# CHAPTER 141

Hydraulic research in the Oosterschelde Estuary.

A.W. Walther

Head of Hydraulics Division, Delta Department of the
Ministry of Transport and Waterways, The Netherlands.

In 1974 a major policy change was made to the Delta plan (fig. 1) to close the Oosterschelde (East Scheldt). For ecological reasons it was decided to replace the originally planned barrier dam with a storm surge barrier. This could be opened to allow normal tidal movement or closed during storm surges.

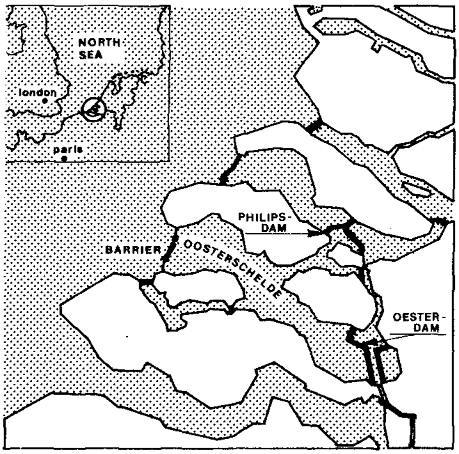



Figure 1: Delta Plan, Netherlands.

Instead of completing the dam in 1978, the new structure (fig. 2) would be finished in 1985. The vertical tidal movement in the estuary would be reduced to about 80 per cent of the original tidal range, while under storm surge conditions the storm surge barrier (with a cross-sectional area of about 15,000 sq.m.) could be closed, thus serving both ecology and safety at the same time. This new concept

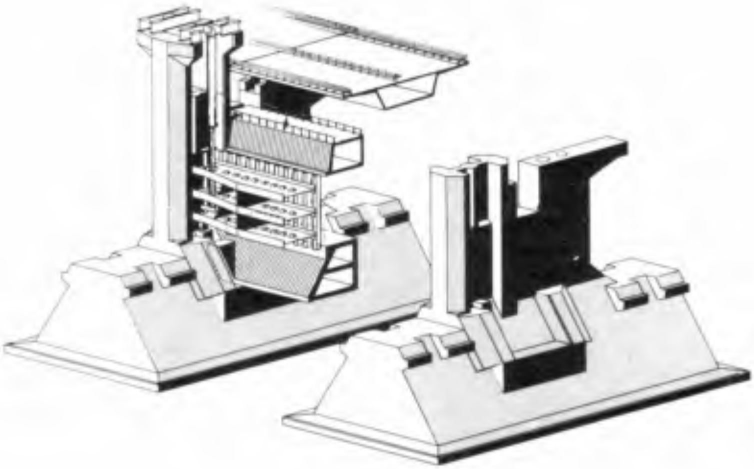


Figure 2: Storm Surge Barrier.

required a large number of new investigations in coastal engineering and soil mechanical fields.
In the "Driemaandelijks Bericht Deltawerken", an illustrated quarterly Dutch magazine with English abstracts (1), both the design of the barrier and the investigations are described.
The soil mechanical research was reported in the "International Symposium on Soil Mechanics Research and Foundation Design for the Oosterschelde Storm Surge Barrier" in 1978 (2).
The results of the hydraulic research will be presented during a symposium in August 1980 (3).
This paper gives a general description of some of the hydraulic investigations.

In the design stage of the storm surge barrier a probabilistic approach of the hydraulic loading conditions of the structure was made. The barrier must survive a force with a frequency of exceedance of $2.5 \times 10^{-4}$ per annum. The starting point in the determination of this force is formed by the three-dimensional probability density function of storm surge levels, wave energy and basin levels. Basically there are two ways of extrapolating the measured data of these parameters and their correlation into regions of low probability of occurence, where measured data are not available viz. statistical extrapolation or extrapolation by means of mathematical models based on physical laws and checked with measured data. A combination of these methods has been used in finding the probability density function of storm surge levels and the conditional probability density functions of wavespectra and basin levels, from which the three-dimensional probability function is derived.

The probability density function of the storm surge level is based on 40 years of historical data; extremes are predicted by statistical extrapolation. The knowledge of the physical laws governing this phenomenon has been used to see whether predicted extremes could be reached.
The conditional probability density function of basin levels depends at least partly on the closing strategy of the barrier during storm surges. A simple model was developed based on the fact that a storm is formed by a random combination of wind set up and astronomical tide. From this model the conditional probability density function of basin levels (conditional on storm surge level) could be derived for different closing strategies. The basin level was found to be virtually statistically independent of the wave energy.
Studies were made on local wave and wind conditions, and their relationship with conditions in the North Sea. It was found that not only the wind but also the water level, currents and swell entering from the sea exerted influence on the wave movement.
In addition, waves were greatly influenced by the shallows in this area. The wave spectra near the barrier show in general two peaks. It appeared from the data that a loose correlation exists between the storm surge level and the significant wave height. Lack of data prevented a reliable extrapolation of this two-dimensional probability function by purely statistical methods. Therefore a mathematical model has been developed. It is based on the hypothesis that the typical double peaked form of the wavespectrum is caused by the fact that the wave energy orgininates from two sources. Waves entering the estuary from deep water via the shoals near the mouth of the estuary are influenced by processes of breaking, bottom dissipation and refraction by depth and current. The wave energy reaching the barrier depends strongly on the storm surge level. In addition, waves generated by local windfields, show a loose relation to the general storm intensity. In fig. 3 the outline of the idea is given. A numerical model which incorporates all these effects is tested in a hindcast of several storms. For these storm conditions the model is in good agreement with the measurements (fig. 3).
The input for this mathematical model are the wave conditions on the border of the Oosterschelde, the storm surge level and the local windspeed. It is clear that for extrapolation to extreme circumstances these quantities have to be known. As reliable statistics of the windfield are difficult to get, starting point is the probability of exceedance curve of the storm surge level. Using a model that relates the wind set up to the windspeed and the maximum storm surge level to the wind set up and the astronomical tide, the two-dimensional probability function of maximum storm surge level and windspeed is obtained. A theory of wavegrowth and wave propagation on water of limited depth gives, combined with the two-dimensional probability density function of windspeed and storm surge level, the two-dimensional probability function of maximum storm surge levels and significant wave heights on the border of the Oosterschelde.
The introduction of the breaker criterion for the shoals shows that nearly all wavefields generated on the North Sea during an extreme storm will break on the shoals. Therefore the wave height at sea will not influence the energy penetrating in the Oosterschelde. The maximum storm surge level is the only parameter that matters for the penetration.

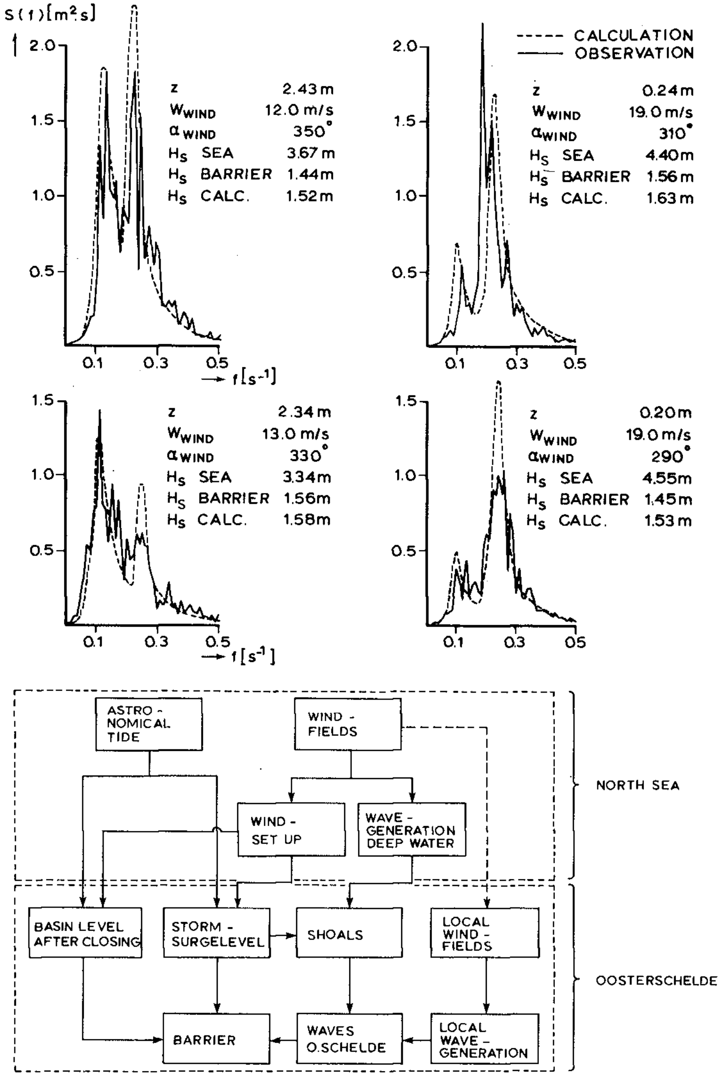



Figure 3: Wave model and results of hindcasts.

The second source of wave energy near the barrier is related to the local windspeed. A relation between local windspeed and the windfields at sea has been established.
The barrier will be maximally loaded during the maximum storm surge level, because the differences between sea level and basin level and the amount of low frequency wave energy penetrating from the North Sea are both maximal.
By joining together the above mentioned models the two-dimensional probability function of maximum storm surge levels and local windspeeds is obtained, where for every combination the wave spectrum near the barrier is known. By adding this to the conditional probability density function of basin levels, the three dimensional probability density function of maximum storm surge levels, wave energy and basin levels is derived. This function is used as input in the calculations of the probability distribution of the hydrodynamic load on the storm surge barrier.

The construction of the barrier across the Oosterschelde mouth will affect the tidal regime in the estuary. Reducing the present 80,000 sq.m. cross-sectional area across the mouth of the Oosterschelde to an effective aperture of 14,000 sq.m. will decrease the discharges through the aperture. As a consequence the tidal range in the basin will be reduced. The tidal regime will not only be affected by the construction of the barrier, however, but also by the construction of compartment dams. Two compartment dams, the Philipsdam and the Oesterdam, (fig. 1), will be incorporated to aid water management and to provide a tide-free shipping route between Antwerp and the Rhine passing through the rear of the Oosterschelde. Due to the compartment dams the storage area of the Oosterschelde basin will be reduced to about 80% of its original value.
The tidal movement in the estuary was studied by means of field measurements, one- and two-dimensional mathematical models, a one-dimensional electric analogue model, stationary hydraulic models and a non-stationary overall hydraulic model (fig. 4).

Figure 4: Hydraulic model of the Oosterschelde

The boundary conditions of the models were obtained from extensive measurements in the prototype (fig. 5).

Figure 5: Flow measurements near the Philipsdam.

A comparison between the various types of models shows that each type has its pecific advantages and specific drawbacks.
Numerical one-dimensional network models can be applied when the estuary is mainly composed of gullies separated by shallow areas. Water levels and discharges are the relevant quantities.
Two-dimensional numerical models (two-dimensional in a horizontal plane) are used in coastal areas and seas and in wide estuaries where the current direction is not related directly to the bottom geometry.
Hydraulic models are applied for estuaries with complex bottom geometries where information about current velocity distributions is very important.
It should be stated, however, that recent development in numerical solution thecniques make it more and more adveantageous to apply

numerical models instead of hydraulic models. However, there is one important exception: near sluices and closure gaps the flow pattern is so very complicated that only a three-dimensional description is adequate.
For the closure-operations of the Brouwershavense Gat (1971) three methods for predicting the velocities were used simultaneously. The concrete caissons could be sunk only during low water slack tide. With higher velocities the forces acting on the caissons would be too large for positioning. A combination of the predictions of the hydraulic model and the electric analogue model Deltar is given in fig. 6 (prediction Deltar).

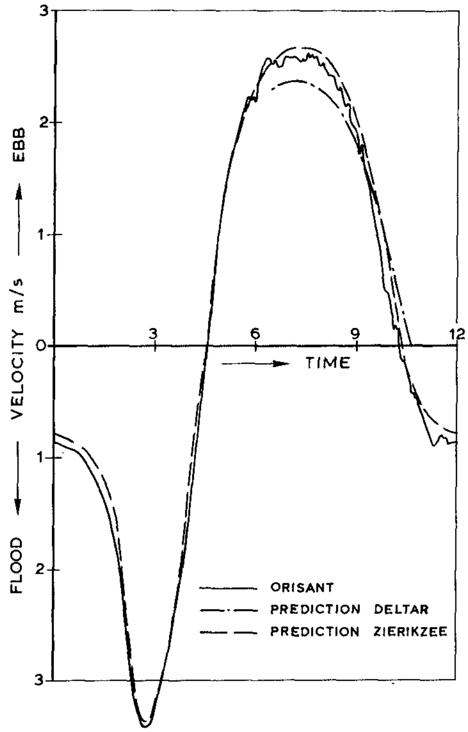



Figure 6: Predicted (see text) and observed (Orisant) velocities during Brouwershavense Gat closure 27 april 1971.

The observations of nature were used of about one tidal period preceding the closure operation. In the figure also a curve is given of a prediction based on the analysis of the measurements of a large number of tidal curves preceding the operation (prediction Zierikzee in fig. 6). This method in general proved to be somewhat more accurate. An example is shown in the figure. From this example the importance of field measurements can be derived.

Knowledge of tidal moevements in an estuary is also important for the study of the salinity since the salinity distribution is mainly influenced by tidal motion and fresh water input.
In the case of the Oosterschelde the main fresh water input is controlled by sluices and kept approximately constant. The discharge of the river Rhine into the North Sea may also influence the salinity in the Oosterschelde under certain circumstances. With northerly winds especially, the water from the Rhine forms a large proportion of the coastal water around the mouth of the Oosterschelde.
The construction of the storm surge barrier is intended to maintain the ecological function of the Oosterschelde. An example is given in fig. 7, depicting the number of species living in the water as a function of the chlorinity.

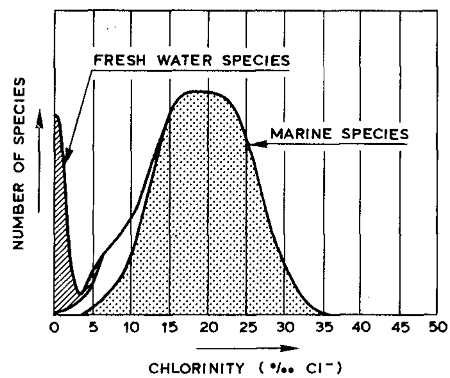



Figure 7: Remane-curve: number of species as a function of chlorinity.

This ecological function depends, amongst others, on the salinity which must be kept as high as possible. This suggests that the fresh water input has to be reduced in order to compensate the decrease of salinity intrusion due to the reduction of the tidal motion.

For the study of the influence of the tidal reduction on the salt intrusion several means have been used:
- the hydraulic model of the Oosterschelde with horizontal scale 1/400 and verticale scale 1/100 (fig. 4),
- the two-dimensional depth integrated mathematical model (4) and
- a one-dimensional tidal averaged mathematical model.

The hydraulic and two-dimensional mathematical model can only deal with vertical homogeneous conditions. In the main part of the Oosterschelde this condition is satisfactory. Because of the small fresh water input the longitudinal salinity gradient is too small to create important density currents and stratifications. This is also the case in the present situation with a much larger fresh water supply.
The one-dimensional model may also be used for situations where moderate density currents are present, but it needs more information about the mixing processes than the two other models. This information is contained in the longitudinal dispersion coefficient D. It is not possible to obtain a general theoretical expression for the dispersion coefficient as a function of tidal parameters and characteristic geometrical and morphological quantities. For particular transport processes in simple geometrical configurations one may deduce from theory the dependance of D on tidal parameters, yielding $D = \gamma u_0^2 T$. Here $u_0$ is the amplitude of the tidal velocity and T the tidal period. The parameter $\gamma$ may still depend on the tidal parameters in various ways according to the considered transport mechanism.
Simulations of the present salinity distribution in the Oosterschelde with the hydraulic scale model by means of a permanent rhodamine injection showed that the tidal flushing was larger in the model than in nature, which might be related to the relative large depth of the model. The influence of the tidal reduction on the salinity distribution in the model was in agreement with $D = \gamma u_0^2 T$ with no significant dependance of $\gamma$ on tidal parameters. Predictions for the salinity distribution were made with the one-dimensional model using a dispersion coefficient reduced proportional to $u_0^2$ with respect to its value in the present situation.
The study of the salt intrusion in the Oosterschelde is focused on the following questions:
- Which constructions are necessary in order to regulate the salinity regime in the estuary?
- How must the locks and the storm surge barrier be operated in order to prevent low salinities?

Possible constructional devices are:
equipment in the locks to keep the salt and the fresh water separated as much as possible during the passage of ships, as will be discussed later on,
connections with other estuaries through which water can be flushed so that circulation in the connected estuaries is increased.
Finally one might consider the possibility of opening and closing certain gates in the storm surge barrier alternately during flood and ebb, stimulating circulatory currents between the different main channels in the estuary.
The use of such interventions depends on the occurrence of external conditions such as intense rainfall or large Rhine discharges in the coastal area. Therefore studies have been undertaken concerning the intensity and the frequency of these circumstances and their influence on the salinity distribution on the Oosterschelde.

In the Philipsdam and Oesterdam, which are to be built in the eastern part of the Oosterschelde, shipping locks will be constructed. These locks

form the connection between the fresh water lake called Zoommeer and the salt Oosterschelde.
The locks are to be eguipped with systems to prevent, as much as possible, the intrusion of salt into the Zoommeer and fresh water into the Oosterschelde caused by passing ships. These systems are called fresh/salt-separation systems.
In the Philipsdam five locks will be built, three large locks, dimensions 24 x 280 $m^2$, and two small locks, dimensions 9 x 80 $m^2$.
The fresh/salt-separation system is, like the lock in the Oesterdam, based on the difference in specific weight between fresh and salt water. During the exchanging of salt and fresh water, the interface between it moves vertically. A similar system has already been designed for a lock in the channel of Mardyck near Dunkirk in France and for the Kreekrak-lock in The Netherlands (5).
When designing the locks in the Philipsdam, it became clear that the guality of the fresh/salt-separation system depends strongly upon the stability of the interface layer between the fresh and salt water. This layer needs to be as thin as possible, as the stability diminished with the thickness of this layer.
In the framework of the study for the locks in the Philipsdam, with a hydraulic model, the factors which influence the mixing during the exchanging process haven been investigated. The way fresh water flows into the lock chamber through openings in the wall turns out to be an important factor in the mixing process. As the Kreekraklocks have been designed with valves, that are halfway in the culverts through the walls, the locks in the Philipsdam will be equippped with valves that are on the lock chamber side of the wall.
Two-dimensional model studies show that the thinnest interface layers occur when the valves move in such a way during the beginning of the downward movement of the interface layer, when fresh water flows into the lock chamber, that at this moment a situation exists in which a practically resting salt tongue is above the valve, over which fresh water flows towards the middle of the lock chamber. Therefore the movement of the lock chamber depends in principle upon the drop of head of the fresh water through the culverts, and upon the difference in density across the locks.
Model studies (scale 1:20) show that with valves and culverts of the Kreekrak locks, interface layers of approx. 2 m thickness occur while under comparable circumstances with valves and culverts of the Philipsdam locks, this thickness is reduced to approx. 1 m. Compared with the Kreekrak locks an improvement of the guality of the fresh/salt-separation system is expected with the Philipsdam locks system, based on the possibilities of optimizing the movement of the wall culvert valves of the Philipsdam locks.

The lock that is to be built in the Oesterdam and equipped with a fresh/salt-separation system, has a lock chamber area of 10 x 90 $m^2$, incidentally to be enlarged to 14 x 100 $m^2$ later. This system differs from that of the locks in the Philipsdam, although this system also means that during the passage of ships the water in the lock chamber around the ships changes with closed gates from salt to fresh water or vice versa. The difference, however, is that this exchange in the Oesterdam lock takes place by moving a large basin, filled with salt water, in a vertical direction.

A ship, sailing from the Oosterschelde towards the Zoommeer, sails into this basin, which is surrounded by fresh water. The edges of the basin are about 10-20 cm above level of the fresh water. After entry the gate is closed and the basin moves downward underneath the ship, while fresh water flows around the basin towards the ship (fig. 8). A similar movement in the opposite direction is performed with a ship sailing towards the Oosterschelde. Such a system is called a submersible salt basin lock.
The submersible salt basin system was chosen for the Oesterdam, as the ecosystem of the Oosterschelde, nearest to the Oesterdam, is more sensitive to fresh water than the part of the Oosterschelde near the Philipsdam.

The sediment movement during and after construction of the barrier is important. The sediment consists mainly of fine sand, mean grain size approximately 0.2 mm. Part of the foundation-bed of the piers and part of the layers of the sill have to be constructed in trenches dredged across the riverbed in all gaps. Siltation in these trenches during the construction may lead to the formation of sandlayers, which may be washed out at extreme storm surge conditons due to the very high pressure gradients over the foundation, when the gates of the barrier are closed. If the sand is washed out unequal settlements may occur which will affect the stability of the barrier.
The degree of siltation per construction stage depends on the duration of the stage, on the supply of sediment, on the hydraulic conditions (wave action and flow) and on the shape of the trench. These factors vary along the alignment of the barrier. The amplitude of the tide is about 3 m, maximum velocities are about 1.5 m/sec.
In order to make a prognosis a calculation method should be available to determine the rate of siltations as function of the above mentioned parameters. A mathematical model[1)] to determine the siltation in trenches in tidal rivers with mainly suspended load was already available. Application of this two dimensional model is only useful for trenches with relatively gentle slopes of non cohesive bed material in quasi steady flow conditions.
As in the design relatively steep slopes were introduced for the trenches, the mathematical DHL-model had to be adjusted accordingly. An additional adjustment had to be made to assess the effects of the grainsize distribution of the sediment in suspension. Finally, the calculation method had to be adjusted to non-stationary situations in which the time lag of settling respective resuspension has to be taken into account. Oblique flow towards the trenches and currents in bends will cause secondary flows and inherent sediment transport in longitudinal direction.
It soon became clear, that it was impossible to develop a model that could well reproduce the three-dimensional hydraulic circumstances within the fixed period of time. Moreover, it is expected that three-dimensional effects will occur only locally in the immediate vicinity of the banks. It was therefore decided to develop two dimensional models (streamlines perpendicular on the axis of the trenches).
The DHL-model was extened and Svasek Engineering Consultants developed the SGB-model[2)].

1) developed by the Delft Hydraulics Laboratory (DHL).
2) SGB stands for the initials of the members of the team which set up the model: J.N. Svasek, M.B. de Groot and A.J. Bliek.

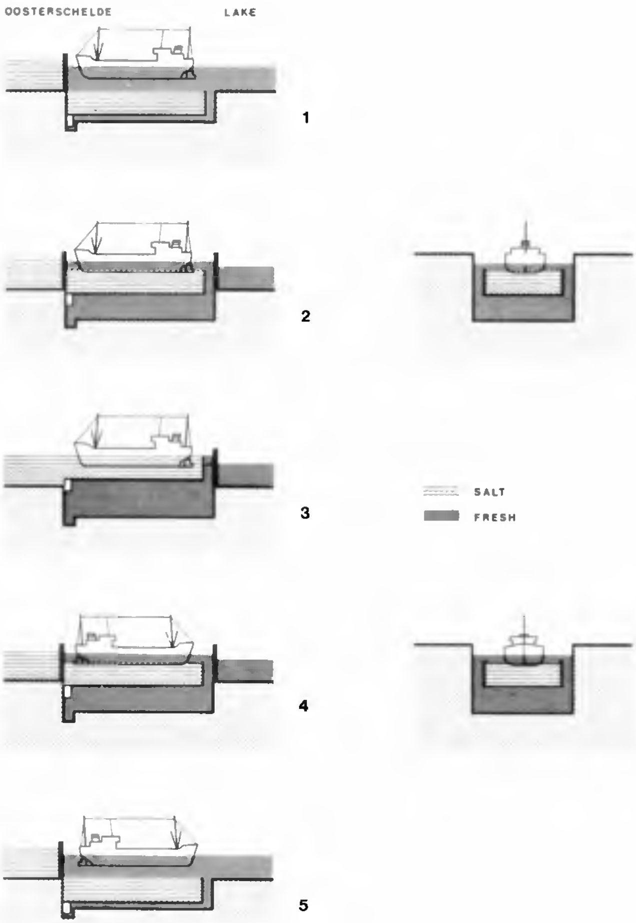
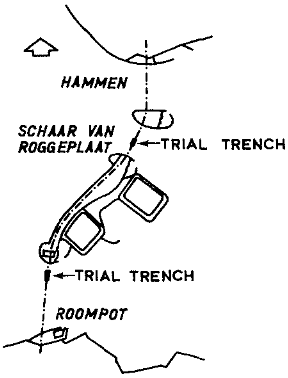



Figure 8: Oesterdam ship lock with vertical shiplift 1-3: Ship traveling from the fresh lake to the salt Oosterschelde, 4-5 ship traveling from Oosterschelde to the lake.

Field tests were made to determine the sediment transport across the alignment of the storm surge barrier and the sedimentation of sand during the construction phase. To establish the reliability of the models the results of the computations were tested against field measurements in trial trenches. Current velocities and sediment concentration were measured simultaneously. The grainsize distribution of the sediment thus collected was analyzed. At the same time the boundary conditions for the flow and the sediment transport could be derived from these field measurements.
The storm surge barrier will be built in the three flow channels present in the mouth of the Oosterschelde (see figure 9).



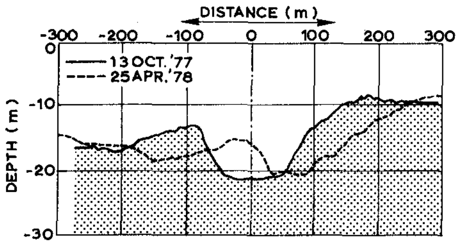




Figure 9: Situation of trial trenches in the mouth of the Oosterschelde. Cross section of trial trench Roompot.

The northern channels, the Hammen and especially the Schaar van Roggenplaat, present a reasonable two-dimensional flow field. The flow field in the Roompot presents a strong three-dimensional character. The two northern channels can be well compared as far as the sediment transport and the presence of a bed protection is concerned. Therefore the result of measurements taken in one of these channels holds also for the other. Measurements taken in a trial trench in one of these channels would be well suited to test the developed mathematical models.
A trial trench was dredged in the Schaar van Roggenplaat as conditions to take measurements there were generally more favourable than in the Hammen. To determine the influence of the three dimensional effects a trial trench was also dredged in the Roompot.
In the trial trench in the Roompot a significant rate of siltation was only found on the steep western slope (1:4); the siltation increased from south to north. Due to the difference in siltation the alignment of the slope rotated and shifted in eastern direction with an average of 0.02 m/day in the southern part and an average of 0.35 m/day in the northern part. As shown in figure 9 the eastern slope was eroded.
The figure shows that the eastern slopes are stable (irrespective of the shifting) and that the eastern slopes are fading away. At the same time on the eastern slope large sand waves haven been formed.
Over the whole area of the trial trench in the Schaar van Roggenplaat continuous siltation took place. According to the sounding results a siltation of 0.01 m to 0.02 m/day takes place over the whole of the trial trench Schaar, whereas the area outside the trench remains stable. On the bottom of the trench, ripples were formed up to a height of 0.5 m. In general the slopes of the trenches decrease with time.
In order to gain more insight into the local variations of sediment-increase, divers placed nine measuring tubes in two sections, which protruded right after the installation 1 meter from the bottom. Periodically the tubes were measured from top to the sand level. It appeared that local significant variations can occur, even more than 0.6 m in a three-day period. This variation is probably caused by migrating bed-ripples.
The rate of deformation of a sandy trench bed was investigated by means of echo soundings. Immediately after having dredged the trial trench in the Roomport, trying to keep the bottom as level as possible, the irregularities proved to be smaller than 20 cm in vertical direction. During the tidal period following the levelling of the trench, ripples were formed up to a height of approximately 1 meter. There was little or no difference between the characteristics of the ripples found one week after dredging the trenches and several months later. The ripples in and adjacent to the trial trench Roompot proved to be approximately twice as high and as long compared to those in the trial trench Schaar, whereas the slopes were more or less equal.
From the results of the field tests and the models, it was concluded that the siltation rate in the trenches will be very high even if short periods are considered. An adaptation of the construction schema was needed so that as many layers of the foundation-bed as possible are constructed in one run. The sandlayers sedimentated in the interval between two runs have to be removed. The period between the removal of the sediment and the next run must be kept very short, less than a few hours. To this end special equipment was developed.

Around 1985 when the Oosterschelde barrier will be completed, the hydrodynamic regime will change and as a result, the sedimentation and erosion pattern will change too.
Under the present conditions the bottom of the Oosterschelde consists mainly of sand. Only the border of the estuary is built up of silt and very fine sand. This area with tidal flats, outer-dike saltings and mudflats, is of very high ecological value. For this reason and because of the use of the shallow areas of the estuary for fishing, a change in silt and clay movement can have important consequences.
Silt consists of organic and inorganic matter. Silt can be transported; it is affected by erosion and sedimentation; it can be consumed. The silt concentration is also influenced by mineralisation and primary production. It is obvious that a full understanding of this complex matter is extremely difficult especially with respect to the consequences for the fauna.
As a first approximation a simple erosion-sedimentation-model was used. This model will not supply a new concentration distribution but will merely indicate areas with possible future silt sedimentation.
Erosion of a silt layer takes place when the velocity of the current causes a bottom shearstress ($\tau$), larger than a critical value ($\tau_c$). Expressed in terms of shear velocity ($v_*$) the following relation between erosion and shear velocity is given by Partheniades (6):

$$\frac{dm}{dt} = M \left[ \left(\frac{V_*}{V_{*c}}\right)^2 - 1 \right]$$

m is mass of eroded matter per unit area and
M is constant.

Sedimentation of silt will occur when $\tau$ is smaller than the critical shear stress for sedimentation ($\tau_1$).
As the value of $\tau_1$ is smaller than $\tau_c$, there can be a period during the tidal cycle in which sedimentation and erosion are in balance.
Krone (7) gives the following relation, expressed in terms of shear velocity:

$$\frac{dm}{dt} = cw \left[ 1 - \frac{V_*}{V_{*1}} \right]$$

c is concentration of the suspension and
w is fall velocity.

The constants in the relations are derived from litterature and no comparison with field data is yet available. The following values for the constants were used:

$V_{*c} = 0.03$ m/sec, $V_{*1} = 0.009$ m/sec, $w = 3.10^{-4}$ m/sec and

$M = 0.210^{-3}$ kg/m$^2$/s.

The values of $V_*$ are derived from a one dimensional tidal model.

Figure 10 shows the schematisation of the one dimensional tidal model and the potential silt sedimentation under present conditions. It is remarkable that sedimentation appears only in branches which come to a dead end. This phenomenon corresponds with collected field data. This is also the case for the sedimentation in the channel which was closed in 1972 near the future storm surge barrier.
Computations with this simple model show that after completion of the storm surge barrier and the secundary dams the areas with silt sedimentation will expand.

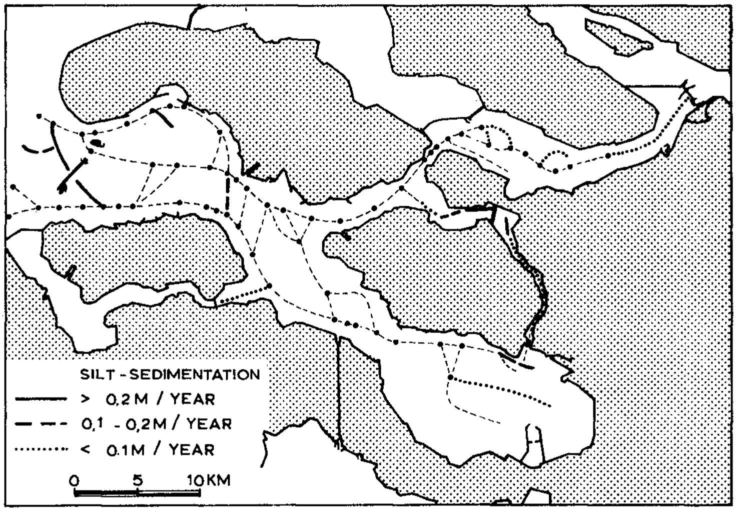



Figure 10: Results of simple siltation model (present situation).

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Mrs. J. den Elzen prepared the manuscript.

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