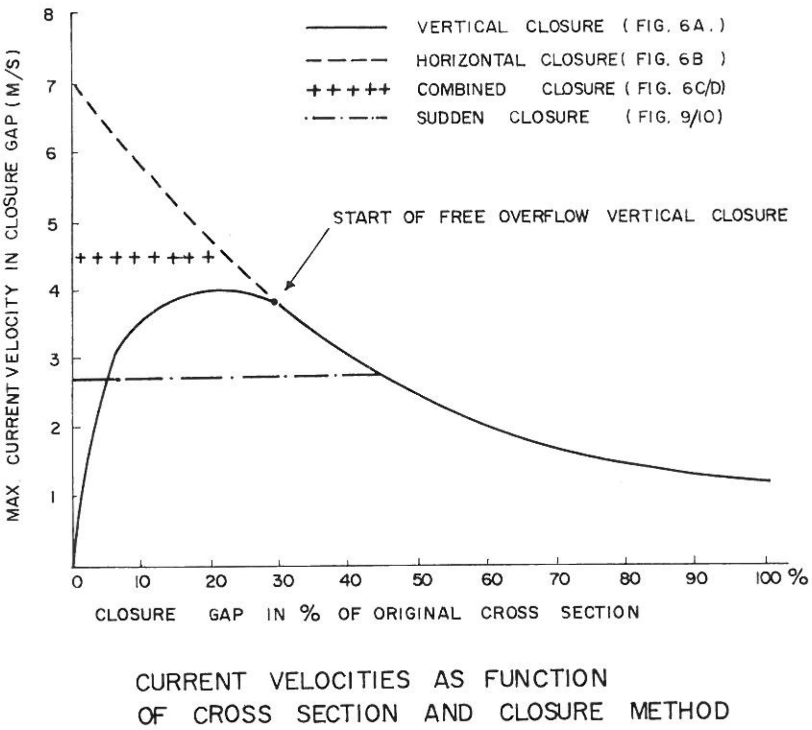


Fig. 7. Current velocities as a function of the closure method (Dutch circumstances).

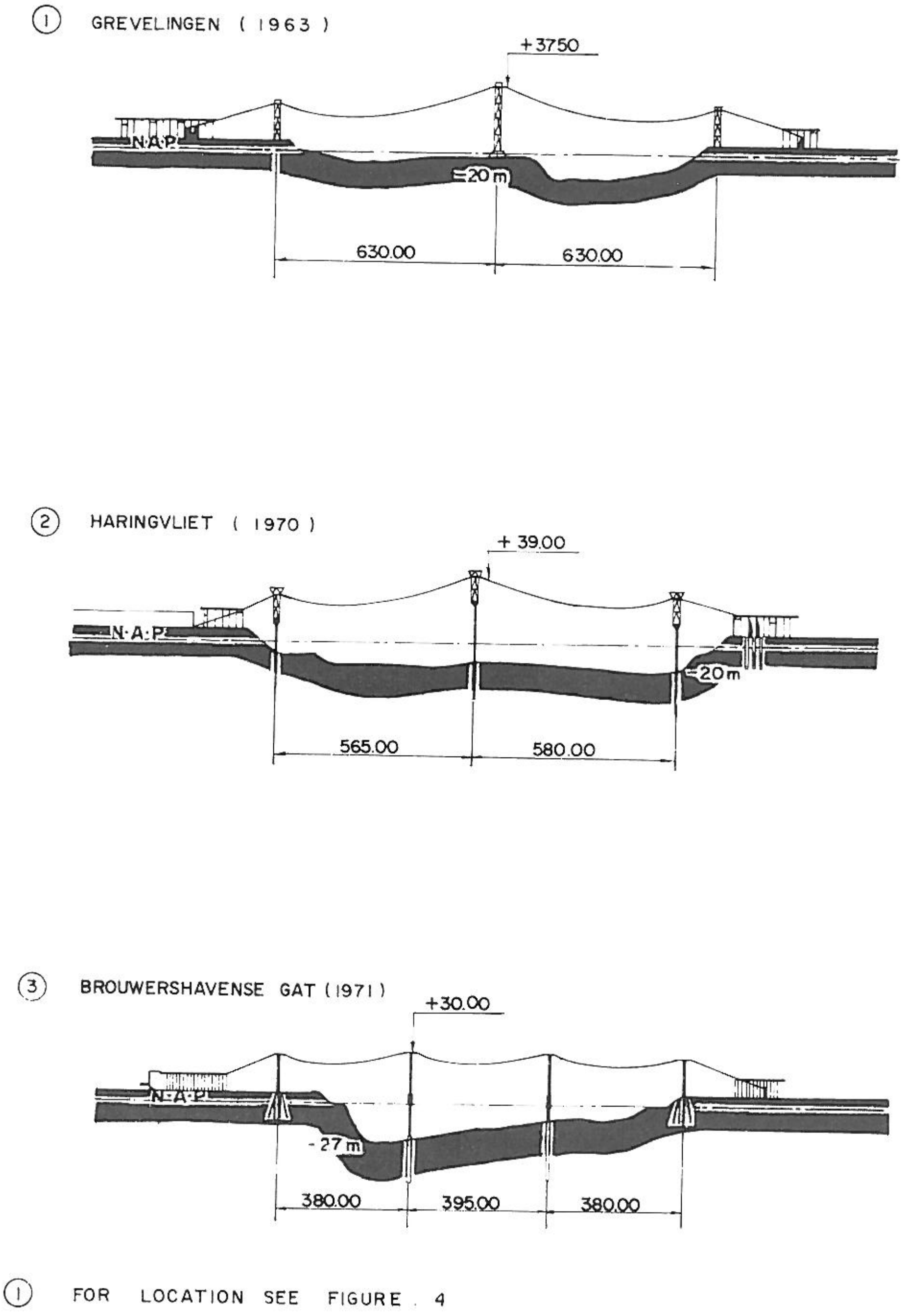


Fig. 8. Cable way closures.

TABLE III

Closing of Delta dams by means of cableways

Location (see Fig. 4)	Material	Pay load	Dead load	Dumping capacity*
Grevelingen (1)	rubble 60—30 kg	10 tons	20 tons	120 tons/h
Haringvliet (2)	4 concrete blocks of 2.5 tons per telpher	10 tons	20 tons	300 tons/h
Brouwershavense gat (3)	6 concrete blocks of 2.5 tons per telpher	15 tons	17 tons	1000 tons/h**

* Maximum capacities.
** Average weekly production 60,000—80,000 tons.

A second method of vertical closure, using helicopters, was tested. The main reason for considering this system is the possibility to use it as a back-up in case of a mishap with the cableway. A Sikorsky Sky Crane owned by the U.S. Army was used for carrying out tests. A total number of 8000 blocks of 2.5 tons were dropped. The tests were a success, a total weekly production of 20,000 tons per helicopter could be reached.

The third mentioned method of vertical closure is the use of a bridge. This method has been engineered as a possibility for closures to be carried out in the eighties. A temporary steel bridge used at this moment in the Delta area was specially designed to enable its use for a closure operation. Trucks are loaded at loading stations at both sides of the bridge. Average weekly productions are expected to vary between 50,000 and 80,000 tons.

The advantage of bridge and cableway closure methods is that they are less vulnerable to meteorological conditions than floating equipment and helicopters.

Horizontal closure methods

The basic principle of a horizontal closure is indicated in Fig. 6B. In the case that rubble or stiff clay is used, the method consists of building out from the sides in a simple way. An alternative to the above is a closure by means of sand pumping. Both methods have been used in the Netherlands. The Zuiderzee dike was constructed with the help of stiff boulder clay. The clay was handled by crane barges. Several sand closures have been carried out. The feasibility of the latter method is largely dependent on the availability of large production dredging equipment, the mean grain size of the sand and the maximum current velocities encountered in the last closure stage. Current velocities should not be greater than 2 to 2.5 m/sec.

Horizontal closure methods are only feasible for comparatively small size closures. This is illustrated in Fig. 7. As can be observed from this figure, the current velocities are increasing up to the final closure stage.

Combined closure methods

Two combined closure methods are illustrated in Fig. 6. The method indicated in Fig. 6C has been frequently used in the Republic of Korea. A sill is built up using floating equipment. As with the first stage in a vertical closure operation, either the maximum current velocities or the available depth are the limiting factors for the height of this sill. In general a situation of free overflow (see Fig. 7) at both maximum ebb and flood velocities is not reached by the vertical part of the combined closure method. This means that when the gap is closed from the sides, e.g. by dumping stone with trucks, a considerable narrowing of the gap is needed before a free overflow situation occurs under flood conditions. The latter may only occur during the final closure stage. Consequently large current velocities will have to be overcome. This leads to the necessity of large stone sizes. If the closure operation takes too long, large scour holes endangering the stability of the dam under construction may occur.

A second method of combined closure is illustrated in Fig. 6D. A sill is built up with rubble. After the sill is carefully profiled, concrete caissons* are placed at slack tide.

In emergency situations, e.g. after dike breaches, even ships have been used in the Netherlands. The feasibility of this closure method is largely dependent on anticipated scouring problems and on the duration of the slack-water period in which the last caisson has to be placed. Moreover, geotechnical stability considerations play an important role as will be discussed further on in this section.

In general, it may be concluded that both types of gradual closure discussed above have a limited applicability. It is for this reason that the large closures in the Delta project have been executed either as gradual vertical closures or as sudden closures, using sluice caissons. The sudden closure method will be discussed below.

The sudden closure

The sudden closure method can be subdivided into two methods: closing a gap in one operation by using a rigid caisson (see Fig. 9A) or using sluice caissons and closing the sluice gates after all caissons are emplaced (see Fig. 9, 10). The first-mentioned method is in fact a variant of the combined closure method. In this variant, one caisson is used. The first stage of a sud-

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*Not sluice caissons, but rigid concrete caissons are meant; as illustrated in Fig. 9A.

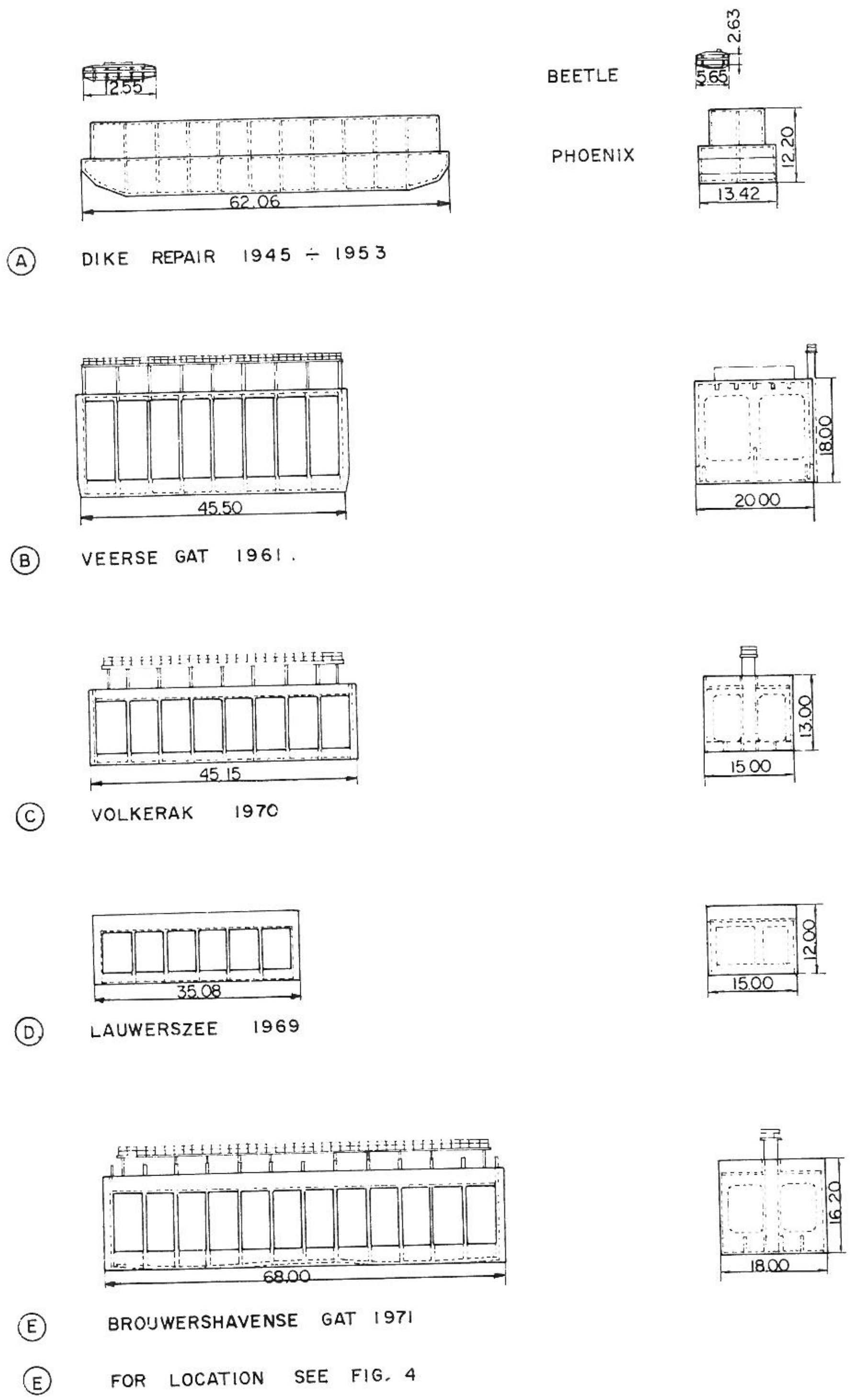


Fig. 9. Caisson closures.

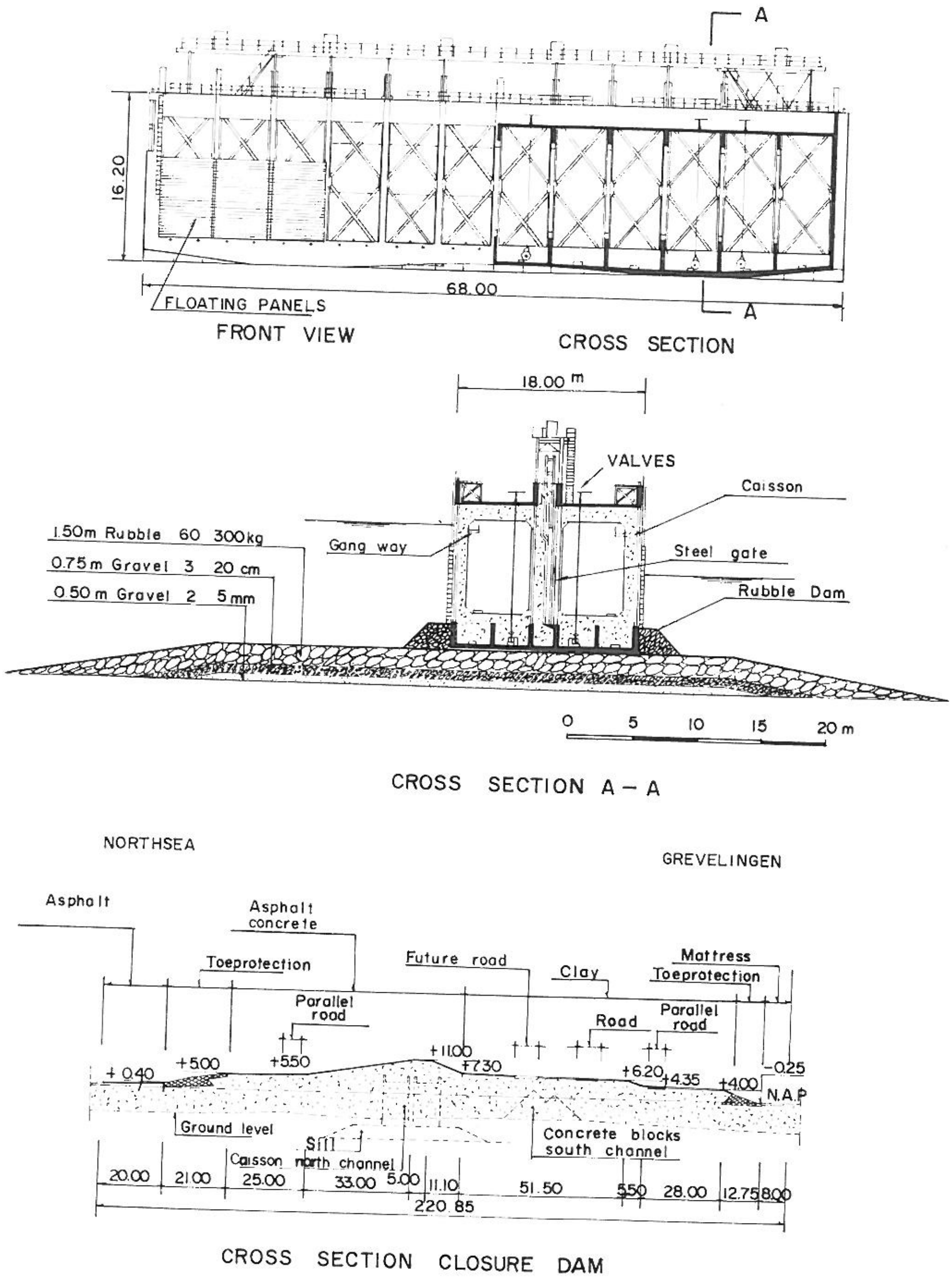


Fig. 10. Brouwershavense Gat sluice caisson.

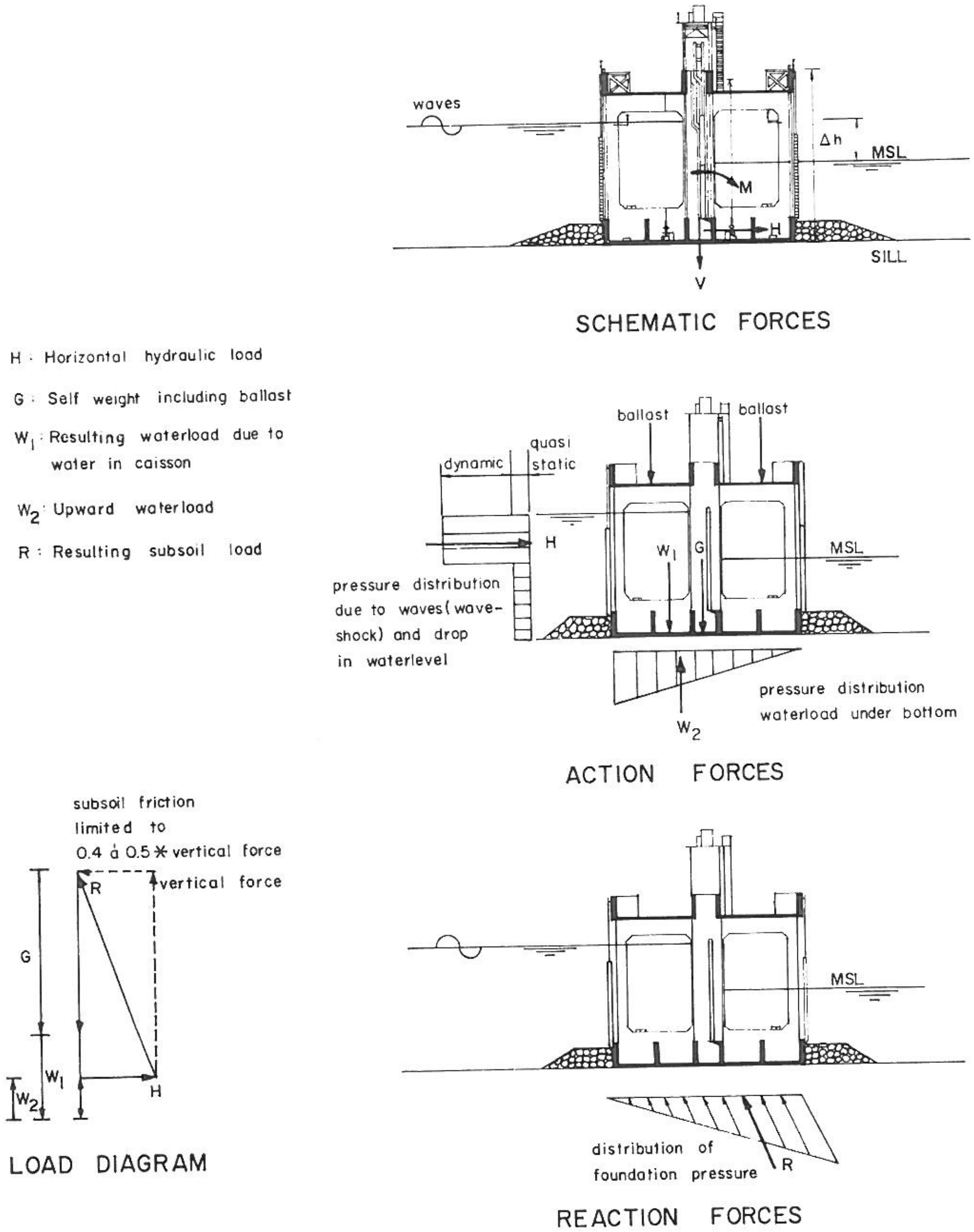


Fig. 11. Loads on a caisson after placing on a sill.

den closure with sluice caissons is the construction of a sill on the seabed protection, with the help of floating equipment. The sill has to be carefully flattened, e.g. with the help of a bucket dredger. During this first stage the sluice caissons are built in a construction dock. After completion of the caissons, the dock is inundated and the embankment of the dock is dredged away. The caissons are towed to the closure gap and carefully positioned at slack tide. The valves are opened and the caissons are sunk on the sill (see Fig. 10).

The floating panels are taken away, enabling the flow through the gap to pass the caissons. Directly afterwards, the caissons are ballasted, and a rubble dam is dumped at both sides of the caissons to reduce seepage and thus to prevent undermining (see Fig. 10).

The whole placing operation has to be very carefully prepared. The behaviour of the caissons under current and wave conditions and the duration of slack water periods is generally studied in hydraulic models. The data from these models are used to draft the plan of operations. In the Netherlands models were used to simulate every caisson placement in advance.

As mentioned above, the steel gates of all caissons are closed simultaneously after the last caisson is placed in the gap. The period after the actual closure and before the completion of the dam is a critical one. During this period the caisson is subjected to hydraulic loads from water level differences and from waves. A schematic picture of the action and reaction forces on a caisson is presented in Fig. 11.

Calculations have to be carried out to ascertain the stability of the caissons, especially under construction-phase storm conditions. The parameters for these calculations were in most cases not available and had to be obtained from large-scale model tests. The caisson's own weight plays an important role in the stability (see Fig. 11). However, this weight has to be limited due to draft and manoeuvrability.

Four major (sluice) caisson closures have been carried out in the Netherlands as shown in Fig. 9 and Fig. 4. Three of these took place in the Delta region. The scale enlargement is clearly illustrated in Fig. 9. In the Brouwershavense gat, 12 sluice caissons have been placed in the Northern closure dam. The width of the final gap was 900 m as illustrated in Fig. 4.

The choice between closure methods

The cableway method (gradual vertical closure) and the sluice caisson method (sudden closure) have both advantages and disadvantages.

An advantage of the sluice caisson method, compared to the cableway method, is the occurrence of smaller current velocities in the final stage, as is illustrated in Fig. 7. Consequently, scouring problems are less severe in the case of a sluice caisson closure, provided the sill is not too high and built quickly.

Disadvantages of a caisson closure are the stability risks and the sophisticated and vulnerable character of the closure operation. In relation to this, the flexibility of the operation is greater in the case of a cableway closure than for caisson closure. This is one of the reasons why the two methods were combined in the Brouwershavense gat, as is shown in Fig. 4.

SEABED PROTECTION

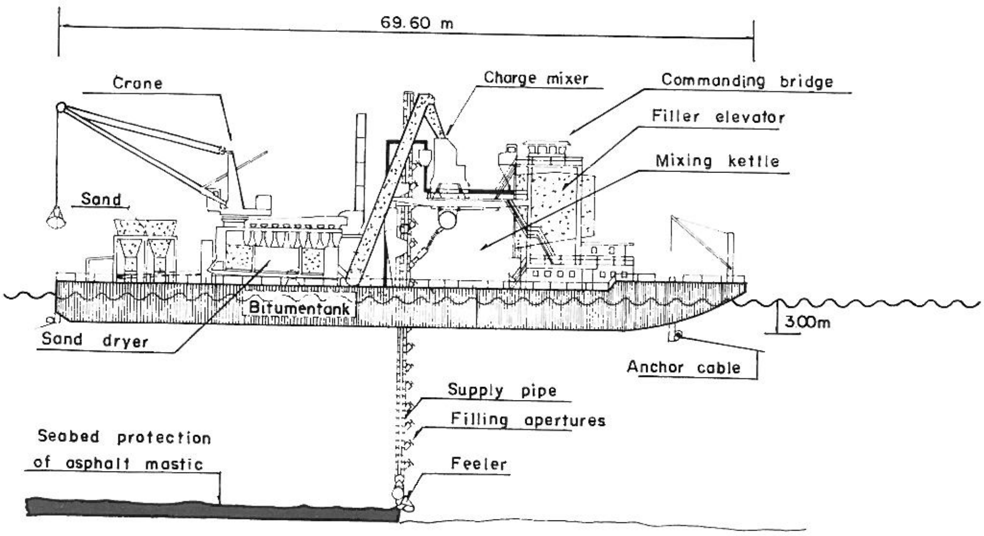
As mentioned earlier in this paper, the construction of seabed protection forms an important and integral part of every closure operation carried out on a base of erodable soil. The length of the seabed protection perpendicular to the closure dam alignment depends on the hydraulic conditions to be expected in relation with the closure method. These hydraulic conditions, together with the period in which they are present, the diameter of the bed material and the protection length determine the scourhole dimensions, which in turn determine the risk of instability of the closure dam. Methods have been developed in the Netherlands to calculate the scourhole dimensions as a function of the different parameters.

The choice of the protection length is based on these computations and physical model tests. Seabed protection lengths perpendicular to the closure dam alignment of around 300 to 400 m have been applied in the Netherlands. For the construction of the Storm Surge Barrier in the Eastern Scheldt, the closure piece of the Deltaplan, a maximum length of 1400 m has been applied. In this case the scouring is not temporary, as in closure operations, but permanent. The scale enlargement in the amount of seabed protection to be applied has led to new advanced techniques. Two of these techniques are illustrated in Fig. 12. Mastic asphalt, an impermeable protection, has been applied with the help of a specially designed vessel. This vessel is a floating mastic factory. The mastic flows through a vertical supply pipe. In fact, the system can be considered as a large underwater "Barber-Green" such as is used in road construction.

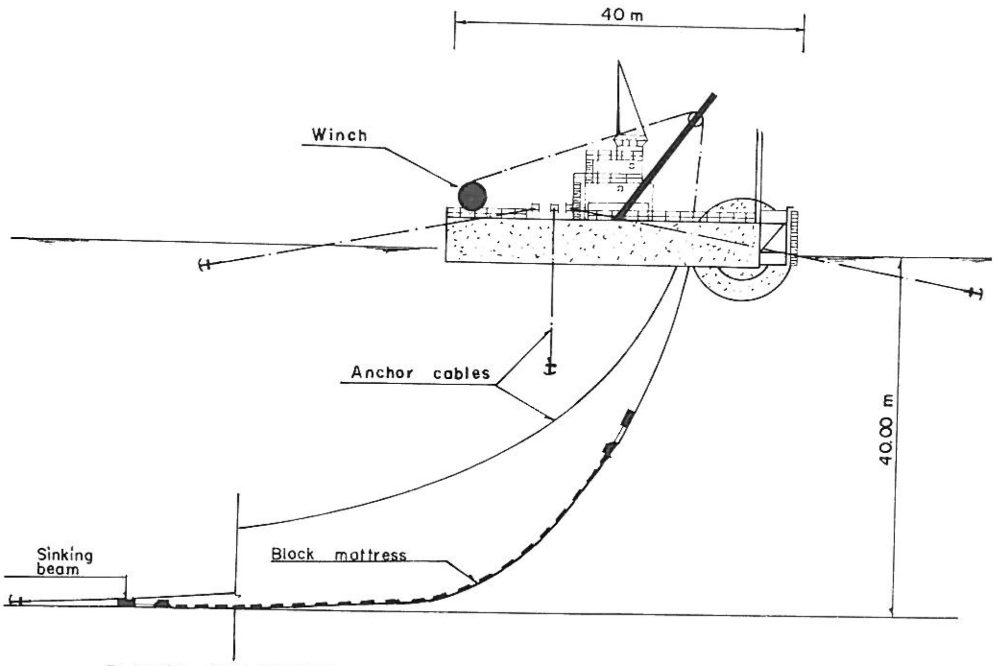
A second new method is the block mattress. A mattress with concrete blocks fixed on it is prepared in a factory and made up as a roll. The roll is then towed to a specially designed vessel and laid on the seabed as a carpet during slack tide. Some 4 km^2 of block mattresses have been laid. High productions can be reached with these two methods, and this was the main reason for developing them.

Figure 13 illustrates the total quantity of seabed protection produced in various years in the Netherlands and the cost of three types. The first type is the traditional willow mattress. The second type is a filter-cloth mattress with loose ballast. The third type is the fixed (concrete) ballast mattress as illustrated in Figure 12. As can be observed from Fig. 13, the costs of the latter become competitive in the case that quantities over 250,000 m^2 are used. For smaller quantities the initial investment costs per m^2 become too high.

As can be concluded from this section, scale enlargement has led to the development of new closure techniques. Traditional hydraulic engineering insight, although still playing an important role, has had to be gradually supplemented by a scientific approach. Model techniques played a predominant role in this development.



MASTIC ASPHALT VESSEL JAN HEIJMANS



BLOCK MATTRESS LAYING VESSEL DOS I

Fig. 12. Modern techniques for sea bed protection.

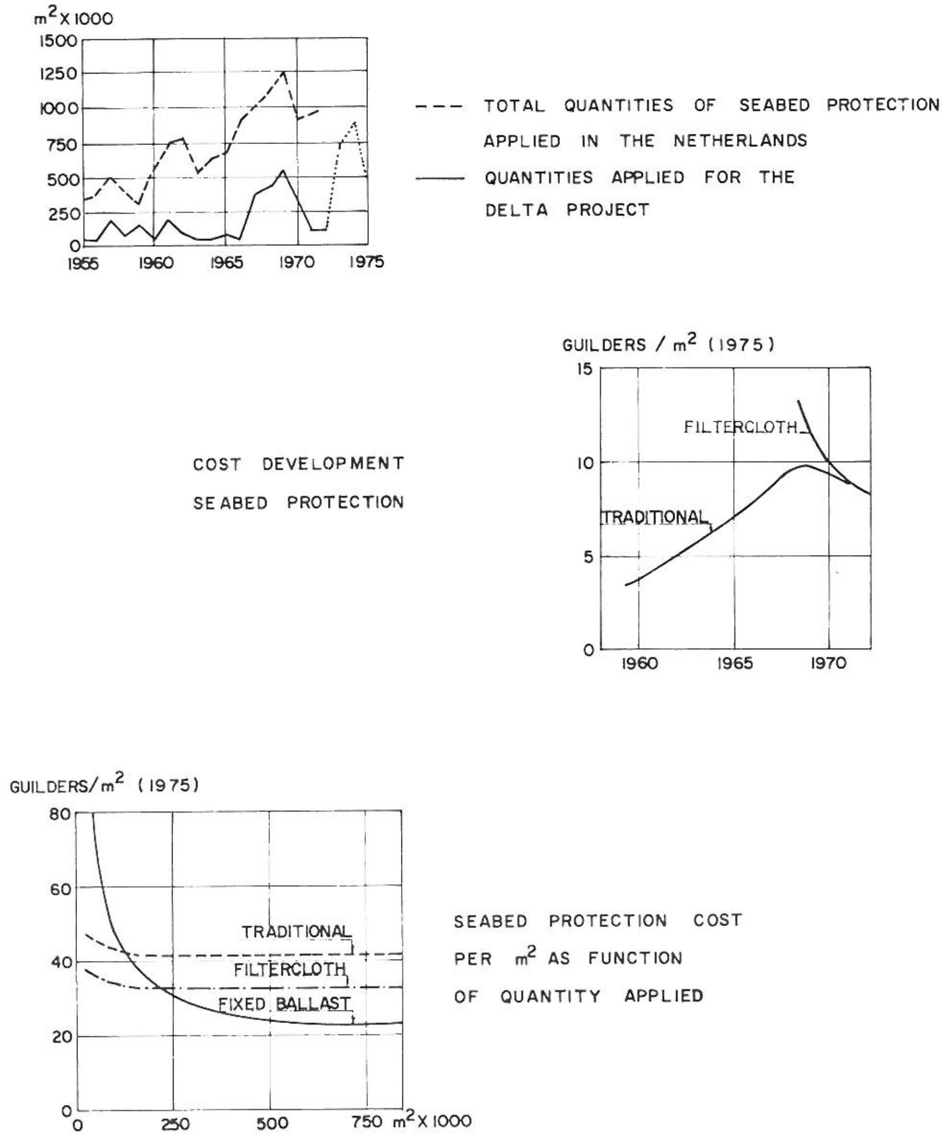


Fig. 13. Cost development of sea bed protection.

THE INCHEON BAY: A BRIEF STUDY

As an illustration of a large potential closure operation in the Republic of Korea, a case study has been briefly worked out. The location at the Incheon Bay (between Incheon and the Han river estuary, see Fig. 14) has been chosen because of its illustrative value. The case study is not related to any existing project.

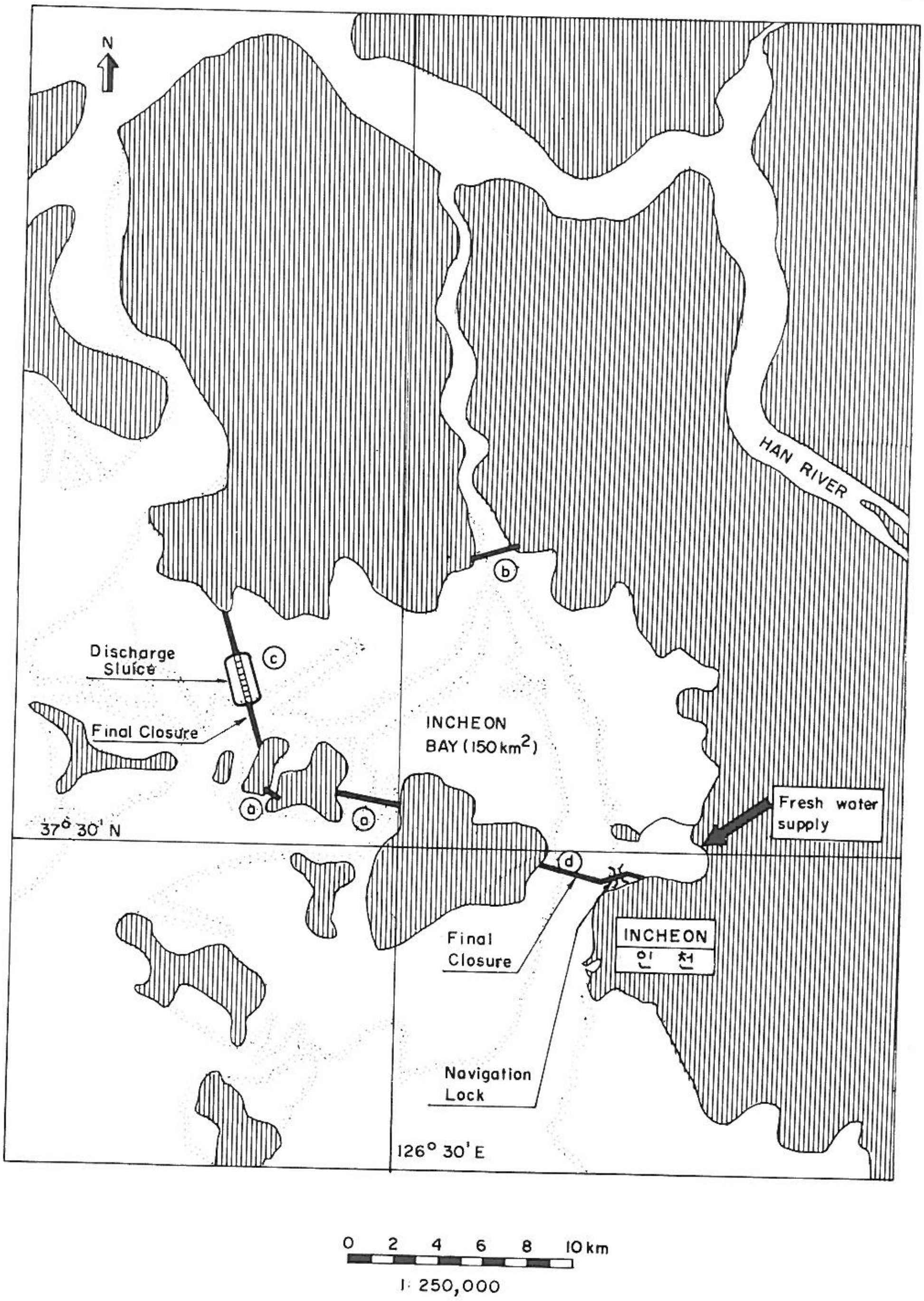


Fig. 14. Situation Incheon Bay.

As the main purpose of the studied project will be land reclamation, a sufficient supply of fresh water is necessary. This water might be conveyed through a canal connecting Incheon Bay with the Han river. The bay has a storage area of about 150 km^2 and is connected with the sea mainly at the west and southeast sides, the channels between the islands are of secondary importance. Furthermore, the bay is connected with the Han river at the north side.

The closure of Incheon Bay will thus require several dams as can be observed from Fig. 14:

(a) Small dams across the secondary channels between the southern islands.
(b) A closure dam in the channel to the Han river.
(c) A closure dam across the western bay entrance.
(d) A closure dam across the main southern inlet near Incheon.

If the dams a and b are built first, the bay will be connected to the sea at the west and the south side through two main inlets. Consequently, the total discharge will be divided over the two inlets. The boundary between the influence of the two tidal inlets will be situated around the middle of the bay.

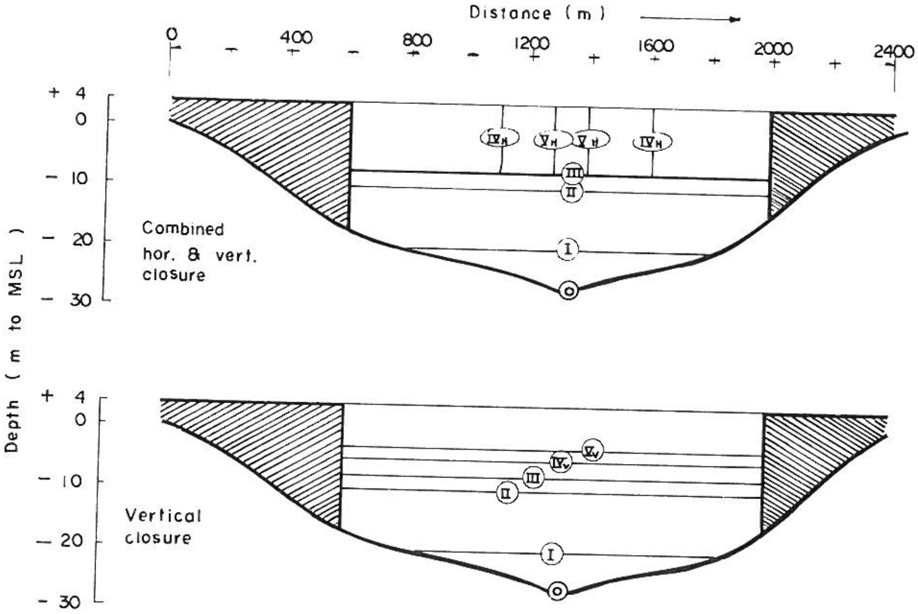
If the closure dams c and d were built one after the other, the total bay would have to be filled and emptied through the last tidal inlet. This situation would lead to a very difficult closure of this last inlet. Moreover the local and overall morphology in the bay would be seriously affected. The closure of both inlets will thus have to be carried out simultaneously and this is therefore assumed in the case study.

Because of its larger dimensions, the closure of the Southern channel near Incheon is considered in this case study. It is assumed that a storage area of about 90 km^2 (mean between high and low water) is connected with the Southern channel. In order to calculate the flow velocities in the closure gap during various closure stages, a very rough mathematical model was prepared. The model is of a so-called basin storage type and does not take into account horizontal water level gradients in the basin.

Assuming a spring tidal range of 8 m, some closure stages with a gradual vertical closure method as well as with a combination of a vertical and a horizontal closure method were reproduced in this model. Although this method might perhaps be feasible, the closure by means of caissons was not considered in this case study because of its complexity.

Fig. 15 gives the maximum ebb and flood velocities resulting from the model computations as a function of the remaining opening (percentage of the original cross section). This figure is of course comparable with Fig. 7, although the maximum velocities in Fig. 15 are much larger than in Fig. 7 because of the larger tidal range. It should be observed that only spring tidal conditions have been considered.

In the case of a vertical closure method, the maximum (flood) velocity will be about 6.5 m/s (in stage $\mathrm{IV_v}$) after that, the velocities will decrease quickly (stage V_v), due to the occurrence of a free overflow situation at ebb and flood conditions.



Closure method	Closure stage	Gap width (m)	Sill level (m to MSL)	% of original section (36500 m^2)
All Methods	O	2400	–	100 %
	I	1400	-20	77 %
	II	1400	-10	38 %
	III	1400	-7.5	29 %
Combined Horizontal & vertical	IV_H	500	-7.5	10 %
	V_H	100	-7.5	2 %
Vertical	IV_V	1400	-5	19 %
	V_V	1400	-3	12 %

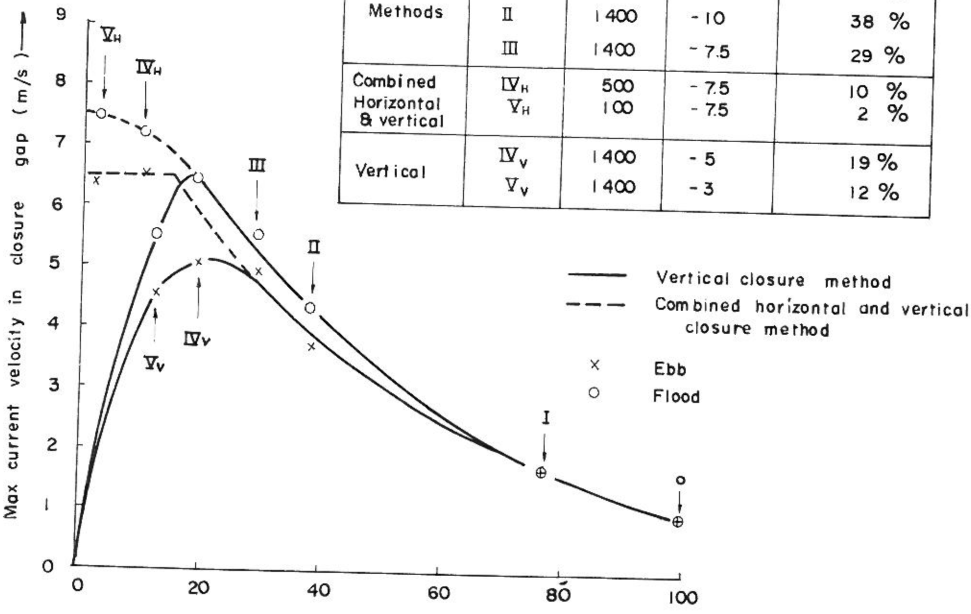


Fig. 15. Current velocities as a function of the closure gap.

In the case of a horizontal closure method in the final closure stages, the ebb velocities remain limited to 6.5 m/s because of the occurrence of free overflow. The flood velocities, however, increase continuously until the closure of the final gap and reach values of about 7.5 m/s (stage V_H).

The two main problems which are connected with the occurrence of these high current velocities are:

(a) the need for very large stones in order to ensure stability in the closure gap. These stones are rather difficult to handle and a long closure time will be the consequence.

(b) the scouring depth at the upstream and downstream sides of the seabed protection might be very large. This endangers the stability of the whole structure, especially when the closure operations take a long time.

A very rough estimate of the required stone sizes, together with an estimate of the duration of each closure stage, is presented in Table IV. Wave action is not taken into account.

The main difference in stone sizes between the two methods is found in stage V. It appears furthermore that the closure with a cableway is much

TABLE IV

Required stone sizes and estimated time schedule

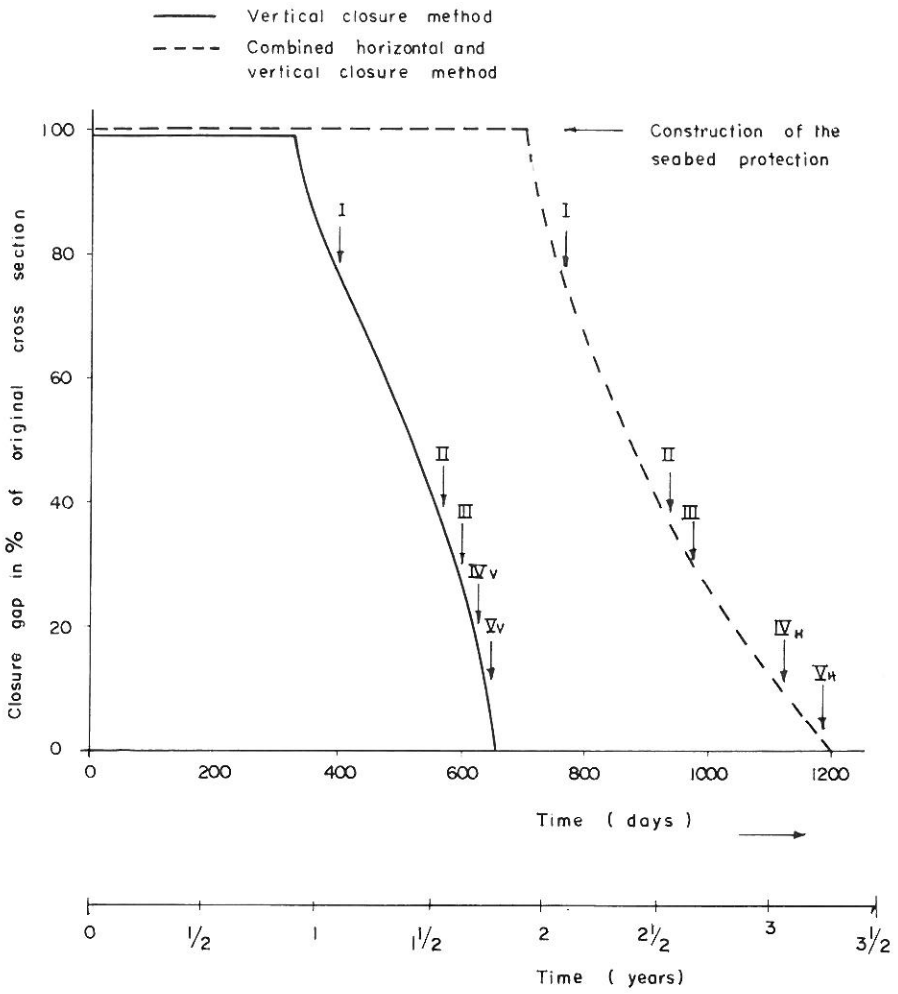
Closure method	Closure stage	Stone size (kg)	Closing equipment	Closure duration (days)
all	I	40	barges	40
methods	II	150	(5000 m^3/day)	180
	III	500		35
combined	IV_H	2000	trucks	145
horizontal	V_H	3500	(2000 m^3/day)	65
and vertical				
vertical	IV_v	2000	cableway	18
	V_v	500	(6000 m^3/day)	55

* Duration until the mentioned stage.

quicker than with trucks. The total duration of the closure operation appears to be about 140 days (43%) longer in the case of a combined horizontal and vertical closure operation.

As mentioned before, a long closing time may be very dangerous with respect to the scouring process on both sides of the seabed protection. The latter has been assumed to have a length of 200 m on each side of the toe of the dam. This implies that more than 700,000 m^2 of seabed protection have to be placed at depths of up to about 30 m before the start of the closure operation. For this kind of huge surfaces, special techniques have to be developed (see preceeding section).

Although in the present case the scouring problems will probably be very



Note : This time schedule does not include preparatory works such as construction of cableway, etc. ----

Fig. 16. Time schedule of closure operations.

limited because of the rocky seabed, some calculations have been carried out for the case of an erodable sandy seabed.

Using the Table IV time schedule in combination with the velocities presented in Fig. 15, the maximum scouring depths at the end of the closure operation have been computed. It appeared that the maximum scouring depth in the case of a combined horizontal and vertical closure was twice the depth reached in the case of a vertical closure. The reason for this large difference is to be found mainly in the relatively long time needed in stage IV_H (Table IV). An increase of the seabed protection length from 200 to some 600 m would be needed in order to reduce the scouring depths to the same (acceptable) values as in the case of a vertical closure method. This obviously requires a very long and expensive operation (see Fig. 16).

A comparison of the time schedule for the two closing methods is shown in Fig. 16. It may be noted that the vertical closure is accelerating in the final stages, while the combined closure is slowing down. This proved to be a very important issue for the scouring process downstream of the seabed protection.

Concluding, it may be said that in the considered case, mainly because of the rocky seabed, a combined closure operation will lie around the limit of feasibility. If a similar closure should be considered on an alluvial, erodable seabed, huge amounts of seabed protection would have to be laid. The execution time of a combined closure operation would be very long and would involve considerable stability risks for the dam.

Vertical closure methods, like the cableway discussed, in combination with large-scale seabed protection production and laying methods, can be introduced. This would enable a safe execution of even larger scale closures than the ones already undertaken in the Republic of Korea.

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