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TECHNICAL COMMUNICATION

State of the Art in Storm-Surge Protection: The Netherlands Delta Project

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ABSTRACT



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A multi-billion dollar complex of coastal construction protects the delta-estuarine region of the south-west Netherlands from a repeat of the 1953 storm-surge flooding that killed 1835. Eight documented storm-surge flood disasters date back to 1717. The Delta Project became effective in terms of flood protection in 1986, but sections of it are still under construction. One of the world's greatest civil-engineering projects, its 11 major and multiple secondary components have the function of (1) closing off three main estuaries which shorten the coastline by approximately 720 km, (2) creating a non-tidal waterway, the Scheldt-Rhine link, which facilitates inland shipping between Antwerp and Rotterdam (120 km), two of the largest ports in the world, and (3) ensuring the partial environmental preservation of the Delta area.

This case history addresses geology and foundation problems, planning and construction sequence, site investigation and foundation preparation, methods of construction, and foundation/structural interaction. The main focus is the megascale control barrier completed in 1986 across the 7.5 km-wide mouth of the Eastern Scheldt estuary, the most difficult and by far the most costly section of the project. Here, and in other parts of the Delta area, strong tidal currents and highly-variable geological materials with relatively poor engineering properties were responsible for foundations requiring up to 80 percent of the total construction time. The new techniques developed on the Project have world-wide application to future coastal and offshore construction.

ADDITIONAL INDEX WORDS: *Engineering geology, civil engineering, coastal engineering, open-water construction, delta-estuarine geology, foundations, storm-surge protection.*

INTRODUCTION

The Netherlands Delta Project covers a multi-river delta area created by the Rhine, Meuse and Scheldt (Figure 1). Like most delta-estuarine environments, this area represents, in its natural state, an extremely complex

hydrodynamic regime encompassing fast-flowing tidal channels, changing estuarine configurations, nonhomogeneous subbottom sediments, a prolific, but delicately-balanced ecosystem, and low-land areas subject to periodic flooding (Figures 1 and 2).

Major storm-surge floods occurred in 1953, 1916, 1912, 1906, 1894, 1825, 1808, 1775 and 1717

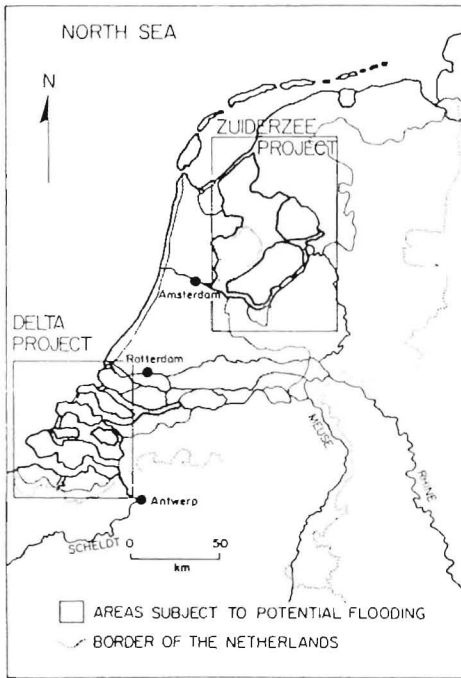


Figure 1. The Netherlands, showing the delta area of the Rhine, Meuse and Scheldt rivers, and the locations of the Delta and Zuiderzee project areas where storm-surge structures have been erected to protect flood-prone areas (shown in stipple). (Modified after DOSBOUW v.o.f., 1983).

(Antonisse, 1986). Unlike many other deltas, Zeeland is densely populated and intensely utilized by man. In 1953 when storm-induced tides, some 4 m above normal, breached approximately 180 km of coastal-defense dikes and flooded 160,000 hectares of polderland, a huge loss of life and property resulted. The official death toll was reportedly 1,835. More than 46,000 farms and buildings were destroyed or damaged, and approximately 200,000 farm animals lost. However, a much larger area of the western Netherlands is susceptible to flooding (Figure 1) and had the storm penetrated the dikes of the Hollandse IJssel (Figure 3) that protect this area, the entire urban conglomeration of Rotterdam, the Hague and Amsterdam would have been inundated. It is important to note that approximately sixty percent of the population of The Netherlands lives below mean sea level (ENGEL, 1987) and that some areas contain

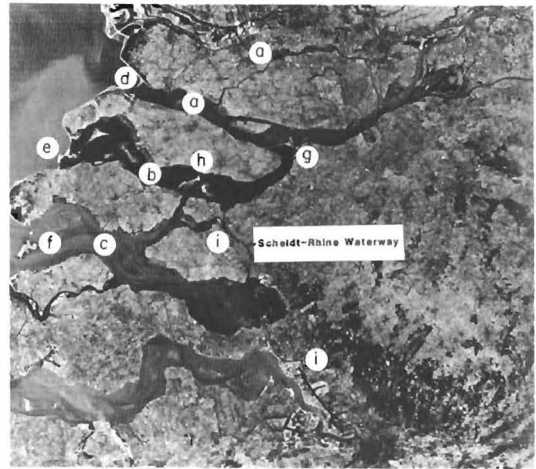


Figure 2a. Satellite image showing the complex hydrodynamic nature of the Delta area, and some major civil-engineering works either built, or under construction: (a) fresh-water Rhine discharge, (b) non-tidal, salt-stagnant water, (c) tidal salt water (shades of grey indicate the intricate network of tidal channels), (d) Haringvliet Sluice-Gate Barrier, (e) Brouwers Embankment Barrier, (f) Eastern Scheldt Lift-Gate Barrier under construction, (g) Volkerak Waterway Dam and Navigation Locks, (h) Grevelingen Tidal-Control Barrier and the (i) Scheldt-Rhine Waterway Link under construction. (Satellite image by the National Aerospace Laboratory).

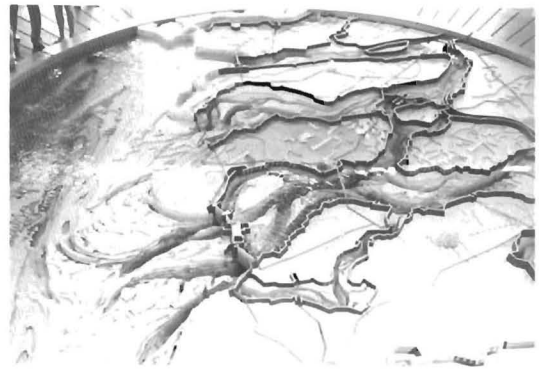


Figure 2b. The working model by Rijkswaterstaat at the Eastern Scheldt Delta-Expo provides a perspective on the mesh of natural hydrodynamic features and structural design incorporated into the Delta works. The Dutch are world leaders in hydraulic engineering.

polders more than 6 m below sea level (Figure 4).

Because of the low mean elevation and premium on space in The Netherlands, the Dutch have a long tradition of coastal-defense con-

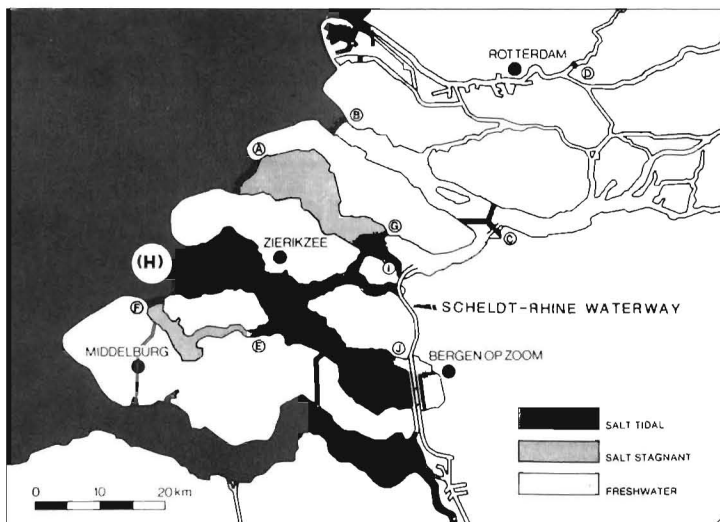


Figure 3. Major components of the Delta Project: (A) Brouwers Fixed Barrier, (B) Haringvliet Sluice-Gate Barrier and Navigation Lock, (C) Volkerak Waterway Dam and Navigation Locks, (D) Hollandse IJssel Drop Barrier, (E) Zandkreek Dam, (F) Veerse Fixed Barrier, (G) Grevelingen Tidal-Control Dam, Lock, and Siphon Sluice, (H) Eastern Scheldt Lift-Gate Barrier, (I) Philips Waterway Dam and Kramer Navigation Locks and (J) Oester Waterway Closure Dam and Navigation Lock. Refer to Table 1 for a more complete description of these components. (Map after DÓSBOW v.o.f., 1983).

struction and land reclamation. This coastal conscientiousness dates back from farm houses built on artificial mounds around 400 BC, to major dike works built in the eleventh and twelfth century (WALTHER, 1987). The need for continual coastal construction has intensified over the years as a result of population growth, land



Figure 4. Approximately 60 percent of the population of The Netherlands live in dike- and/or barrier-protected areas below mean sea level.

subsidence and rising sea levels. The people of The Netherlands have responded to the challenge of coastal protection with projects such as the Zuiderzee Works (Figures 1 and 5), enclosed in 1932 but still in the process of having approximately 150,000 ha of new land reclaimed and, more recently, the Delta Plan formalized in 1958 by an act of the Dutch parliament. The latter scheme became functional, in terms of storm-protection, in 1986 but considerable construction effort is still required on roads, bridges and other secondary structures to complete the project. The continued maintenance and improvement of dikes and waterways remain a life-long preoccupation.

The core of the Delta Project called for the raising of existing dikes, the storm closure of all main tidal estuaries and inlets, but with provision for continued international shipping access to Rotterdam and Antwerp, a non-tidal inland waterway link between these two ports and last but not least, an integrated network of dams, salt/fresh-water separation locks and flushing mechanisms to separate and manage the salt and fresh-water environments in the Delta (Table 1).

Table 1. Summary of the major project components of the complete Delta Works, presenting the construction sequence, and the type and purpose of individual structures.

DATE	MAJOR PROJECT COMPONENTS	TYPE	CONSTRUCTION	PURPOSE
1 1958	HOLLANDSE IJSEL Drop Barrier	P*	Guillotine steel-gate drop barrier Navigation lock	Open Mode: Facilitates navigation & Rhine discharge (± 250 (± 250 m ³ /sec) Closed Mode: Storm-surge flood protection
2 1960	ZANDKREEK Tidal-Control Dam	S	Caisson-core & dredged-sand embankment dam & Navigation Lock	Reduced tidal-current velocity for construction of primary Veerse barrier Provides navigation to stagnant Lake Veerse
3 1961	VEERSE Fixed Barrier	F	Caisson-core & primary dredged-sand embankment dam, with asphalt cover	Storm-surge estuary closure (with Zandkreek Dam creates Lake Veerse)
4 1965	GREVELINGEN Tidal-Control Dam, Lock, & Siphon Sluice	S	Combination cableway block & caisson core, with dredged-sand dam, Artificial island for navigation lock & Flushing siphon sluice	Reduced tidal-current velocity for construction of Brouwers barrier Facilitates navigation access to Lake Grevelingen Siphon helps flush Lake Grevelingen
5 1970	VOLKERAK Waterway Dam & Navigation Locks	S	Artificial-island & coffer-dam construction on large lock complex (two locks for commercial traffic, one lock for pleasure craft)	Reduced tidal-current velocity for construction of IJaringvliet barrier Contributes to Scheldt-Rhine non-tidal waterway link
6 1971	IJARINGVLIET Sluice-Gate Barrier & Navigation Lock	P	Artificial-island & coffer-dam construction on piled piers, for pivot-gate sluice barrier Also cableway block-core embankment section	Closed Mode: Storm-surge barrier Part Closed & Open: Rhine discharge (fresh-water management) Shipping access to North Sea
7 1972	BROUWERS Fixed Barrier	F	South Channel: Cableway block core with dredged-sand embankment dam Central: Dredge-improved sand bank North Channel: Caisson core & sand embankment	Fixed storm-surge estuary closure, sluice & crest road
8 1983	MARQUISATE-OUAY Waterway Closure Dam	S	Core of riprap and gravel placed by barge & truck dump Core partially replaced by dredged-sand fill	Closure forms part of the Scheldt-Rhine waterway link Reduced tidal velocity for Oester Dam construction & Controls salt-water intrusion to the east
9 1986	EASTERN SCHELDT Lift-Gate Barrier	P	Two dredge-improved artificial islands Three sections of pier-and-lift-gate sluice barrier	Closed Mode: Storm-surge flood protection Open Mode: Tidal flushing for preservation of salt-water estuary Shipping access to North Sea
10 1987	PHILIPS Waterway Dam & KRAMMER Navigation Locks	S	Large-scale artificial-island & coffer-dam construction of Kramer Lock Complex Dredged-sand embankment closure	Contributes to non-tidal conditions in the Scheldt-Rhine waterway Kramer Locks provide shipping access to Eastern Scheldt, but preserves salt-water eastern Scheldt & fresh-water waterway
11 1987	OESTER Waterway Closure Dam & Navigation Lock	S	Artificial-island & coffer-dam construction of navigation lock Dredged-sand embankment closure	Part of Scheldt-Rhine compartmentalization closure Facilitates shipping access between waterway and the Eastern Scheldt Controls salt-water intrusion to the east

* P = Primary storm-surge control barrier, F = Primary storm-surge fixed embankment dam, S = Secondary tidal-control and/or waterway embankment

Much has been written about various aspects of the Delta Project and the purpose of this case-history review is to summarize important features of engineering-geologic application, in particular, remedial works that were implemented to cope with potential foundation problems. The references cited address related aspects of investigation, design and construction in greater technical detail than the present text.

GEOLOGY AND FOUNDATION PROBLEMS

“It is pointless to try to increase the accuracy of prediction (of foundation stability) by 10 percent using advanced methods while soil parameters may vary between 100 and 300 percent.” (NIEUWENHUIS, 1987a).

Overview

Both the nature of the project and the geology of the area precluded the usual option of relocating structures to sites of significantly better foundation conditions. In the western



Figure 5. Air-photograph oblique of the Zuiderzee closure works. (Photograph courtesy of Bart Hofmeester, Aerocamera. Rijkswaterstaat, Meetkundige Dienst Afdeling Reprografie).

Netherlands hard rock can be found only at depths of one kilometer and more (ENGEL, 1980). This is, therefore, a soils (*i.e.* unlithified sediments) project area exhibiting highly-variable and consistently-poor engineering-geologic conditions. Figure 6, a geologic cross section through part of the subsurface-foundation

materials of the Eastern Scheldt estuary provides an example of the rapidly changing soils conditions that are typical of the Delta region (DE MULDER and VAN RUMMELEN, 1978). Nonhomogeneous subsurface conditions pose potential foundation problems such as differential settlement. More specifically, peats are susceptible to creep consolidation and must often be entirely demucked. Soft clays and loose sands exhibit poor bearing capacity, while the latter are subject also to scour erosion, piping beneath barriers, and wave and/or ocean swell-induced liquefaction (BJERRUM, 1973; DE LEEUW, 1976). At first sight, such soil conditions might justifiably have been considered entirely unsuitable for the size and complexity of proposed project construction works and the heavy foundation loads that these would impose. However, conventional and new techniques were adapted to cope with these problems and are discussed in the "Foundation Preparation" subsection of the Eastern Scheldt.

It is of considerable interest to note that as a broad-based guideline to foundation design, money was considered to be spent more cost-effectively on the accurate delineation of the engineering-geologic characteristics of subsurface materials than on the use of sophisticated numerical foundation-prediction methods. The first-principles approach to foundation design is best summarized in the further words of NIEUWENHUIS (1987a), the Chief Geotechnical Project Engineer:

"...We would therefore conclude that a knowledge of basic soil mechanics, combined with experience and sound engineering judgement, should enable a construction work such as the closure of an estuary to be properly and economically designed and constructed."

Engineering Geology

In very simple terms, the engineering geology of the Project area may be divided into two broad units:

(1) An upper sequence consisting of interbedded layers of clay, clayey-sand, sand and peat exhibiting relatively poor engineering characteristics. This sequence was deposited during a marine transgression in the Holocene period (the last approximately 10,000 years), in response to a warming trend, the melting of ice sheets and a

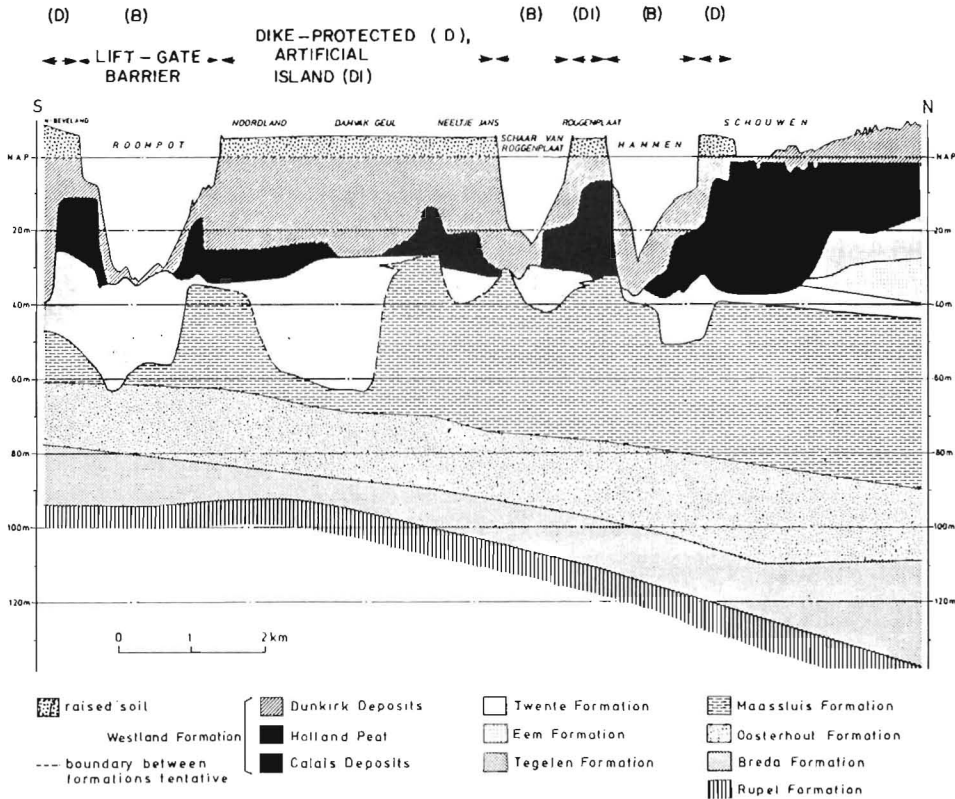


Figure 6. Geologic cross section through the Eastern Scheldt barrier alignment, showing changing soil conditions typical of the general Delta area. (B) lift-gate barrier, (D) dike-protected land, (DI) dike-protected artificial island. (Cross section modified after De Mulder and van Rummelen, 1978).

consequent global rise in sea levels following the most-recent "ice age." As shown in Figure 6 (see base of Holocene Westland Formation deposits) this unit reaches a depth of up to 30 m beneath the seabed; however, it is considerably thinner in tidal channels where the upper, predominantly sandy layers have been removed by scour erosion.

(2) A lower sequence of interbedded clays and sands with somewhat better engineering characteristics (than the overlying Holocene sediments described). This lower unit consists of both marine and terrestrial materials deposited during a period of changing sea levels, above and below present sea level, dating from Middle-Oligocene time (Figure 7). The better engineering characteristics of these older soils may be attributed in part to the consolidation produced by the weight of presently-existing Holocene sediments, and in part by the over-

consolidation load of sediments that have been subsequently stripped away by erosion.

The sediment wedge of engineering-geologic interest does not extend much below -100 m (MSL) and is characterized by rapidly fluctuating sea levels in response to glacial and interglacial periods. The result was the complex mix of marine, littoral and terrestrial (including periglacial) sediments shown in Figures 6 and 7.

In reviewing the geologic section, it may be noted that some deposits, like the Eem Formation shown, were at one time far more extensive, but have been removed in large part by erosion (DE MULDER and VAN RUMMELEN, 1978). This occurred particularly during the onset of respective glacial periods when sea levels began falling and previously-inundated land was exposed above sea level. For example, during the Weichselian, the most-recent glacial period (approximatley

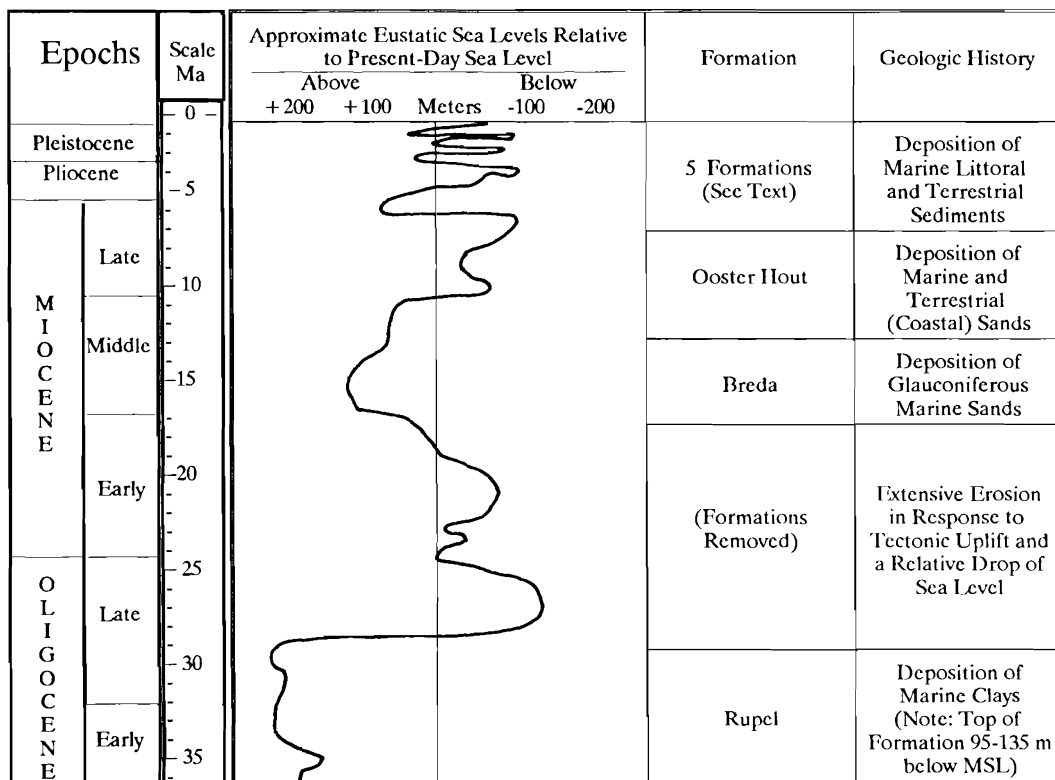


Figure 7. The post-Eocene geologic history of the project area is largely a function of fluctuating sea levels.

70,000 to 10,000 years before present) the entire "delta" area was exposed well above sea level.

With the warming trend at the beginning of the Holocene, rising sea levels initiated, as mentioned, the marine transgression which resulted in the deposition of clays and peats of the near-surface Westland Formation. Finally, reactivated transgression, starting about 500 years BC, was responsible for the deposition of the Dunkirk sands, the uppermost deposits of the Westland Formation (DE MULDER and VAN RUMMELEN, 1978). These authors note further that it was as recently as 700 AD that the Western Scheldt estuary began to form and capture the principal discharge of the Scheldt River. In the past few years, geologic processes have accelerated again, this time in response to the works of man. For example, nature's compensation for the upset in the hydraulic equilibrium initiated by the construction of ar-

tificial islands in the Eastern Scheldt Estuary was to significantly increase flow and scour in the tidal inlets that remained open. This added considerably to the problems of foundation design for the barriers that subsequently had to be constructed in these tidal inlets.

Foundations

Besides being a function of the engineering-geologic characteristics of the site, the technical aspects of foundation design are dictated in major part also by (1) the purpose of the project and (2) the nature and size of civil-engineering structures that best serve this project purpose.

As shown in Figure 8, barriers exposed to the North Sea had to have both their structural and foundation components designed to withstand storm-surge and wave loading resulting from a combination of probable maximum storm condi-

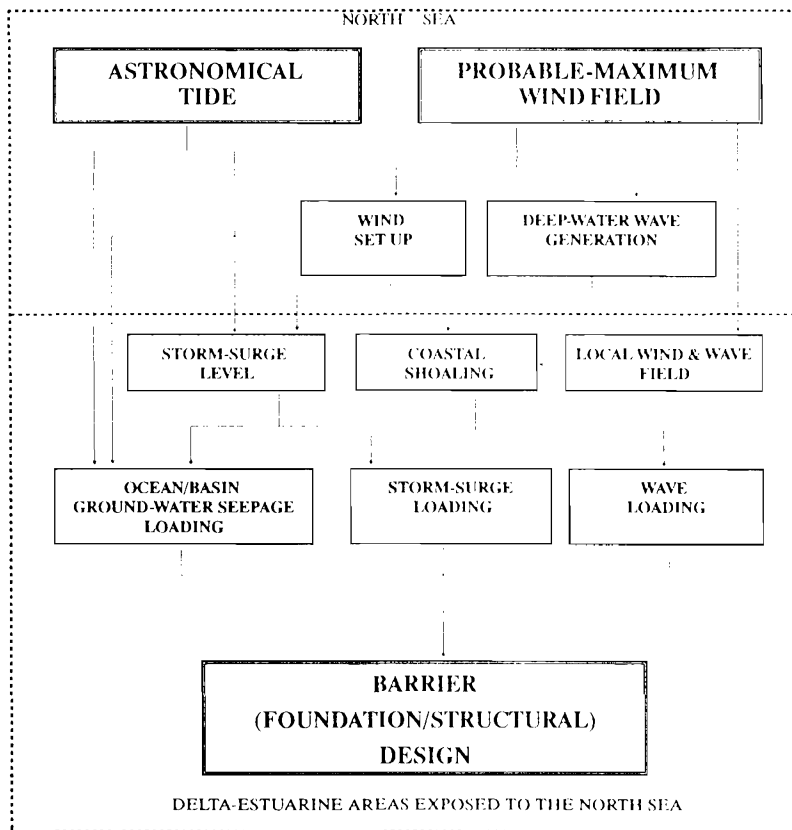


Figure 8. Simplified diagram showing the impacts on design of worst-case storm and tidal loading.

tions and maximum spring-tides.

A number of closure, construction and foundation options were available to engineers, and some of those that were successfully used are shown in Figure 9. In general, rigid (concrete and steel) structures are more expensive than flexible (largely geologic-material) structures, so that use of rigid components was generally restricted to lift or sluice-gate structures, navigation locks and the caisson-core units for flexible embankment dams.

Foundation/structural options in themselves presented certain advantages and disadvantages and these are briefly summarized in Figure 10. The authors suggest that the combination of stabilized soil, mattress and prefabricated piers, designed for the closure of the Eastern Scheldt estuary, may be more widely used on the long closures of other projects in the future, in

place of the more-conventional foundation caisson used, for example, on the Thames Barrier in England (Figures 11 and 12).

As far as foundation design *per se*, the main considerations are summarized in Figure 13. As shown, the foundations of both flexible and rigid structures must be designed in terms of (1) stability against bearing-capacity failure and (2) deformation against excess, or differential settlement.

Figure 13 also lists the main design stresses that must be considered. As shown, open-water construction requires special emphasis on dynamic forces. Discussion of these is beyond the scope of the present text, but the following references may be consulted for further detail:

(1) current-induced scour (PILARCZYK, 1987b),

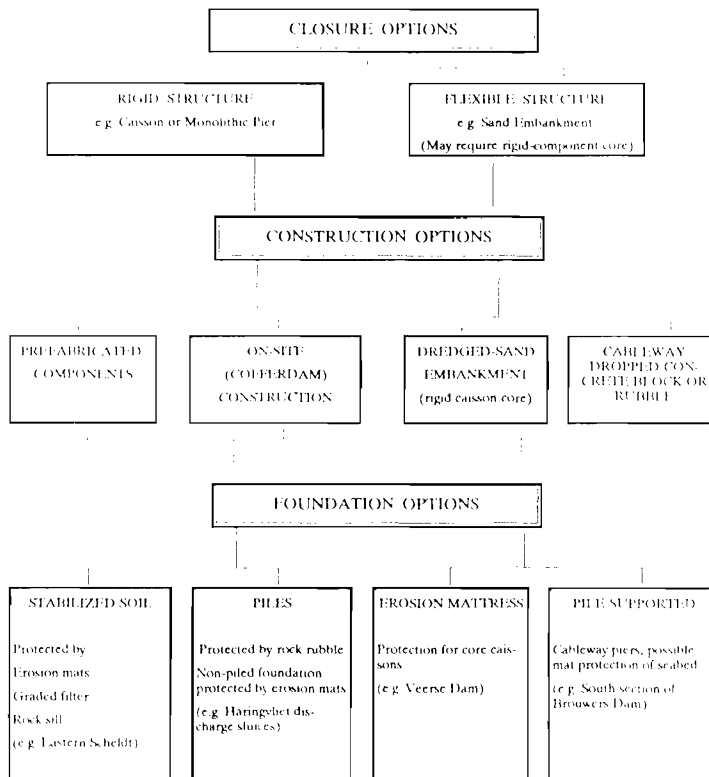


Figure 9. Some closure, construction and foundation options available to Delta-Project design engineers.

(2) seepage-induced uplift pressures and piping (PILARCZYK, 1987a; v.d. BURG and NIEUWENHUIS, 1987),

(3) wave and/or earthquake induced liquefaction (AMBRAYSEYS AND SARMA, 1967; DE LEEUW, 1976; NIEUWENHUIS, 1987B; SEED, 1979; VAN AALST and BRUINSMA, 1987) and

(4) ice-jam loading (PILARCZYK, 1987a).

General discussion, including design against static-loading conditions, may be found in BJERRUM, 1973; BRUUN and JOHANNESSEN, 1976; BRUUN and KJELSTRUP, 1981; SMITS, *et al.*, 1978.

PLANNING AND CONSTRUCTION SEQUENCE

An important ingredient in the planning of the project was to follow a construction sequence

(where practical) that was predicated by least-to-most-complicated design requirements. This simple philosophy enabled relatively rapid progress to be made at the outset of the project, and established a learning process that proved invaluable in the latter stages of construction.

The sequence, type and purpose of construction of major components of the scheme are presented in Table 1. This highlights a major technical factor influencing the construction sequence, namely the need to reduce tidal-current velocities in the four main estuaries before the construction of primary barriers could be undertaken. Tidal velocities were lowered by constructing secondary compartmentalization barriers (e.g. Zandkreek Dam, Grevelingen Dam, and Volkerak Dam — Figure 3) to reduce the extent of the Delta area subject to tidal influence (RIJKSWATERSTAAT, 1987). This resulted, in turn, in a reduced tidal volume and, therefore, lower current velocities through the main estuaries.

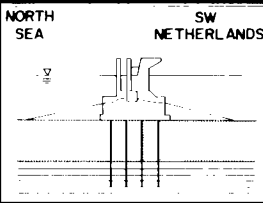
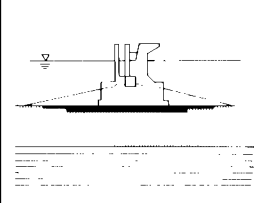
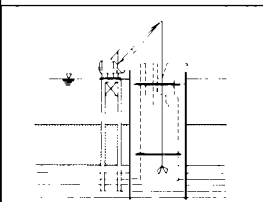
FOUNDATION/ STRUCTURAL TYPE	SECTIONAL SKETCH	ADVANTAGES	DISADVANTAGES
PILES SUPPORTING CAISSONS OR PIERS		MINIMAL FOUNDATION PREPARATION LARGE FACTOR OF SAFETY	LONG PERIOD OF OPEN-WATER AND/OR COFFERDAM CONSTRUCTION
STABILIZED SOIL (PROTECTED) SUPPORTING CAISSONS OR MONOLITHIC PIERS		FACILITATES MAXIMUM USE OF PRE FABRICATED COM- PONENTS MINIMIZES DEEP- WATER CONSTRUC- TION TIME	REQUIRES STRINGENT QUALITY CONTROL ON: Soil Stabilization (e.g. compaction & density) FOUNDATION PREPARATION (e.g. levelling)
FOUNDATION CAISSONS SUPPORTING PIERS OR CAISSONS		MINIMAL FOUNDATION PREPARATION LARGE FACTOR OF SAFETY	TIME CONSUMING & LABOR-INTENSIVE UNDER DIFFICULT & POTENTIALLY DANGEROUS ON-SITE CONDITIONS

Figure 10. Advantages and disadvantages of some foundation/structural options.

It may be noted further, that secondary compartmentalization works also served the dual purpose of (1) impounding the Rhine/Scheldt water way and (2) creating a fresh-water buffer zone to inhibit salt-water intrusion from the Delta region to the agricultural areas east of Bergen Op Zoom (Figure 3).

All of this construction, in turn, imposed a new environmental regime on the Delta, that relies for its preservation on the design of a complex support system of flushing structures. A good example is provided by Lake Grevelingen, where a desirable salt content is maintained by circulating sea water through an inlet sluice in Brouwers Dam (Figure 14), and discharging excess water from the Lake to the Eastern Scheldt with a siphon sluice built into Grevelingen Dam (Figure 15).

With respect to planning the construction sequence for individual structures, it is important to remember that the preparation of complex foundation sections consumed a high proportion of the total construction time. The schedule shown for completion of the Roompot channel

in the Eastern Scheldt is typical (Figure 16). This figure shows approximately 80 percent of construction time (not including site investigation) spent on compaction and other soil-improvement procedures, building of the foundation bed, and completion of the rock-rubble sill to protect the foundations of the gate-piers (VAN DER SCHAAF and OFFRINGA, 1980).

METHODS OF CONSTRUCTION

Rather than discuss in detail each of the project components summarized in Table 1, the construction-methods used for these various structures are outlined under three subheadings: (1) primary embankment dams, (2) artificial islands and cofferdams, and (3) secondary structures (gravel-and-sand-embankment dams). A fourth method employing prefabricated monolithic piers on a stabilized foundation is discussed in the section on the Eastern Scheldt.

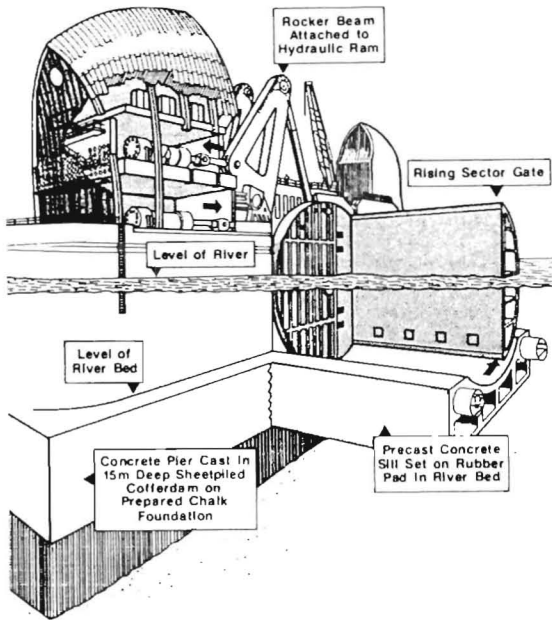


Figure 11. The Thames Barrier Design. The authors note that the combination of stabilized soil, mattress and prefabricated piers, designed for the foundations of the Eastern Scheldt estuary, may be more widely used on the long closures of other projects in the future in place of the more-conventional foundation caisson(s) used, for example, on the Thames Barrier in England.

PRIMARY EMBANKMENT DAMS

Large embankment dams are used for the total closure of estuaries (*e.g.* Veerse Dam, as depicted in Figure 17). As shown, construction consists of an inner core of ballasted caissons, or concrete blocks, covered by a bulk shell of dredged sand.

The inner core of the dam is the most critical component. It is also the most difficult to complete, because construction must contend with the full force of tidal currents. Without the core in place, attempts to close the estuary with dredged fill would be futile because sand would be constantly washed away. The two main techniques used for core construction are discussed in what follows.

Cableway and Block Gradual Closure

This method employs a pile-supported cableway on a continuous loop. The cableway carries



Figure 12. The Thames Barrier, large as it is, is dwarfed by the closure of the Eastern Scheldt estuary, let alone the combined works of the Delta Project (the small vessel approaching the barrier from a downstream direction provides an idea of scale).

a vehicle capable of dropping cast concrete blocks (Figure 18). These blocks accumulate in a line on the seabed and eventually rise above sea level. The method has advantage over rubble placement by barge and other dumping vessels because when near completion, barges can float over the retaining dam only at high tide (HUIS IN 'T VELD, 1987a). A cableway, on the other hand, may be operated independently of tidal cycles and in most weather conditions. The advantage of a cableway system over caisson construction lies in the fact that slow loading and overall bulk minimize the need for foundation preparation. This phenomenon is characteristic of all rubble-mound structures (WATSON *et al.*, 1963) and is an economical construction technique because problems associated with excess settlement tend to be built out during construction.

The technique was first used on the Grevelingen Dam (1963) and subsequently in a final section of the Haringvliet Dam (1970); it was also deployed again in 1971 for the large southern section of Brouwers Dam (VAN WESTERN, 1987).

Caisson Sudden Closure

This alternative method of core construction (as opposed to gradual closure) employs prefabricated box caissons with a built-in steel lift gate forming one (long) side of the caisson, and temporary timber panels forming the other side.

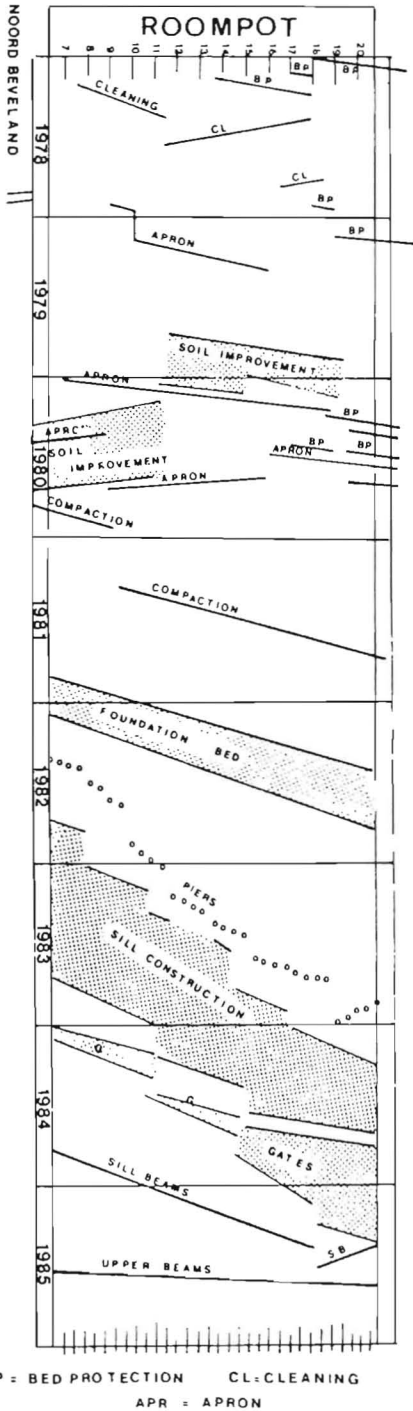


Figure 16. Construction sequence for the Roompot channel, Eastern Scheldt; note that about 80 percent of the total construction time was spent on foundation preparation. (After van der Schaaf and Offringa, 1980).



Figure 17. Veerse primary-embankment barrier showing: (a) tugs positioning the last caisson for the "sudden closure" core of the dam. (b) The approach embankment with a crest road; this will eventually extend over the caisson core. (Photography by Bart Hofmeester, Aerocamera. Rijkswaterstaat, Meetkundige Dienst Afdeling Reprografie).

were conveniently constructed in the dry. On completion, the cofferdam was flooded, removed and the sluice gates incorporated in the barrier dam.

Figure 22 shows a further example of the use of a dredged artificial island, for the cofferdam construction of the Kramer locks in the Philips Dam.

Secondary Structures

A great number of secondary embankment dams and transitional structures were built to serve as approaches for primary barrier closures, as connectors between barriers and dikes, or as compartmentalization structures for waterways. These consist essentially of dredge sand, reinforced against erosion by one or a combination of asphalt, concrete, paved stone, or rip rap (SCHELLEKENS *et al.*, 1980).

In the case of the Marquisate Quay, closed in the spring of 1983 (Figure 23) to serve as a section of the Scheldt-Rhine waterway (Figure 2), initial stone rip-rap construction was completed by a combination of stone-dump barges, rubber-tired tip trucks and hydraulic scoop cranes. Once the rip-rap core was raised above water level, dredged sand was placed in such a way that a large volume of the (short-supply) rip rap could be conveniently removed for other sections of the project (RIJKSWATERSTAAT; 1987).

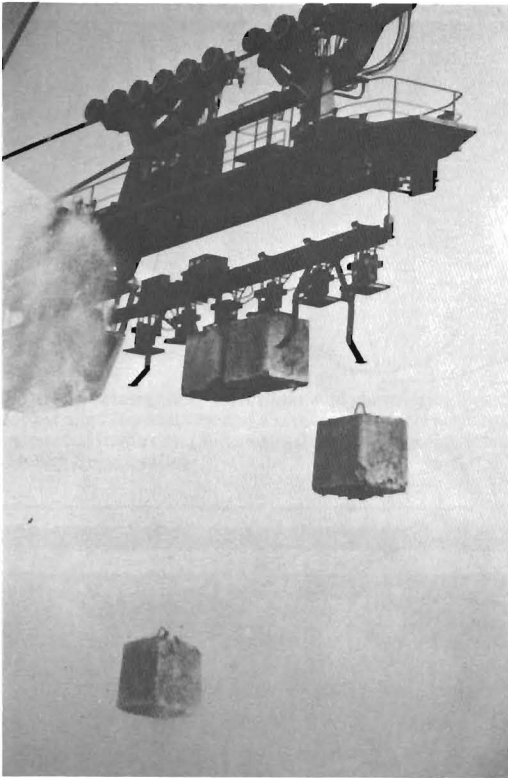


Figure 18. Cableway vehicle used to drop concrete blocks for the "gradual-closure" method of core construction for embankment barriers. (Rijkswaterstaat, Meetkundige Dienst Afdeling Reprografie).



Figure 19. A graded-filter foundation mattress constructed of both natural and synthetic materials offers protection against: (1) scour and currents, (2) piping (seepage erosion) induced by the differential head of water when barrier gates are closed, (3) excess pore water pressures caused by pier-placement loading and (4) liquefaction due to storm waves.



Figure 20a. The Dutch are the dredge masters of the world and frequently, as here in the Eastern Scheldt estuary, made use of artificial islands to facilitate cost-effective construction. This photograph (looking south) shows two dredged islands: (a) Roggenplaat and (b) Neeltje Jans, originally used as a construction base, and presently home of the Delta-Expo museum. See Figure 20b for further details. (Photography by Bart Hoffmeester, Aerocamera. Rijkswaterstaat Meetkundige Dienst Afdeling Reprografie).

EASTERN SCHELDT

Overview

The original master plan for the closing of the Eastern Scheldt estuary called for a complete closure, a primary embankment dam. However, to preserve the natural salt-water environment of the estuary, the design subsequently was changed to a sluice-gate barrier (ENGEL, 1980; DE JONG *et al.*, 1987). The revised plan called for a control barrier consisting of some 65 pre-fabricated concrete piers to support sliding steel gates in the three tidal channels (which

would remain after the completion of two large artificial islands, see Figure 20).

The new design, although vastly more complex from a technical standpoint, and considerably more expensive, facilitated the continued tidal flushing of the estuary, and was, therefore, justified on environmental grounds. Some examples of food chains in an estuarine web which would have been destroyed as the water behind a fixed dam gra-

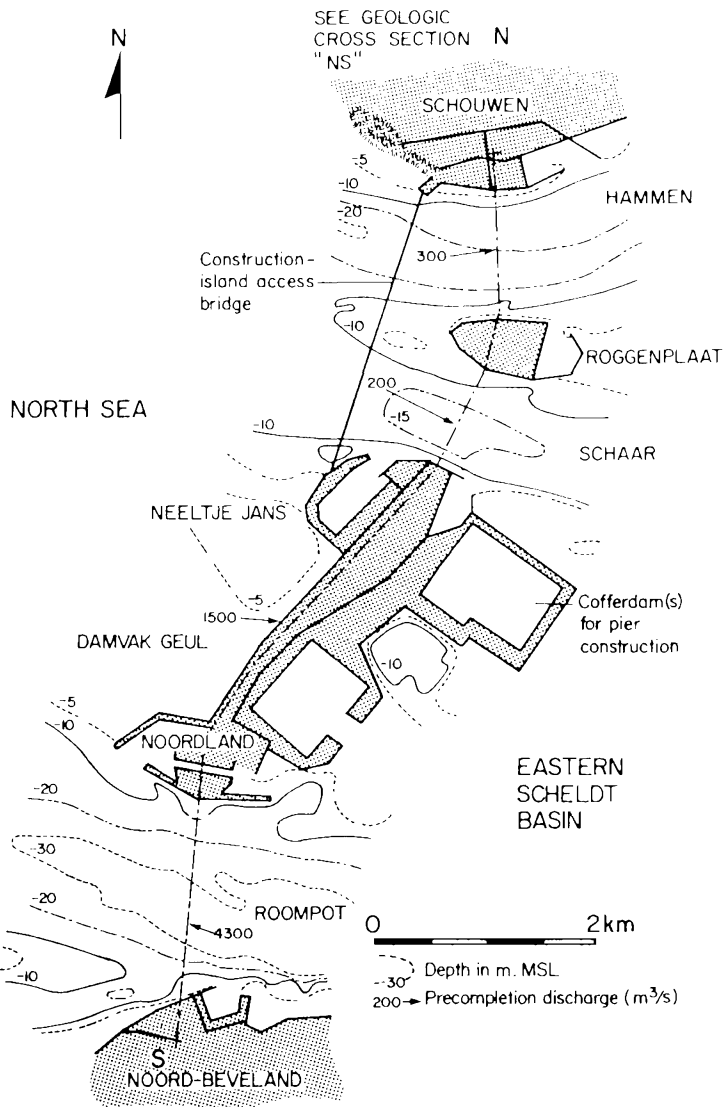


Figure 20b. Plan of the Eastern Scheldt estuary showing the two dredge-improved sandbank islands and three tidal channels controlled by the lift-gate barriers.

dually became fresh are shown in Figure 24.

The Eastern Scheldt barrier, as redesigned, remains open during normal circumstances, but may be closed for routine testing, and perhaps once a year when storm-surge flooding is predicted as a result, especially, of north-west storms (VAN AALST and BRUINSMA, 1987). A locking system facilitates shipping access to the North Sea.

Artificial Islands and Construction Cofferdams

Further to previous discussion, the first phase of the Eastern Scheldt scheme consisted of an extensive dredging operation to convert two natural sand banks in the estuary into permanent artificial islands. The larger of these was designed to serve as a convenient construction complex (Figure 20). Four cofferdam compart-



Figure 21a. Haringvliet cofferdam and dewatering system enabled piled foundations and sluice-gate support piers to be constructed in the dry. (Rijkswaterstaat Meetkundige Dienst Afdeling Reprografie).

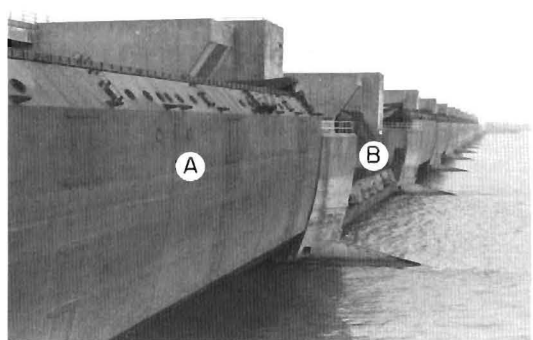


Figure 21c. Haringvliet sluice-gate barrier in operation. Note gate "a" open to facilitate Rhine discharge; gate "b" closed.



Figure 21b. Following completion of the Haringvliet sluice-gate barrier, the cofferdam was flooded and subsequently dismantled. (Rijkswaterstaat Meetkundige Dienst Afdeling Reprografie).

ments were built within the island, to match a four-phase construction sequence for barrier piers. The ring-dike cofferdams were excavated to approximately 15 m below sea level, to provide sufficient draft for the subsequent transport of piers. As soon as all of the piers in one section were completed, the compartment was flooded and a specially designed lifting vessel (Figure 25) was used to move the piers to the barrier center line.

Foundation Requirements

As emphasized, one of the most demanding

engineering-geologic aspects of the Eastern Scheldt project related to the preparation of foundation materials to support the barrier piers. In pier-and-gate design, foundation integrity is critical to ensure jam-free gate operation. Hence, the tolerances on initial levelling, on differential settlement, and on tilt resulting from foundation failure, are extremely stringent (NIEUWENHUIS, 1987; BOEHMER, 1978; BJERRUM, 1973).

As with previous barriers, foundation problems were compounded, on one hand, by the loose and/or soft and extremely variable nature of typical estuarine subbottom sediments (Figure 6), and on the other hand, by the scour potential of sea-bed sands in response to strong tidal currents (PILARCZYK, 1987).

Furthermore, to reap the full benefit of rapid prefabricated pier construction, piled foundations such as those used on the Haringvliet sluice gates, could not be used.

Engineering geologists and civil engineers, therefore, designed an extensive program of foundation investigations and preparation, to be implemented in a series of steps. These are summarized in the discussion that follows.

Site Investigation and Foundation Preparation

Investigation Phase 1

Conventional geophysical, drilling and sampling surveys and *in-situ* tests were conducted in an effort to delineate the 3-dimensional distribution of subbottom sediments. Combined

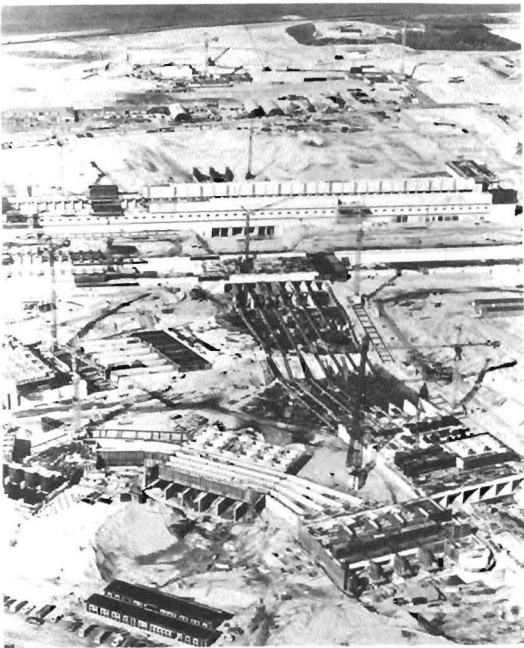


Figure 22. A further example of mega-scale cofferdam use for the construction of the pump house, support culverts and Kramer navigation lock system in the Philips dam. (After Rijkswaterstaat, 1987).



Figure 23b. A dredged-sand embankment over the rubble core completes the dike and eliminates a tidal influence on this section of the waterway. The Kreekrak lock system is in



Figure 23a. A critical section of Marquisate Quay under construction on the Scheldt-Rhine waterway link. Note the strong tidal flow through placed-fill core materials in the closure dike. (After Rijkswaterstaat, 1987).



Figure 23c. The 120 kilometer protected waterway between Rotterdam and Antwerp has created one of the busiest and most economical links in Europe for the transport of commercial cargo: this picture shows barges emerging from the Kreekrak locks. (After Rijkswaterstaat, 1987).

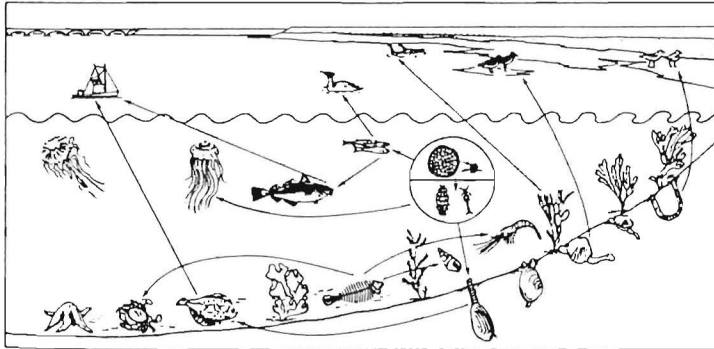


Figure 24. Some components of the estuarine food chain that would have been disrupted under the original master plan which called for complete closure of the Eastern Scheldt. (After de Jong *et al.*, 1987).



Figure 25. A specially designed vessel, *Ostrea*, transports a gate-support pier from the flooded cofferdam construction yard on Neeltje Jans, to the Eastern Scheldt barrier alignment. (Photograph by Bart Hoffmeester, Aerocamera. Rijkswaterstaat Meetkundige Dienst Afdeling Reprografie).

with laboratory-testing support, these surveys and tests assisted in the assessment of the engineering-geologic characteristics of each defined layer (VERMEIDEN AND LUBKING, 1978; WATSON and KRUPA, 1984; NIEUWENHUIS, 1987b).

Demucking

Soft, compressible clays and peats were excavated and replaced with sand.

Coarse Levelling

Depressions in the tidal channels were filled with sand to a design elevation, and covered with a layer of protective gravel to inhibit scour erosion.

Vibrocompaction

Large-scale vibratory compaction equipment was used to improve the bearing capacity of granular materials in the proposed vicinity of piers (VAN DER SCHAAF and OFFRINGA, 1980). Compaction was accomplished over a period of three years using a special compacting rig, *Mytilus* (Figure 26). The method, pioneered by the Dutch with smaller-scale equipment, is used to compact granular soils. The technique relies on the vibration of probes introduced into the ground, to rearrange the packing of discrete particles of soil into a denser configuration, and hence improve its mass per unit volume in the vicinity of the probe. As shown in Figure 26, *Mytilus* employed the simultaneous use of four vibrating probes, and at each set-up location was capable of compacting soils to a depth of approximately 15 m, over an area of about 6 X 25 m².

Investigation Phase 2

A second phase of geotechnical investigations assessed the results of compaction. This program employed a survey barge the *Johan V*, equipped with a conventional drilling rig for obtaining both "undisturbed" samples for laboratory testing and performing *in-situ* tests on site. An example of the latter is the dynamic Standard Penetration Test (SPT) used to determine the relative density of granular soils, and the consistency of cohesive soils (WATSON and KRUPA, 1984). In addition, *Johan V* was

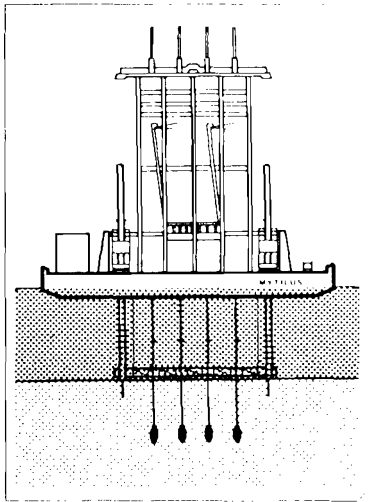


Figure 26. The Dutch are the pioneers of the vibrocompaction method used over a period of three years to improve the foundation characteristics of subbottom granular soils in the Eastern Scheldt estuary. Schematic diagram shows the specially-designed craft *Mytilus*, which employed the simultaneous use of four large-scale vibratory probes to achieve compaction. (After DOSBOUW v.o.f., 1983).

equipped with a diving bell which enabled *in-situ* seabed density measurements to be undertaken (VAN DER SCHAAF and OFFRINGA, 1980).

Anchor Piles

During construction a large number of vessels were required to work along the barrier alignment. Therefore, to prevent anchor damage to the prepared seabed, and to the erosion-protection mats that would subsequently be placed, underwater mooring piles were driven into the seabed. These were fitted with heavy mooring cables (attached to a marker buoy) which could be hauled aboard to secure a vessel for a particular task, and then cast off to rest on the seabed until needed again.

Erosion Mats

To protect the prepared seabed from severe erosion by tidal currents, a combination of polypropylene and concrete-block mats, asphalt slabs and graded-filter mattresses were used. This protection followed the proposed barrier alignment and extended for approximately 500 m on either side of the center line. As shown in Figure 27, the concrete-weighted erosion mat

and asphalt slabs formed the outer periphery of the seabed protection apron, while the more expensive graded-filter mattresses, subsequently discussed, were used under the gate-support piers.

Foundation Mattresses

Graded-filter foundation mattresses, each 36 cm in thickness, consisted of natural sands and gravels grading coarser in an upward direction; sand and gravel is held and separated by synthetic fabric and flexible stainless steel mesh, pins and cable (Figure 19).

The function of these mattresses, as discussed, was to prevent the erosion of foundation sands, but filter mats were designed also to meet a number of additional needs related to foundation integrity (PILARCZYK, 1987; V.D. BURG and NIEUWENHUIS, 1987; and VAN DER SCHAAF and OFFRINGA, 1980). For example, filter mattresses helped to dissipate porewater pressures created by pier-placement loading, and thus ensured that settlement was rapidly built out prior to the installation of gates. Furthermore, during storm-surge operation, filter mattresses will inhibit potential piping erosion due to the differential head of water across the barrier (when closed). Finally, graded filters were designed to prevent potential liquefaction of foundation soils by storm waves.

Foundation mattresses were placed by a specially-constructed barge *Cardium* (Figure 28). This vessel is fitted with a levelling dredge and compactor for final preparation of the seabed, before mattress placement. Each mattress is unrolled at slack tide from a large reel mounted on the after end of the barge. The lower mattress was laid in sections measuring 200 X 42 m². A second smaller mattress measuring 60 X 29 m² and again 36 cm thick was then placed at the proposed location of each gate pier. To ensure level placement of the pier base, fine-leveling adjustment was achieved with a third (block) mattress (Figure 29). Finally, a fourth, heavy stone-ballast mattress was laid down in sections of 200 X 13.5 m², to protect the filter-mattress joints. The foundation bed, prepared in this way along the entire center-line lengths of the lift-gate barrier sections, was now ready to receive piers.



Figure 27. Concrete-weighted erosion mats form the outer periphery of the seabed-protection apron of the Eastern Scheldt barrier (illustrated in Figure 29); an 18-cm geological notebook shows scale.

Pier Placement

As mentioned, a special pier transporter, the *Ostrea* was designed to move one prefabricated pier at a time from the flooded coffer dams, to the barrier alignment (Figure 25). The design of the Barrier called for 65 piers with base dimensions of 25 X 50 m² and a maximum height of 43 m (VAN DER SCHAAF and OFFRINGA, 1980). Positioning was achieved by securing the *Ostrea* to a mooring pontoon, the *Macoma*. *Macoma* was fitted with a broom-type suction dredge capable of removing any sand which might have collected on the upper foundation mattress (DOSBOUW, 1983).

Rip-Rap Sill

To provide for the long-term stability of installed piers, and the adjacent foundation area surrounding piers, an extensive sill of graded rip rap was placed so that, on completion, piers were embedded within several layers of rock (Figure 30).

The sill required some five million tons of rock rubble supplied from quarries in Belgium, Finland, Germany and Sweden. The selection of suitable rock and the design of such a large structure represents a significant engineering-geologic undertaking in itself (BRUUN and JOHANNESSON, 1976; BRUUN and KJELSTRUP, 1981; WATSON *et al.*, 1975).

Rock borrow was imported over a period of four years and stockpiled on the construction islands (Figure 31). It subsequently was placed



Figure 28. As part of the foundation for the Eastern Scheldt barrier, a specially-designed barge was used to lay down filter mattresses on the prepared seabed (from reel on the aft-end of the barge). Drawing shows: (1) foundation mattress being unrolled, (2) weighted beam which holds the end of the mattress in place, (3) small surface compactor and (4) a small leveling dust-pan dredge. (Photograph by Bart Hofmeester, Aerocamera. Rijkswaterstaat, Meetkundige Dienst Afdeling Reprografie).

in the barrier configuration over a period of two years.

Like the foundation mattresses, the sill was of graded design, with four layers of rip rap quarry stone, increasing in size in an upward direction above a filling-in layer of 5-40 kg slag and stone on the upper foundation mattresses. Above this sill, layers consisted of stone rubble in the weight ranges of: (1) 10-60 kg, (2) 300-1000 kg, (3) 1-3 tons and (4) a shell of 6-10 ton armor stone, protecting the outer seaward side of the barrier (VAN DER SCHAAF and OFFRINGA, 1980).

Smaller quarry-run stone was dumped, but to avoid damage to piers, larger rip rap had to be placed with special vessels (Figure 32).

Placement of the armor stone completed the foundation.

Superstructure

Sill Beams: As shown in Figure 30, the lowest components of the superstructure consist of prestressed concrete sill beams. These beams resting on and embedded in rip rap, serve as a smooth closure base for the steel drop gates.

Road-Bridge Box Girders: These consist of prestressed concrete beams, 45 m in length (Figure 30). The spaces within the box girders protect part of the hydraulic gate-operating machinery from corrosive sea spray.



Figure 31. Some five million tons of rock rip rap were imported from quarries in Belgium, Finland, Germany, and Sweden to protect the foundations and lower sections of structural components of the Eastern Scheldt barrier. (Rijkswaterstaat Meetkundige Dienst Afdeling Reprografie).



Figure 32. Larger armorstone rip rap had to be placed by a special vessel to avoid damage to piers. (Photograph by Bart Hofmeester, Aerocamera, Rijkswaterstaat Meetkundige Dienst Afdeling Reprografie).

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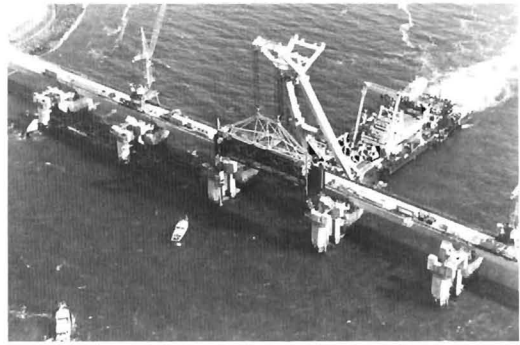


Figure 33a. All large superstructure components of the Eastern Scheldt barrier were installed by the 1,600 ton floating *Taklift 4*. (Air photographs by Bart Hoffmeester, Aerocamera, Rijkswaterstaat Meetkundige Dienst Afdeling Reprografie). (a) installation of a gate.



Figure 33 cont. (b) Installation of a road-section box girder (Photograph shows the barrier across one of the three channel sections of the Eastern Scheldt estuary).

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Figure 33 cont. (c) A close-up of the pier-supported, lift-gate sections of the barrier.

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□ ZUSAMMENFASSUNG □

Ein Multi-Milliarden-Dollar-Komplex von Küstenbauwerken schützt die Delta- und Ästuar-Regionen der südwestlichen Niederlande vor der Wiederholung der Sturmflutereignisse von 1953, bei denen 1835 Menschen ums Leben kamen. Insgesamt sind seit 1717 8 grosse Sturmflutkatastrophen belegt. Das Deltaprojekt gewährt bereits seit 1986 vollen Sturmflutschutz, obwohl immer noch Teile davon unvollendet sind. Als eines der grössten zivilen Bauprojekte der Erde haben seine 11 Haupt- und zahlreichen Nebenabschnitte die Aufgabe (1) drei Hauptästare abzuschneiden und damit die Küstenlinien um ca. 720 km zu verkürzen, (2) als Verbindung zwischen Schelde und Rhein einen gezeitenfreien Wasserweg zu schaffen, der die Schifffahrt zwischen Antwerpen und Rotterdam (120 km), zwei der grössten Häfen der Welt, erleichtert, und (3) Teile der Deltafläche zu schützen.

Diese Fallstudie beschreibt die geologischen und Fundamentierungsprobleme, die Planung und den Bau, die Voruntersuchungen und Vorbereitungen der Fundamente, die Methoden der Konstruktion und die Wechselwirkung zwischen Untergrund und Aufbauten. Hauptgegenstand ist die reisige Kontrollbarriere von 7,5 km Länge, welche 1986 die östliche Scheldemündung abschloss und die bei weitem der schwierigste und teuerste Bauabschnitt war. Hier und in anderen Teilen des Deltas haben die mangelnde Erfahrung mit solchen Bauwerken, die komplexe lokale Geologie und die starken Gezeitenströmungen dazu geführt, dass allein die Fundamentierung 80% der gesamten Bauzeit in Anspruch nahm. Die dabei neu entwickelten Techniken werden in Zukunft weltweit bei Küsten- und Seebauwerken verwendet werden. — *Dieter Kelleat, Essen, FRG.*

□ RÉSUMÉ □

C'est un complexe de constructions côtières coûtant plusieurs milliards de dollars qui protège la Hollande d'une répétition de la catastrophe de 1953 qui fit 1835 morts. Depuis 1717 huit invasions de la mer avaient été enregistrées. Le projet de Delta ne protège efficacement le pays de l'inondation que depuis 1986, mais certaines sections sont encore en construction. Ce projet d'ingénierie civile est un des plus vastes du monde. Il a onze composantes majeures et de multiples autres, secondaires. Leur fonction est de: (1) fermer les principaux estuaires, ce qui raccourcit la ligne de rivage à 720 km; (2) créer un accès non soumis à la marée au "Scheldt-Rhein" pour faciliter l'accès aux navires d'Anvers à Rotterdam (120 km), deux des plus importants ports du monde et (3) assurer une préservation partielle de l'environnement du delta.

Cette histoire de cas concerne la géologie et les problèmes de fondations, la planification et les séquences de construction, la recherche sur le site et la préparation des fondations, les méthodes de construction et l'interaction fondations-structures. Le point clé est la digue-barrière de protection à grande échelle terminée en 1986, traversant sur 7,5 km l'estuaire de Scheldt de l'Est qui constitue de loin la partie la plus difficile et la plus coûteuse du projet. Ici comme dans d'autres parties du delta, les forts courants de marée et la grande variabilité des matériaux géologiques peu appropriés aux constructions d'ouvrages ont fait que 80% du temps de la construction ont été nécessaires à l'établissement des seules fondations. Les nouvelles techniques qui ont été développées pour le projet ont une application à l'échelle mondiale pour les futures constructions côtières et offshore. — *Catherine Bressolier, Géomorphologie EPHE, Montrouge, France.*

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