Closure works

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Cover photo: Closing of the Saemangeum estuary, Korea (Maartje van der Sande/TU Delft).

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1. Introduction

For this book we have deliberately chosen that the text should follow a more or less logical design procedure for closure dams. It is emphasized that only the construction aspect of stopping the water movement is considered in this book. This means that only the closing operation itself is treated; the transformation of the closing dam into a permanent structure like an embankment is beyond the scope of this book.

It is expected that the reader possesses basic knowledge of hydraulic engineering. Only in some cases, where they are deemed useful for a proper understanding of the actual design process, are aspects of basic hydraulic engineering presented. For more background info on the interaction between water and bed protections is referred to SCHIERECK, G.J. [2001].

This book is an educational textbook, not a design manual or a reference book. Part of this book is based on a lecture note by VAN ROODE [1994].The focus of this book is the understanding of the basic principles. It is not an overview of all existing formulas pertaining to closure dam design. Also, because the results of new research will modify existing formulas, it is not useful to focus on the minute details of such formulas, but more on the physical concepts behind the formulas. For a reference book describing all aspects related to closure works is referred to HUIS IN 'T VELD, *ET AL*. [1984].

2. Positioning the subject

In this chapter the subject "closure works" is positioned. It is related to other works, the different types are explained and a historical overview of the subject is given.

2.1 General aspects

Closure dams are constructed for a variety of very different purposes; such as the creation of a separate tidal basin for power generation or as sea defence structures to increase safety. Compared to closure works, few other engineering works have such an extensive impact on the environment in all aspects. For instance, the main purpose of the construction of the Afsluitdijk closure dam in the Netherlands was to provide protection against high storm surge levels and to facilitate land reclamation. Additional advantages were fresh water conservation and a road connection between the provinces of Holland and Friesland. The purpose of a closure dam may be one or more of such objectives, but these are automatically accompanied by other side effects, some of which may be negative. A thorough study of these impacts is part of the design process. A feasibility study that does not detail and forecast the negative aspects of the closure works is incomplete and valueless. These partly unforeseen negative effects for the Afsluitdijk include: the drastic change in tidal amplitude in the Waddenzee, consequential impact on the morphological equilibrium of the tidal flats and channel system, the social impact on life and employment in the bordering cities, the influence on drainage and the ground water table in the surrounding land areas, the changes to the fisheries industry, and effects on flora and fauna.

Non-technical aspects, including environmental, social and cultural values, cannot be expressed in financial terms. The evaluation of such considerations is not within the scope of this book. Nevertheless, engineers must identify the consequential effects to the best of their ability and present them in such a way that they are understood by decision-makers.

This book focuses on the technical aspects of the construction of a closure dam in a variety of circumstances. Every closure operation is a struggle against nature. Every action taken to obstruct the water flow will immediately be counteracted by nature itself. The knowledge gained from experience, whether successful or not, is supplemented by the results of advanced research and experiment. Nevertheless, the changes in conditions during the progression of the closure are sometimes difficult to predict. Allowing for flexibility in operations that are incorporated in the design provides an important tool.

2.2 Functions of a closure work

There are three main categories of closure works:

- closure of tidal inlets, estuaries, etc.
- closing works in rivers, mainly to create diversion dams
- closing of existing dikes around low lying land, usually after a breach in such a dike

It is good to mention that the construction of reservoir dams is not a part of this course on closure works. There could be many functions of closure works. Sometimes a combination of several functions is present. Functions of closure works could be:

Land reclamation

An example of such a closure is the Afsluitdijk in the Netherlands. The dam creating a non-tidal lake, not influenced by storm surges where the creation of reclamation works was relatively easy. Also in Korea this was often the main driver for closure works.

Photo: Saemangeum dam, SGFEZ Authority

Shortening of the length of a sea defence

After the storm surge disaster of 1953 it was decided in the Netherlands to close off a number of estuaries and inlets. The main reason was that in this way the length of the sea defence could be reduced with several hundreds of kilometres. This decreased the maintenance effort considerably. Also the closure of the Feni river in Bangladesh is an example of such a closure.

Photo: Brouwersdam, Netherlands, beeldbank Rijkswaterstaat

Creating a fresh water reservoir

In many locations in the world there is during the dry season a shortage of fresh water. Often a tidal inlet is present and can be used. The Duriangkang reservoir on Batam island (Indonesia, near Singapore) is an example. But this was also one of the major reasons for the closure works in Korea.

Photo: Duriangkang reservoir dam, T. Palgunadi, Panoramio

Creation of a tidal energy basin

The dam through the Rance estuary in France was constructed for this purpose. But also the closure dam of the Siwha estuary just south of Seoul in Korea is a dam for the creation of tidal power[1].

Photo: La Rance tidal basin "Barrage de la Rance" by Tswgb/Wikipedia

Creation of a fixed-level harbour basin

An example of this is the navigational fairway from Antwerp to Rotterdam (Schelde-Rijn verbinding). The Oesterdam has been constructed especially for this function.

Photo: Oesterdam, Beeldbank Rijkswaterstaat

[1] Originally this dam was created for reclamation and as a freshwater reservoir. However managing the lake as a freshwater reservoir proved impossible, and later the reservoir was converted to a tidal power reservoir.

Creation of a construction dock
In order to build large structures in the middle of a large waterbody a dry hare has to be created. An example of this is the building dock for the construction of the Haringvliet sluices.

Photo: Haringvliet sluices under construction, postcard

Providing a road or railroad
In Germany the connection from the mainland the island of Sylt is an example. In the Netherlands the railroad from Brabant to the city of Middelburg had to cross two tidal channels (Sloe and Schelde); these channels were closed with a closure dam

Photo: Hindenburgdam in the sixties, from a German postcard

Repair a dike breach
After the storm surge of 1953 many dikes in the Netherlands were breached. Especially in the tidal area closing is a complicated job. But also non-tidal breaches in rivers are sometimes a problem, especially when the surrounding land is lower than the normal water level in the river. This was for example the case during the floods of Yangtze river in 1998.

Photo: closure of the Schelphoek-breach in 1953, KLM-Aerocarto

Control of upland flow
In many places river water has to be diverted to other locations. This can be achieved by closing part of the existing river and divert the water into a new channel. In fact such a diversion work is also a closure work. In the Rock Manual the diversion dam near Kainji is discussed in detail.
Photo: Granite Reef Diversion Dam, US Bureau of Reclamation

Creating fish ponds
These are relatively small closure works, so usually these closures can be executed without any special preparations.
Photo: fish pond, Nau Wale No, Hawaii

Cutting of river bend
Because of the meandering effect of rivers the total length of a river my increase considerably. This has quite some drawback on river discharge, river management and navigation. A shortcut through the meander is then often a good solution, but his also means that the remaining meander has to be closed.
Photo: cutting off river meander in the Maas river, the Netherlands, photo KLM

All closure works have side effects. Side effects may be negative or positive. Sometimes it is difficult to determine why a specific effect is termed a side effect and in historic cases it has turned out that what were initially side effects became important aspects of the situation that was created. This is especially the case with positive side effects. For example, one of the secondary purposes of the Grevelingen reservoir in the Netherlands was the creation of a fresh water basin for irrigation purposes. However, it proved that maintaining a good quality of fresh water in a relatively deep lake was quite difficult, and also it was found that a (non-tidal) salt water environment has a very high ecological value. Based on this the original idea of creating a freshwater lake was abandoned and ancillary works have been built to maintain a good quality salt water system (exchange sluices).

2.3 Side effects

Various possible side-effects could be (dependent on circumstances):

- change of tide (amplitude, flows) at the seaward side of the dam
- change in bar and gully topography, outside the dam
- disappearance of tides on the inner side of the dam
- change in groundwater level in adjoining areas
- alteration of drainage capacity for adjoining areas
- loss of fish and vegetation species
- loss of breeding and feeding areas for water birds
- rotting processes during change in vegetation and fauna
- stratification of water quality in stagnant reservoir
- accumulation of sediments in the reservoir
- impact on facilities for shipping
- impact on recreation and leisure pursuits
- change in professional occupation (fishery, navigation)
- social and cultural impacts

In the past, watercourses were mainly closed for the purposes of land reclamation and controlling the water levels on marshy land. In both cases this was linked to agricultural development. It is typical of these damming activities that the control of river and storm surge levels becomes essential. Follow-up action, like the repair of dike breaches and sometimes the cutting off of river bends has been necessary throughout the ages. The other purposes mentioned, like generation of tidal energy, harbour and construction docks, dams for road or rail connection and fish ponds are incidental works and have a smaller impact on the surroundings. Today, since the quality of life is becoming an important aspect for society, certainly in the industrially developed countries, damming activities are initiated to serve various other purposes. These include the creation of fresh water storage basins, the prevention of water pollution in designated areas, the provision of recreational facilities and the counteraction of salt intrusion or groundwater flow.

Depending on the circumstances, there will always be a number of side effects. These are sometimes temporary, but sometimes generate long-term developments that are difficult or impossible to predict with any degree of accuracy. The above list gives an indication of possible effects but does not pretend to be complete.

Worldwide there is at this moment quite some opposition against closure works. The main reason is the fear of a change in the environment, based on the axiom that the present situation is ecologically the best system. This opposition is comparable to the opposition against hydropower dams.

Therefore it is essential that the effects of closure works are studied in depth before starting the works. In this course this aspect is not worked out.

2.4 Types of closure dams

Several names have been adopted to distinguish various types of closure operations. The names used may refer to different aspects. However, the adoption of names has been random rather than systematic. Some names are typically Dutch and there may be no literal English translation.

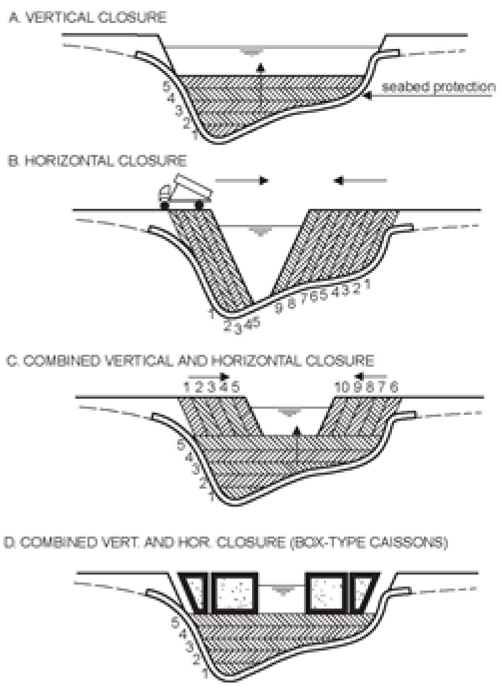

Figure 2.1 Basic methods of closure

A main distinction can be made according to the construction method. This is illustrated in Figure 2.1.

The construction method is related to the equipment used, which is either land-based or water-borne[1]. This leads to a distinction between horizontal closure or vertical closure and the possible combination of these two methods. Using large structures (caissons) is a type of horizontal closure with very large units. Figure 2.1 illustrates these methods.

[1] In very exceptional cases helicopters are used

Closure Works

There are two basic methods of closure:

- Gradual Closure
  Relatively small sized, flow resistant material is progressively deposited in small quantities into the flow until complete blockage is attained. This can be used for either a vertical, horizontal, or a combined closure:
  - Horizontal (gradual) closure: sideways narrowing of the closure gap.
  - Vertical (gradual) closure: consecutive horizontal layers closing the gap.
  - Combined vertical and horizontal closure: a sill is first constructed, on which sideways narrowing takes place.
- Sudden Closure
  Blocking of the flow in a single operation by using pre-installed flap gates or sliding gates or by the placing of a caisson or vessel

Methods of closure may also be distinguished according to:

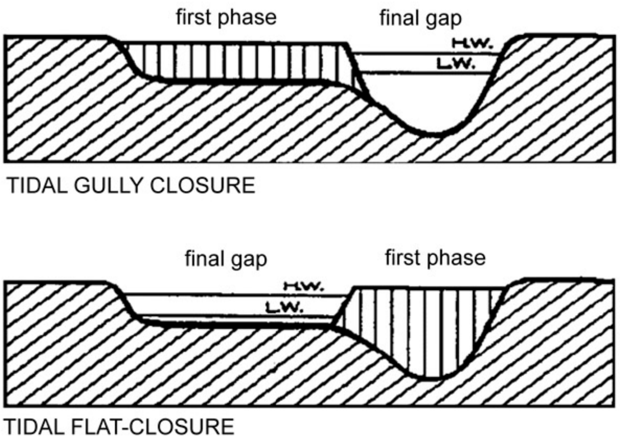

Figure 2.2 Closure named after topography

The *topography* of the gap to be closed, as is illustrated in Figure 2.2:

- Tidal gully closure [stroomgat-sluiting]: closure of a deeply scoured channel in which high flow-velocities may occur.
- Tidal-flat closure [maaiveld-sluiting]: closure across a shallow area that is generally dry at low water. This is characterized by critical flow at certain tide-levels.
- Reservoir dam (beyond the scope of this book): used in mountainous areas; this requires temporary diversion of the flow in order to obtain solid foundation in the riverbed at bedrock level.

The hydrologic conditions that determine the type of closure (see Figure 2.3):

- Tidal-basin closure: characterized by regularly changing flow directions and still water in between; mainly determined by the tidal volumes and the storage capacity of the enclosed basin.
- Partial tidal closure: a closure in a system of watercourses, such that after closure there is still a variation in water-level at both sides of the closure dam.
- River closure (non-tidal): closure determined by upland discharge characteristics and backwater curves.

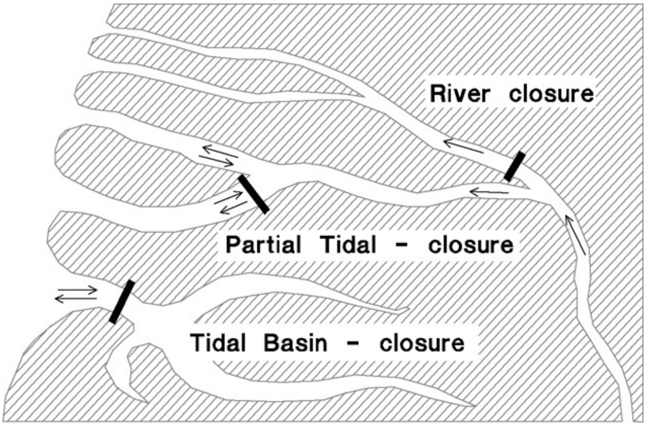

Figure 2.3 Closures named after hydrologic conditions

The *materials used*, which may vary according to the method of closure:

- Stacking-up mattresses: Closure realized by successively dropping mattresses (made of willow or bamboo faggots, ballasted by clay or cobbles) onto each other.
- Sand closure: Closure realized by pumping sand at a very high rate of production.
- Clay or boulder-clay closure: Lumps of flow-resistant clay.
- Stone-dam closure: Closure realized by dumping rock, boulders or concrete blocks in the gap, either by using dump-barges and floating cranes, or by cableway.
- Caisson closure: Closure by using large concrete structures or vessels, floated into position and then sunken in the gap (possibly provided with sluice gates).

Special circumstances leading to typical closure types:

- Emergency closure is characterized by improvisation. The basic idea is that quick closure, even at the high risk of failure, prevents escalation of conditions. The method is mainly used for closing dike breaches quickly which may require strengthening afterward.

- Temporary closure is used to influence the conditions elsewhere; for instance, by stepwise reduction of the dimensions of the basin. This type of closure needs to be sufficiently strong during the required period but is easily removable afterward.

2.5 Some other aspects

For closure dams, there are a few main directions the designer can follow. The first one is the choice between basic methods, the second one is the optimal use of the natural conditions and boundary conditions and the third concerns the selection of materials and equipment. There is no single prescription suitable for all closures because there are too many variables and boundary conditions. The unequivocal case is that of a well-defined tidal basin with a single closure gap of uniform dimensions. In practice, the situation is frequently more complex. Sometimes special conditions may so strongly determine a case that they either restrict or offer possibilities. Five typical examples of such criteria are detailed below:

1. The area of the basin can be easily subdivided into separate compartments

In essence, this is a matter of cost. Subdividing the area diminishes the storage capacity of the individual areas. Each closure can therefore be a lot easier, probably permitting the use of locally available materials so the total cost of these small-sized closures may be less than the cost of a single closure of the total area. However, additional costs may be incurred in the construction of the embankments separating the compartments.

Because of the later use of the area, the embankments may have to be removed. Sometimes, re-use of materials is a possibility, but some of the material is certainly lost. Depending on the layout of the area, subdivision can be designed in two ways. An elongated basin with a single channel can be taken in successive sections, while a complex channel pattern may require the successive closure of adjacent sections.

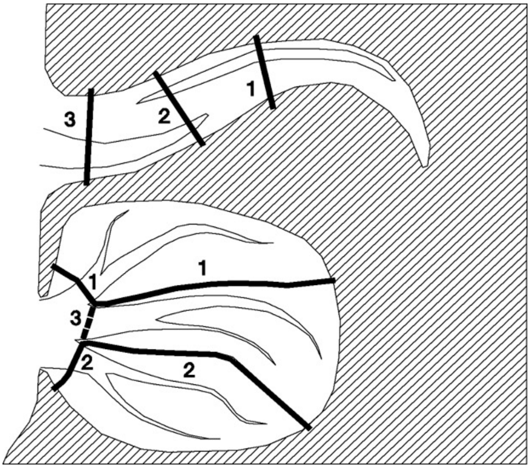

Figure 2.4 Two ways to reduce the area of a basin

2. The basin is penetrated by tide via two separate entrances

Closure of the basin means closure of both entrances, with the option to close either one first or to close both simultaneously by any combination of methods, materials and phasing. All actions in one entrance will certainly affect the conditions in the other entrance and the balance between the two may be quite sensitive. In the case of a major imbalance, the tide conditions in the entire basin will also be affected and this will lead to changes in flow and subsequent erosion at several locations.

In such a case, a mathematical hydraulic model may be complex and difficult to calibrate. The problem is that somewhere in the basin the tidal waves will meet. Since these waves have a different history, their shapes, phases and amplitudes are not exactly the same. Nevertheless, generally a tidal divide (in Dutch called "wantij") is characterized by low flow velocities and an unusual relation between water level and flow.

The difficulty is how to estimate the correct Chézy-value for the gully system in this meeting area. For the existing situation, a wide range of values used in the mathematical model may give acceptable results and thus calibration gives no clue. However, as soon as the tide changes owing to the progress of the closure works and the meeting area moves, the unchecked value may be very important. Calculations with various assumed values will at least show the possible impact on the conditions.

For simultaneous closure, the impact of every combination of construction phases on the tide penetration has to be determined. As for a single closure, this is done by calculating with weir formulae. In these several schematic simplifications and practical coefficients are used. The resulting deviation has little impact on a single closure but for a dual system the balance may soon become unstable. Therefore, closure plans must allow for these deviations.

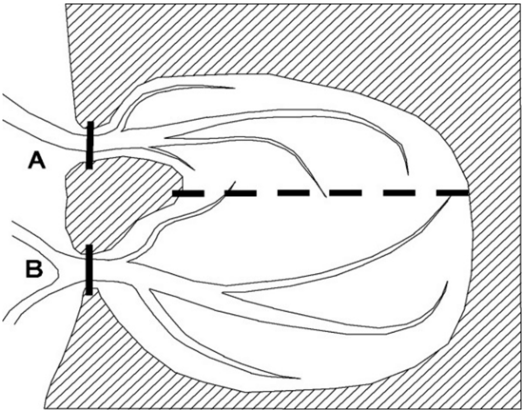

Figure 2.5 A basin with two entrances

Even in the case of a very well thought-out plan of concurrent closure methods, a setback in the execution of one, also affects the other. Moreover, a major failure in one closure may lead to a complete disaster, as the other one has to be dismantled to maintain the balance of the basin.

The easiest way to overcome the problem is to make a temporary or permanent closure dam across the meeting point, which separates the two tidal systems and divides the basin into two compartments. Then, the two primary closures of the basin area are fully independent. The mathematics is more simple and reliable. The closure design for each one is independent of the other, as is the execution. Constructing the separating dam is a partial closure and frequently an obvious solution. However, in some cases this may not be allowed, for instance because it blocks a navigation route.

Another method is to plan to close the two entrances one after the other. The order of activities then is:

- fix the bottom topography of entrance "A" by protecting bottom and shores against future scour.
- close the entrance "B" by any closure method and accept the change in tide and conditions in the basin as well as in entrance "A".
- next, close the entrance "A".

The advantage is that the closures are independent in design, method and execution. The uncertainty about the response of the basin to the imbalance after the first closure has to be covered. This can be done by assuming that deep gullies scour across the meeting area and by taking the whole basin as a storage area for the tide calculations for the second closure. Compared with the closures for separated basins, the closure "B" may be easier because "A" is still an open entrance. However, "A" with the full basin behind the gap will be much more comprehensive.

It might have been possible to stabilize the meeting area and prevent the erosion of deep gullies. Then, the flow velocities would have increased but the topography would have remained intact. However, the cost involved in such erosion prevention will generally be higher than that of providing a temporary partial-closure dam to fully separate the systems.

3. The closure profile consists of two (or more) main gullies and shallows

Between the main gullies there will be an area of tidal flats. These more or less separate the gullies during the low water periods. During rising and falling tides, on the one hand they are storage areas and on the other hand they ensure balance between the gullies. Although not considered a tidal meeting, this has a lot in common with such a meeting. For this case too, the first problem for the designer is to prepare the mathematical model. Tide penetration is calculated by adopting a gully network, while tidal flats are assumed to provide a storage area only. However, imbalance creates flow, which results in erosion and the development of a gully across the shallow area.

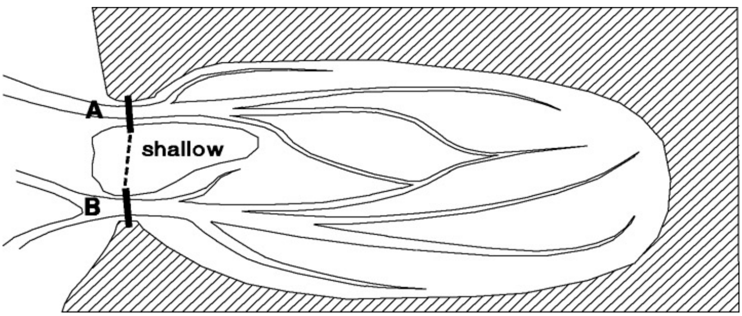

Figure 2.6 An estuary with two channels

How quickly will that occur, how deep will this gully be and what will be the Chézy roughness? Separating the systems by dividing the basin is not logical as both gullies run into the same main storage area. Therefore, after construction of the dam-section across the shallow, the only possibilities remaining are:

- to close the two gullies simultaneously in a very balanced way.
- to close one gully first, accept or prevent erosion across the tidal flat and then close the other gap, taking into account a fully adapted situation.

In the second case, it is most likely that the dam section across the tidal flat will be built before the closure of the first gully. Since the main gullies are relatively close to this, the erosion of the short cut across the tidal flat will most likely develop along this section of the dam. Thus, the toe of this dam has to be heavily protected. In addition, flow conditions in the remaining gap will be very adversely affected. A better solution may be to create a short cut by dredging at an appropriate location to guide the tide towards the last gap.

4. The gap to be closed is not in an equilibrium state

This situation occurs in the case of a calamitous breach of a dam or dike. It may also happen when a construction phase goes wrong and creates unexpected conditions at the site of the gap. In these cases, time is a very important factor. Every day natural processes will try to achieve the equilibrium state and change the existing situation.

A first consideration is to analyse how quickly definite measures can be taken. Over this period, the situation will adapt and the magnitude of the change has to be estimated in order to plan the right measures. If this change is undesirable, temporary measures to halt or retard the deterioration can be considered. Such temporary measures include:

- stabilizing the attacked bottom of the gap by dropping coarse material. Stabilizing the sides of the gap is easier but may induce deeper scour. Generally, deeper scouring is worse than wider scouring.
- trying to avoid the erosion of gullies in the storage area, for instance by protecting critical spots with mats or quarry stone. A more developed gully network will result in easier penetration of the tide and increase the tidal volume.

In the meantime, data on the existing conditions can be measured and recorded, while a definite closure strategy is being drafted.

Usually, the existing situation has to be determined and secured before any construction phase can start. In some cases, such as calamities where life is endangered, a direct counter-attack is justified. The risk in such a case is that if the action fails, the situation is usually much worse than it was before the action. If an emergency closure cannot be obtained in a few days, certainty is more important than speed.

An example of a successful emergency closure was the blocking of the dike breach near Ouderkerk aan den IJssel (Holland) during the major storm flood in February 1953. A relatively small breach cut the dike, which secured a vast, densely populated area of Holland, north of Rotterdam. Several hours later on the same night, a small vessel was taken and put onto the remainder of the outer slope of the dike, with neither any erosion protection nor any re-profiling of the gap to fit the vessel’s shape. Piping under the vessel and around stem and stern could easily have scoured another gap. Then, the vessel would have broken and been pushed away, leaving a very large gap. However, the piping was blocked by using tarpaulins ballasted with sandbags (see Figure 2.7). The closure was a success and this central area of Holland remained dry.

Figure 2.7 Closure dike breach Ouderkerk aan den IJssel 1953

5. Various alignments with different longitudinal profiles can be selected

These occur for instance, in a river branch with variable bottom topography. In a river bend there may be a deep triangular channel while in the cross-sections between bends a shallow box-profile may be available. (As in the alignments 1 or

2 in the upper half of Figure 2.4, but this time as alternative locations.) Which of the two alignments is preferable?

Another example gives the situation which occurs after a dike located in a shallow area breaches. The breach will erode a deep scour hole very close to the original alignment of the dike. Owing to spreading of the flow, the surrounding shallow area will remain intact for some time, although erosion will gradually create gullies. The option is to restore the original dike or to build around the scour hole, either along the river (or sea) side or via the inside. Various considerations determine which option is the most attractive.

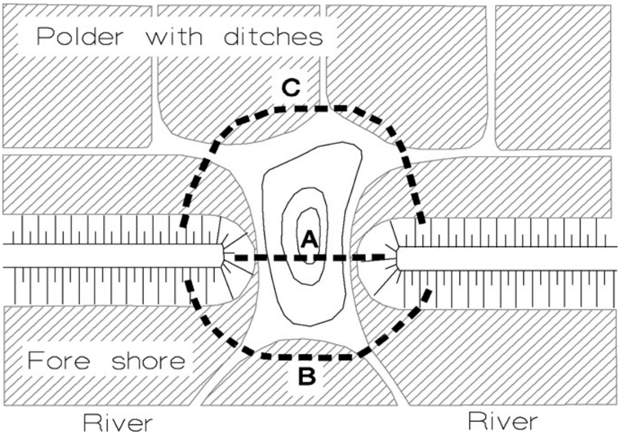

Figure 2.8 Closure alignments

For many dike breaches in the past, closing around the scour hole was preferred. The old method involved sinking mattresses vertically. In order not to lose area, where possible, the alignment at the river side was taken, so that the scour hole became situated within the enclosed polder. Nowadays, in the Netherlands, these former scour holes still can be seen in the landscape as small circular ponds just at the inner toe of the dike where the alignment of the dike winds around them in a semi-circle. In Dutch such a pond is called a "wiel".

An important parameter is the amount of material needed to block the gap. The flow is determined by the nett cross-sectional profile of the gap in m^2, while the gap has to be blocked by m^3 of material. For instance, a dam with slopes 1 in 1 with height "s" along a gap length "l", used to block a profile "$l \times s$", has a volume of "$l \times s^2$". An identical dam, of half the height along twice the length, blocks the same profile but requires only half the volume. On the other hand, the bottom protection (if needed) is twice as wide but may be more than half as long (in the flow direction). Other parameters relate to the equipment, the materials and the closure method used. A shallow gap may be difficult for large operating vessels to approach. It is preferable to use caissons in deep gullies. For a vertical closure, however, a long gap is advantageous because of the resulting lower current velocities.

2.6 Some historical closures

Closure dams have most likely been constructed since mankind started performing agriculture and needed water for irrigation. Another reason for their construction could be political strategy because of the need for road or navigational connections. There are little recordings of these activities in ancient times, but the irrigation projects that once existed in ancient Babylon and Egypt suggest the presence of such works. As such dams would have been constructed from locally available perishable materials, no remains are found today, even though they might have been quite extensive, considering that the builders were able to construct the pyramids.

The damming of the rivers Rhine and Meuse in the late Middle Ages

In the delta area of the rivers Rhine and Meuse, the damming of rivers and water sources developed in the early Middle Ages. Because of the need for agricultural expansion, areas of marshland that were flooded only during extremely high tides or when rivers are in spate, were artificially drained. This caused the soil, mainly peat, to compress causing the land to subside. This led to increased flooding. Therefore, small earthen walls were built to surround the areas and the natural drainage channels were dammed off. Many cities and villages in Holland are named after such dams (e.g. Rotterdam, Amsterdam). In the period of 1100 to 1300, damming activities drastically changed the courses of the two main rivers.

In order to prevent the river Rhine, choked by sediments, from overflowing its banks, the ruler of Utrecht dammed the river at Wijk bij Duurstede around the year 1200. The flow was diverted via the Lek river-branch and the original river mouth near Katwijk shoaled and disappeared.

In 1270 the river Meuse was diverted by damming it at Maasdam (near the city of Dordrecht) and upstream near Heusden, where the flow was directed towards the town of Woudrichem.

From the Middle Ages to 1920

Historic recordings give a fair idea about the old methods used. The dams had to be constructed from locally available materials that could be lifted by hand and simple equipment. These materials were typically not stable under conditions of high flow velocities. Therefore the procedure was to limit the flow velocities during the closure process in accordance with limitations on the size and weight of these materials. One way to achieve this was to split the basin area into separate small compartments and then to close these compartments successively. Experience from trial and error indicated the maximum area that could be closed in relation to tidal rise. Furthermore, flow velocities were kept low by using the vertical closing method, as will be clarified later in this book. Branches cut from willow trees (osiers), were the main construction materials. With these, an interwoven structure (fascine mattress) was made. When ballasted with clay this could be sunk onto the bottom. The closure was created by sinking these mattresses successively one on top of the other on every tide during the short period of slack water. In this way a stack of mattresses created a sill in the closure gap. This continued up to about low water level. Further sinking was then impossible, as the mattresses could not be floated above the sill. The closure was completed by using a different type of structure. This was again composed of willow (osier) and clay, but this time built out from the sides of the gap and directly positioned on the sill.

The closure of the Sloe between the isles of Walcheren and Zuid-Beveland in the south western part of the Netherlands in the year 1871 is a good example of this procedure. The gap was 365 m wide at low water-level and had a maximum water depth of 10 m, with a local tidal range of about 4 m. By sinking mattresses, a sill was constructed up to the low water level. This sill had side slopes of 1V:1H and a crest width of 18 m. The next stage was to construct an osier revetment on top of the sill. In consequence of the added weight, the sill settled 1.80 m. In order to fabricate the wall up to high water level (at a height of 4 m above the original height of the sill), a 5.80 m high dam had to be made which took a full month to construct. Part of the final profile was made by adding a clay cover over the osier revetment.

In the cases where the construction of an osier revetment failed, an attempt was made to position a vessel in the final gap and sink it onto the sill. This was not a simple operation, as transport was done by sailing or rowing and hand winching was the only driving force. Timely ballasting and the prevention of the escalation of piping under and around the vessel were very critical. This method can be seen as the precursor of the caisson closure.

A historic example is found in the closure of the "Bottschlottertief" near Dagebüll (northwest Germany) in 1633. Clay had to be transported over a long distance by sailing vessels and it took an estimated 5500 labourers to execute the job. The closure was completed by sinking a vessel in the gap. This was then ballasted by 350 cart loads of clay.

1920 until 1952

Gradually mechanization started to influence the work methods. The steam engine had already been in use for decades but the equipment was voluminous and heavy, both of which were troublesome in swift water and on soft ground. However, steam power could be used to drive winches, to drive sheet-piles and poles, to power the cranes used to transfer materials, and for ship propulsion. Transport across the foreshore and newly constructed dam bodies was easier when locomotive engines were used, for which a stable railway had to be constructed. Therefore, initially, the only change in construction method was the substitution of hard manual labour by engine work. However, better foundations for the transport roads and rails were needed since these were vulnerable to settlement in freshly created ground.

The difficulties encountered in building such closure dams are illustrated by the closure of the Hindenburgdam. This connection between the Isle of Sylt and the mainland of northwest Germany was completed between 1923 and 1927. The area was very shallow and sailing was impossible. (The average tidal range was 1.70 m, but local wind effects much influenced the tides.) The selected working method was to extend a wooden sheet-pile wall into the gap. The piling process was followed by the tipping of quarry stone on both sides to support the wall. The stone was transported on rails laid on a bridge that was constructed alongside the sheet-pile wall. Progress was much slower than anticipated and the erosion in front of the works consequently much more severe. The piling thus had to be done in highly turbulent water in a scour hole that preceded the sheet-pile construction and therefore more stone was needed for stabilization. On the inshore side, the railway was installed on newly created ground, which often subsided, and derailments frequently occurred, thus escalating the problems. Later, the work method was modified. The preceding scour was solved by laying a 10 m wide stone protection on the bottom and the railway foundation was improved. Thus the problems were overcome.

Apart from the above-mentioned problems, a disadvantage of this type of steam driven equipment is that failure of the engine leads to halting of the complete works. The system is less flexible than one using manual labour.

Learning how to adapt existing methods and the use of the new equipment also stimulated the development of new methods. New engines could handle heavier units and reach higher production capacities. The advantages of engine use are:

- Heavier units:
    - can deal with higher flow velocities
    - give reduced material losses
- Higher production capacities:
    - give a shorter critical phase
    - permit more progress in a still water period
    - lead to shorter execution time, thus greater production during the workable periods and reduce the risk of incidental bad weather

Owing to these new techniques larger projects and projects with more critical conditions became feasible.

For instance, in 1932 a very large closure was realized in the Netherlands when the former Zuiderzee was cut off from the sea by the Afsluitdijk. The 32-km long dam crossed two main gully systems. During the execution of the works large deposits of boulder-clay were found. This material appeared to be very stable in the flow and could be handled by large cranes. A complete set of newly-designed floating cranes and transport barges were built and the closure was entirely constructed by these large floating units.

Another important change in the closure design was the development of mathematical modelling. Originally, designing had been a matter of experience and feeling, but calculations now started to replace the trial and error system. This reduced the risk of failure and was essential for the very large projects. In 1932, for the damming of the enormous tidal basin, the Zuiderzee (now called IJsselmeer), the differential equations for tide-propagation had to be solved. Professor Lorentz, a Nobel Prize winner in physics, was able to achieve this. Three questions had to be answered before the job started:

- How would the tide change when the works were in progress, and would this affect the closing conditions?
- How would the tide change when the works were completed, and would this affect the design water level of the dike?
- What other design conditions would affect the profile of the dike in the new equilibrium state of the sea (storm set-up and waves)?

Another challenge was presented in 1944, when, for military reasons (World War II), the island of Walcheren was inundated by the bombing of the surrounding dike. This action dislodged the enemy troops and opened the fairway to Antwerp for the allied army fleet. However, at the same time, it demolished the sea-defences and opened the low-lying island to tidal penetration. Restoring the sea-defences had to be completed quickly in order that the island would not be permanently lost. Again, the mathematical basis for calculating tide-propagation improved. The four gaps in the dike, (three of these affecting one storage-basin), each with its own tidal amplitude and phase, and the propagation over inundated land with obstacles and ditches, and partial drying out at low tide, were a very complex system for a mathematical approach. Moreover, owing to the progressive erosion of gullies, the hydraulic resistance changed with time. Mathematical analysis was needed to establish the most favourable order of progress and also to ascertain risks that would arise if a different path should occur in practice.

Immediately after the bombing, the gaps in the dike were still relatively small. With the tide flowing in and out twice daily with ranges of 3.5 to 4 m, erosion deepened the gaps and a system of gullies was scoured out, eating back into the inland area (Figure 2.9). In the left figure the extent of the flow is indicated (note that there is an overlap in the basins, some of the water entering the island through the gap of Westkapelle is leaving the island via the gap of Veere). In the right figure the gully formation is indicated.

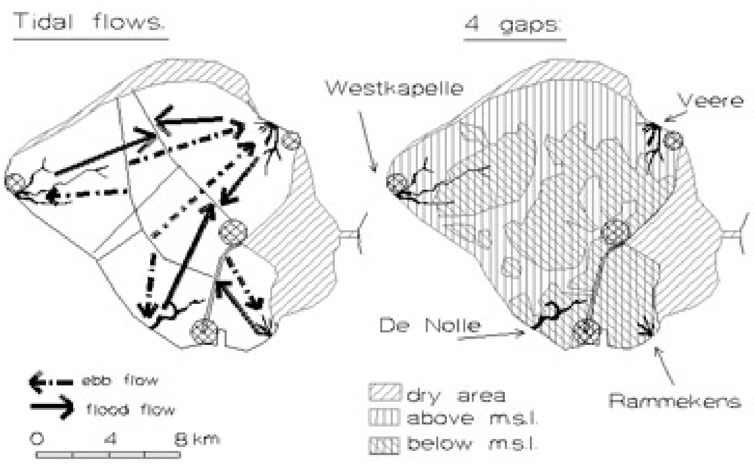

Figure 2.9 Walcheren – four gaps on one island

Due to the concurring war, there was no material or equipment available and the areas were covered with mines. In June 1945, when at last construction could start, closure of the gaps was nearly an impossible task. The traditional methods of closure failed because they progressed too slowly or because the equipment and materials could not cope with the circumstances. The four gaps had to be closed simultaneously within a period of four months before the winter storms and these closures were inter-related.

The only available suitable means to achieve these closures were the caissons of the Mulberry Harbour, used temporarily a year before during the invasion of the Allied Army in Normandy (France). After laying scour-protection in the gaps, a variety of large units, such as pontoons, caissons, concrete, steel vessels, and even large quantities of anti-torpedo-nets, were dropped or positioned in the gaps. The job was not finished before the winter and conditions worsened. Several times, initial success was followed by failure a few days later due to storm surges and piping. However, by the end of January 1946, the gaps were closed. A very good description of the difficulties encountered is given in the novel "Het verjaagde water" by DEN DOOLAARD. A. [1947].

Through this project, experience was gained in the handling of caissons and vessels in closure gaps, and ideas for the design of purpose-made caissons developed. The closure process could be improved by either creating a gap profile in accordance with the shape of the caisson or constructing a caisson to fit the requirements of the desired gap profile. In addition, the sinking could be controlled in a better way by regulating the water inlets by means of valves and separate chambers.

Different plans to improve the sea defences of the delta area in the Netherlands were drawn up and several closures were made. In 1950, the river mouth of the Brielse Maas was closed, using a purpose-made caisson. In 1952, the Braakman, an estuary along the Western Scheldt river, was closed using two caissons, one of which was equipped with sluice gates. These temporary gates could be opened after the positioning of the caisson in the gap in order to reduce the water head in the basin after closure and thus restrict the forces.

1953 and the Deltaworks

On February 1st, 1953, a flood disaster occurred in the southern North Sea. Storm surge, together with spring tide-high water, inundated 2000 km^2 of land in the Dutch Delta, creating 73 major dike-breaches and numerous smaller ones. Again, all available technical experience, equipment, and improvisation had to be used on many sites simultaneously to close these gaps before the next winter season.

Initially, the gaps varied in degree of difficulty or dimension. However, many gaps could not be dealt with immediately because of the disrupted infrastructure and as a result they scoured to tremendous dimensions. This is illustrated in Figure 2.10 for the Schelphoek breach on the Isle of Schouwen along the Eastern Scheldt river. While not initially a threat, this became one of the major dike breaches that occurred. The scouring process continued during the actual closure works as well. The gap increased from an initial 40 m width (on February 1st) to 525 m after 6 months, while the maximum depth increased from 10 m to over 35 m.

A typical example of successful quick improvisation is the closure of the gap at Ouderkerk on the IJssel. The storm surge at this spot reached a level of 3.75 m above mean sea level, overtopping the dike. The unprotected inner slope of the dike slid down over a length of approximately 40 m and the top layer of the dike scoured away. However, the slope protection on the outer side remained intact up to the level of +1.70 m as it rested on century-old clay-core. Six hours later, at tidal-low water (still reaching a level of +2.00 m), two small vessels were positioned on the outer slope, which broke the force of the falling water; although piping underneath was severe. Jute-bags filled with sand were carried in by hand and a small embankment was created on top of the remains of the dike. At the next high water (+2.80 m), the emergency provision remained intact and could be strengthened.

These numerous difficult circumstances led to various innovative actions, which resulted in complete repair within 10 months. Table 2.1 illustrates this enormous achievement.

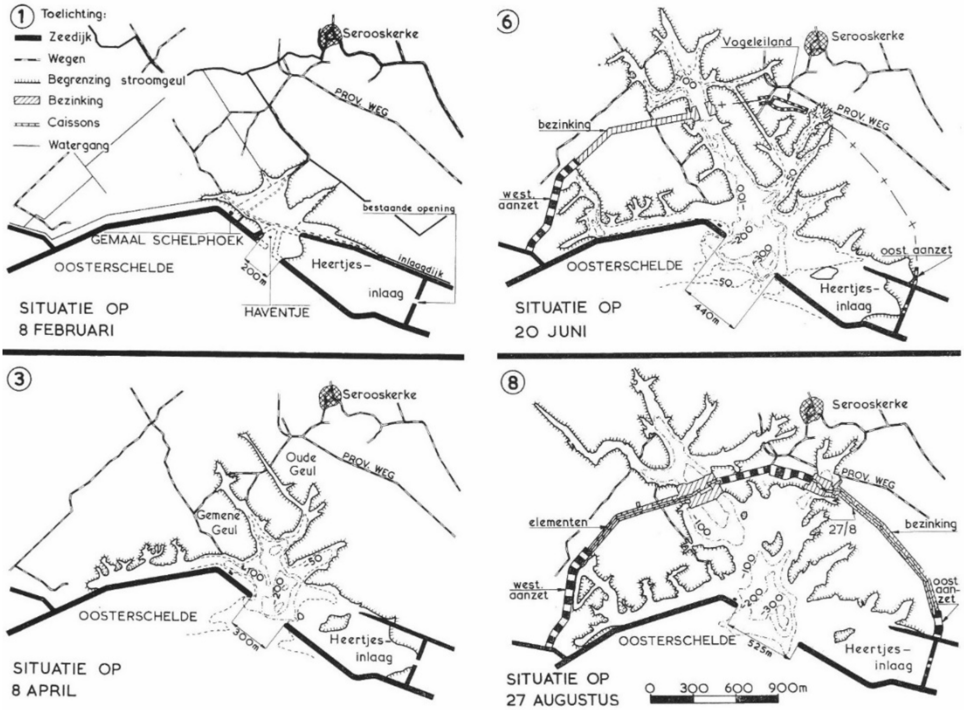

Figure 2.10 Development of erosion gullies in Schelphoek (after the breach of 1 February 1953)

Once again, the experience was used in later developments of closing technology. This is shown by the following example: The principles of a temporary closure made in 1953 near Kruiningen (in the south west of the Netherlands) were copied on a much larger scale, in 1985, to close a major estuary in Bangladesh (Feni River). In this case 1,000,000 bags filled with clay, totalling about 20,000 m^3 and stored in 12 stockpiles along the alignment, were carried by 12,000 Bangladeshi labourers into the 1000 m long gap to construct a dam in 5 hours.

Date	No. of gaps closed	Remaining gaps	Inundated area (km^2)
2 February	3	70	2000
8 February	+ 8 = 11	62	2000
15 February	+ 6 = 17	56	2000
1 March	+20 = 37	36	1400
1 April	+17 = 54	19	800
1 May	+ 7 = 61	12	220
1 June	+ 4 = 65	8	150
1 July	+ 3 = 68	5	150
1 November	+ 4 = 72	1	100
December	+ 1 = 73	-	getting dry

The main closures of the Deltaworks are:

Name	Length	completion	Type of dam – closing method
Volkerakdam	5000	1969	Separation dam – caisson
Brouwersdam	6000	1971	Cable car / sluice caissons
Grevelingdam	6000	1965	Separation dam – Cable car
Haringvlietdam	5000	1971	Cable car (and a sluice complex)
Zandkreek	830	1960	Two closed caisson
Veerse Gat	2800	1961	Sluice caissons
Oesterdam	10500	1986	Compartmentation dam - sand closure
Philipsdam	6000	1987	Compartmentation dam – Sand closure

Table 2.1 Closure scheme of gaps after the flood of 1953 and the main clousrs of the Deltaworks

The disastrous flooding in 1953, was a catalyst for a new decision making process for the reconstruction of sea defences in the Netherlands. In order to avoid strengthening all existing dikes, it was decided to shorten the lengths of the defence works by closing the estuaries. This was accomplished during the succeeding 25 years. Although many closures were beyond the scope of current experience, it was possible to develop the required new methods during the period of construction by working from the small to the large-scale projects. This period was therefore characterized by many experiments, a lot of research, and the introduction of new materials and technology.

Period after 1975

In the north of Germany also a number of closure works were realised. The original purpose of the closures was land reclamation and safety against flooding. In a later phase the importance moved to safety and ecological protection. Closures were made in Meldorf (1978), Nordstrander Bucht (Husum, 1987) and Leyhörn (Greetsiel, 1991).

Around 1975 enhanced world views regarding ecological importance altered the design of closures. Because of this in the north of Germany a number of closures were completed in a different way than planned. For example it was planned to dam the full Leybucht near Greetsiel, but eventually only a small part was closed, just sufficient to guarantee safety and water management requirements.

Figure 2.11 Plans and realisation of the closure of the Leybucht in Germany (chart basis Google Earth)

In the Netherland the largest estuary, Eastern Scheldt, was provided with a storm-surge barrier, which took another 8 years to construct. Since parts of the closure dam had already been constructed and the creation of the new design and its execution were parallel, many problems arose in this period. A lot of new ideas were generated and tested. The much-improved computer and measuring facilities played important roles. As a result of all these efforts, the present day designer has many rules, formulas, graphs and test-results at his disposal. Because of the changed plans the compartmentation dams (Philipsdam and Oesterdam) were needed.

In Korea in the sixties there was an enormous shortage of agricultural land. So, large reclamation works including closure dams were planned. Execution took place between 1975 and 1995. The experience from the Netherlands was used in detail. Also there a change in attitude towards closing works happened. Therefore the plans for the Hwaong and Saemangeum were considerably delayed, and also adapted.

Name of Estuary	Total length of closure dike	Tidal range (m)	Area (km^2)	Closing date
Saemanguem	29	7.00	400	April 2006
Hwaong	19	9.40	62	Mar 2002
Siwha	13	9.30	173	Jan 1994
Sukmun	11	9.42	37	Nov 1991
Busa	3	7.48	13	Mar 1988
Yongsan	4	5.59	109	Feb 1983
Sabkyo	3	10.4	28	Mar 1978

Table 2.2 Recent closures in Korea, from YOON [2003]

Figure 2.12 Flow in the Saemangeum closure gap just before closure

A number of closure works in Bangladesh are also worth mentioning. Also there a combination of safety against flooding, need for agricultural land and availability of irrigation water was the driving force. Fundamentally the closures in Bangladesh were not different from elsewhere, but because of the low labour costs and the huge unemployment in the country, execution methods were selected including as much as possible local manpower.