CHAPTER 32

INVESTIGATIONS OF THE TIDES AND STORM SURGES FOR THE DELTAWORKS IN THE SOUTHWESTERN PART OF THE NETHERLANDS

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The purpose of this paper is to summarize investigations of the tides and storm surges for the deltaworks in the southwestern part of the Netherlands.

The investigations into the tidal currents and H.W.levels in the coastal area will be treated more in detail.

INTRODUCTION

In order to protect the southwestern part of the Netherlands against inundation by storm surges, the "Delta project" has been undertaken. This entails the closure of three large sea arms situated between Western Scheldt and Rotterdam Waterway and will bring about radical changes in the tidal movement and stormflood levels of the estuaries and tidal rivers.

The contours of the project are shown in fig. 1. It includes three big dams to be built in the mouths of Eastern Scheldt, Brouwershavense Gat and Haringvliet, as well as two smaller ones to be constructed further inland. An idea of the extent of these works may be gained by knowing the tidal volumes of the estuaries: Veerge Gat 2,5.10^9 cu. ft; Grevelingen 4.10^9 cu. ft; Haringvliet 9.10^9 cu. ft; Brouwershavense Gat 12,5.10^9 cu. ft and Eastern Scheldt 39.10^9 cu.ft.

The waters of the Delta area will then be divided into two separate basins by means of a dam in the Volkerak. The southern basin will be entirely cut off from the sea, becoming a fresh water lake. The northern, comprising the mouths of the Rhine and the Meuse will remain in communication with the sea, because the Rotterdam Waterway must stay open to shipping. Consequently, the tides and storm surges will still be able to penetrate inland via this mouth, but they can cause high waterlevels in the Waterway only; in the rest of the basin their effect will be considerably weakened. In the situation at present, however, the upland flow of the rivers Rhine and Meuse is mainly into the Haringvliet estuary and not the Rotterdam Waterway. As the Haringvliet estuary will be closed, large sluices are to be built in the enclosure dam as a substitute for the existing free discharge of the river water.

Until this project is completed the inhabitants of the area which it will affect are insufficiently safe against storm surges. It is, of course, always possible that floods too high for existing dike systems will occur, but in the present situation the risk is too great. This was demonstrated in February 1953 when the southwestern part of the Netherlands was suddenly hit by an exceptionally high storm surge which caused many dike breaches and vast inundation. The occurrence of a similar surge or a higher one may be estimated as once in two hundred and fifty years, as an average, which is much too high. After the realization of the Deltaplan and the heightening of the dikes of Western Scheldt, Rotterdam Waterway and the northern parts of the country, the dikes are safe up to very high storm surges of which the occurrence is smaller than once in ten thousand years, or in other words there is only one procent chance in hundred years that a major inundation will occur.

In the paper: "Hydraulic investigations for the Deltaproject" H.A.Ferguson 1) describes in general terms the field observations, office computations and model studies made in connection with the hydraulics of the Delta projection and reclamation project under construction in the Netherlands in 1958. These studies include among other things investigations of tides, waves, currents, salinity, sediment movement, and drift of ice.

In this paper the investigations concerning the tides, which are mentioned in Mr. Ferguson's article, will be dealt with in more detail. These tides are those which exist before the execution of the Deltaworks and those which will result after the project is fully realized.

The main tidal features which had to be investigated in connection with the project in question were the determination of the highest levels which occur on the Rotterdam Waterway and further riverbranches of the Deltaregion during storm surges with given highwater levels at Hook of Holland at the outermouth of the Waterway, the division of the upland flow of the Rhine and Meuse into the various channels of the northern Deltaregion, the determination of the discharge programme of the sluices in Haringvliet and the flow velocities in the different navigation channels.

As a result of the changes in the flow conditions the riverbranches whose profiles are accommodated to present conditions, may have to be altered artificially. Further the possibilities for the suppression of the saltwater penetration of the Rotterdam Waterway by aid of the discharge programme had to be investigated.

Moreover, the changes in the tides and stormflood levels in the coastal areas outside the dams have to be determined in order to calculate the height of the enclosing dams and dikes which are exposed to the sea.

The tidal currents in the coastal waters of the delta will be changed considerably when the inlets are closed. The strong transverse currents, running to and from the estuaries will then have disappeared so that the prevailing current will be parallel to the coast. This change will undoubtedly cause important modifications in the pattern of banks and gullies. In the outermouth of the Haringvliet estuary the situation will become particularly complicated by virtue of the discharging of the upland flow through the sluices in the river. It is important, therefore, to determine the changes in the tidal currents in the coastal areas.

THE PROJECTS AND ITS EXECUTION

A few months ago (May 1960) the first closure, forming a part of the Deltaworks, was completed, i.e. the closure of the Zandkreek.

1) Journal of the Waterways and Harbours Division. Proceedings of the American Society of Civil Engineers, March 1959, New York.

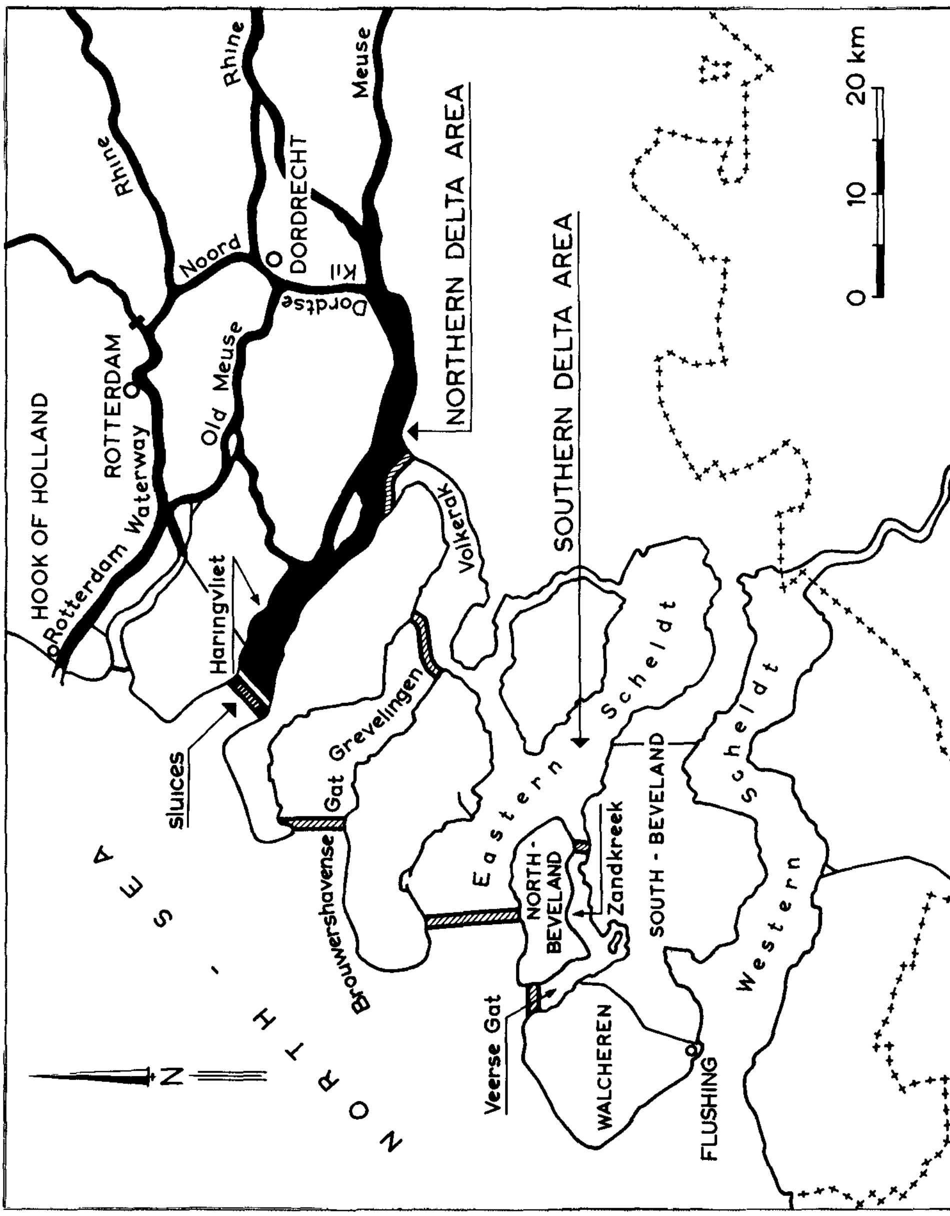

Fig. 1. Plan of the Deltaproject.

This channel separates the island of North Beveland in the province of Zeeland from South Beveland (see fig. 1). During this closure no great difficulties were encountered. The difference in head of water at both sides of the closure dam was not more than one feet in the final stage of the construction.

Next year the final closure of the Veerse Gat will take place as a result of which the islands of North Beveland and Walcheren will be connected and the estuary of Veerse Gat and Zandkreek will be changed into a lake.

This closure is considerably more difficult than the closure of the Zandkreek, for after it the maximum difference in the water levels at the different sides will be about 5 ft at springtide.

In 1959 the building of the huge sluice in the mouth of the Haringvliet was begun; the width is about 1150 yards and the depth is 17 ft below mean sealevel. An island surrounded by a high dike had already been constructed, taking one year to complete. The construction of the sluice will be finished in 1966 or 1967 if no serious difficulties are encountered. After that, the further closure of the Haringvliet will take place in 1968.

Next year (1961) the government intends to begin the works for the enclosure of the Grevelingen, the estuary between the islands of Schouwen Duiveland and Overflakkee (see fig. 1). This enclosure will be completed in four years.

Further extensive projects are planned for the following years. After the works in the Grevelingen the closure of the mouth of the Brouwershavense Gat will commence and be finished in 1970, and finally the closure of the mouth of the Eastern Scheldt will take place. It is hoped that the complete Deltaworks will be finished in 1978, thus providing a more comfortable safety margin against floods, and leading to important changes in the coastal waters.

A few years ago extensive studies commenced for the so-called Europort, which will involve the construction of harbours at the outer mouth of the Rotterdam Waterway. Piers will have to be built in the coastal waters.

It is obvious that these works will have an important influence on the coastal currents and consequently on the sediment movement also. Moreover, this problem is much complicated by the fresh and salt water motion outside the Rotterdam Waterway. The construction of the piers depends also to a large extent on the influence of the waves.

THE MEANS FOR RESEARCH INTO THE TIDES

Calculations of the tides and investigations into the tidal movement by means of model tests are very important for the planning of the Deltaproject, and for the construction of the dams during the closure operations. Both methods are considered indispensable and are complementary to each other.

The tide calculations afford a better knowledge of the physical aspects of the tidal movement and, if carried out in sufficient detail they may produce more exact results than those by using models.

The calculations are confined to cases which are regarded as highly important from a practical and theoretical point of view and which will afford a check on the results of the model.

In a model far more situations can be investigated in a short time than by means of calculations; model tests are therefore especially suitable for examining whole series of situations.

The tidal model of the Deltaregion has the disadvantage that it is not very suitable for examining the effect of profile changes of channels, as frequent and time consuming modifications of the model would be necessary.

A new electric analogy has been developed, therefore, by which the comprehensive research programme may be accomplished within a comparatively short time and with sufficient accuracy.

THE TIDES BEFORE AND AFTER THE EXECUTION OF THE DELTAPROJECT

The tides vary greatly along the Netherlands' coast from South to North. At Flushing the tidal range at mean tide is about 12 ft, at Hook of Holland, the mouth of the Rotterdam Waterway, it is 5 ft and further North it decreases to about 4,5 ft at Den Helder. From that point the coast bends in northeasterly direction towards the German Bight, and the tidal range increases again. At the most eastern place, Delfzijl, the range is about 9 ft. From these figures it appears that after the closing of the southwest estuaries (apart from the Western Scheldt), the high tides in the southwest will be cut off and that only at Hook of Holland, where the range is lowest, will they be able to penetrate into the Deltaregion. Furthermore it is clear that in the Deltaregion, the tidal wave will be greatly decreased, depending on the distance of propagation. As a consequence, after the Deltaproject, the tidal ranges in the northern Deltaregion (north of Volkerak) will be much smaller than at present. The modifications in the ranges follow from fig. 2, in which the highwater and lowwater levels are shown. Especially in the Haringvliet estuary the decrease of the tidal range is very important in comparison with the present situation. At mean tide at Hook of Holland and with the Haringvliet sluices closed, the tidal range will in the Haringvliet lake be decreased by 90%, becoming about ½ ft.

The water motion in the northern region, however, is very complicated due to the upland discharge of the Rhine and Meuse. In the present situation this water mainly follows the Haringvliet estuary, but in the future it must be discharged by the large sluices in the enclosing dam of the Haringvliet. The upland discharges of the river Rhine may vary greatly from about 35.10^3 cu. ft/sec in a dry season to about 350.10^3 cu. ft/sec in a very wet season (wintertime). In extreme cases an upland discharge of 450.10^3 cu. ft/sec or higher may occur (mean frequency of occurrence: once in twenty years). Therefore the sluices must be very large; when fully opened the cross-sections are 57.10^3 sq. ft below mean sealevel. In the case, however, of an upland discharge lower than about 210.10^3 cu. ft/sec only a part of the maximum sluice opening will be used. The reduction of the discharge will be affected by partly closing all of the 17 individual sluice openings. From the point of view of scour of the downstream bed, this is preferable to closing part of the sluices entirely. Although a bed protection against scour will be provided, it remains advisable to distribute the total discharge over the greatest possible width.

Furthermore the sluices will remain closed during the period of higher water levels at the seaward side than at the landside in order to prevent saltwater to penetrate into the Haringvliet estuary.

From the preceding consideration it follows that many variatior can occur in the waterlevels of the northern Deltaregion, due to astronomical and meteorological circumstances (springtide, neaptide, storm surges) of the tides at Hook of Holland, the variations in upland discharge and the discharge programme of the Haringvliet sluices.

In any case, however, the waterlevels in the Haringvliet estuary will be much lower than at present. In fig. 2 the H.W.levels and L.W.levels in case of closed sluices are shown for various places in the northern region in comparison with the levels found now.

THE SUPPRESSION OF THE SALTWATER PENETRATION OF THE ROTTERDAM WATERWAY BY AID OF THE DISCHARGE PROGRAMME OF THE HARINGVLIET SLUICES

In the present situation about 55% of the upland discharge of the Rhine and Meuse passes through the Haringvliet and 38% through the Rotterdam Waterway. The remaining 7% discharges to the IJssel lake. The upland discharge suppresses the salt penetration via the Rotterdam Waterway to some extent but it is an insufficient deterrent. In point of fact, the drinking water of Rotterdam is very often mixed with salt to a disagreable amount in times when the upland discharges are low. In those times, therefore, the upland discharge of the Waterway has to be increased relatively to the discharge through the sluices. This can be done by decreasing the opening of the sluices. Then the discharge of the sluices decreases also and therefore the freshwater discharge through the Rotterdam Waterway increases. As a consequence the saltwater penetration will decrease, but it depends on the tides and on the upland discharges.

In the case of very small discharges of the Rhine and Meuse, the sluices in the Haringvliet will be closed during the whole tide so that all available freshwater which is not be needed for domestic and agricultural use can be discharged through the Waterway.

The full value of this effect can be asserted after a thorough investigation of the motion of fresh and saltwater in the riverbranches concerned, a motion which is complicated by the mixing effect of the harbour basins.

In any case the saltwater penetration in the Rotterdam Waterway will be suppressed to an important extent after the execution of the Deltaworks.

It must be noted, however, that this suppression is limited, because the freshwater from the rivers Waal (the most important branch of the river Rhine) and Meuse has to be discharged by the rivers Old Meuse and Noord (see fig. 1). The amount of this discharge is limited by the cross-section area and the fact that the velocities of these rivers may not exceed certain values dependent upon navigational requirements and the maintenance of the profiles. In cooperation with this, the benefit proceeding from the eventual construction of a barrage in the Old Meuse near its confluence with the Waterway has to be studied. By closing the Old Meuse in times of small upland river discharges all available freshwater will then flow past Rotterdam. It is to be expected that this concentration upon one branch will be favourable for the suppression of the salt penetration.

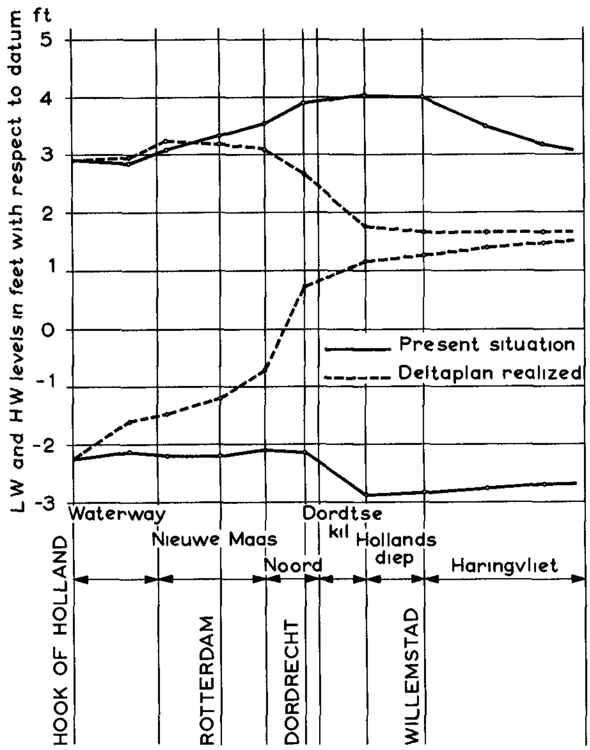

Fig. 2. High and low water levels in the present situation and after the realization of the Deltaplan.

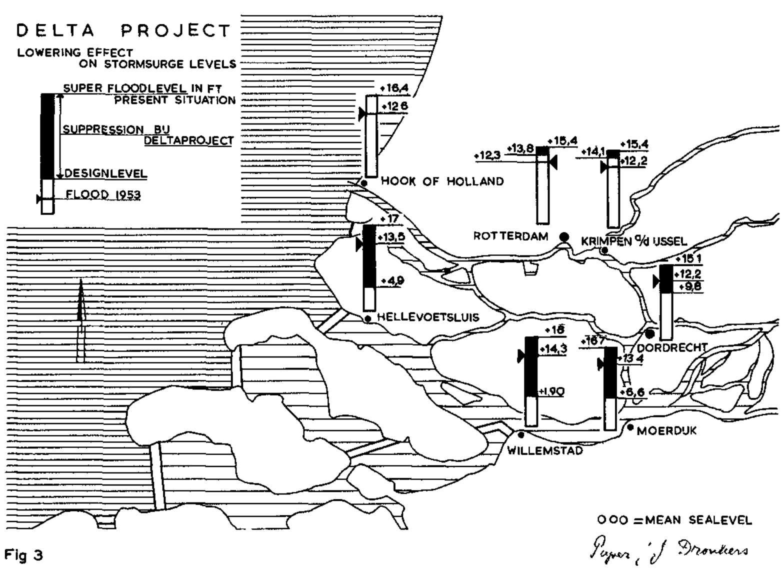

Fig. 3. Lowering effect on storm surge levels.

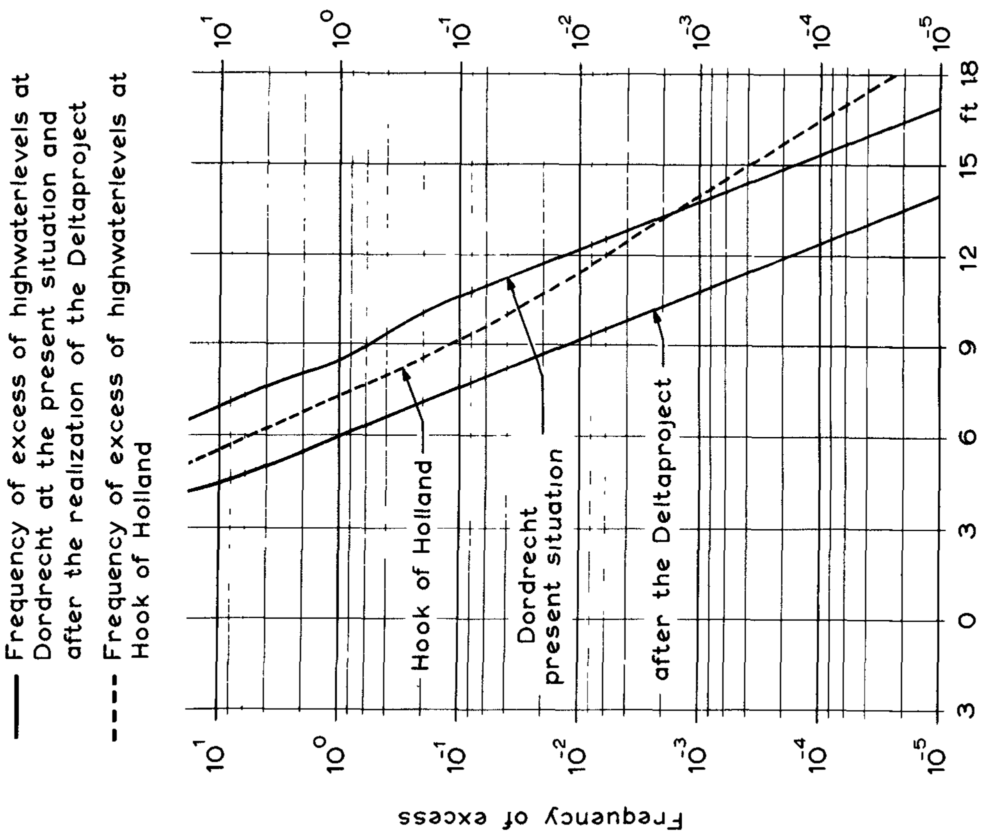

Fig. 5. Frequency of excess at Hook of Holland and Dordrecht.

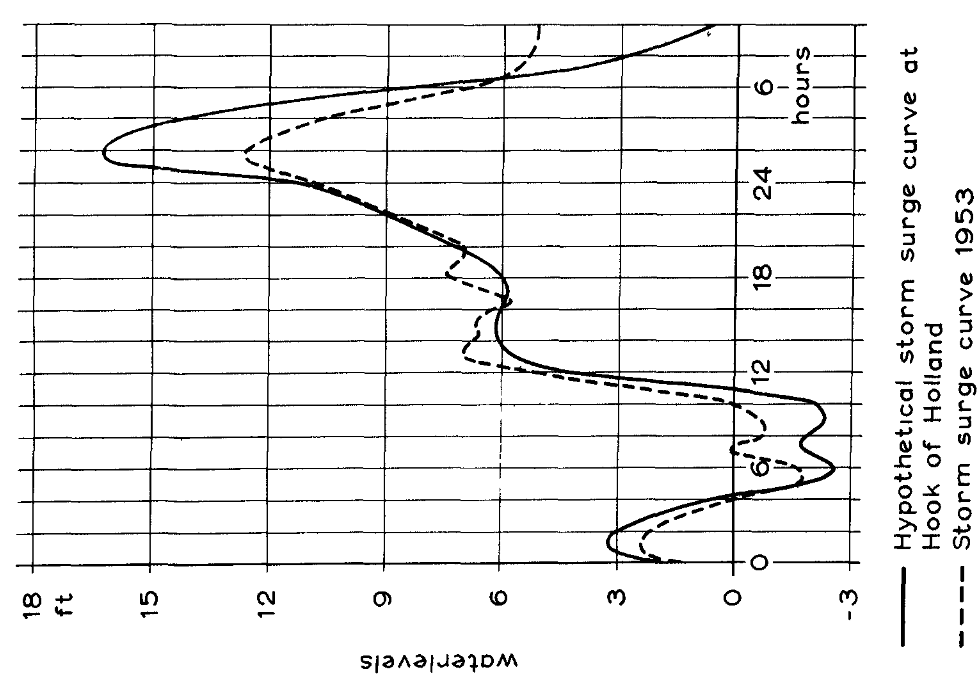

Fig. 4. Storm surge curves at Hook of Holland.

THE DECREASE OF THE STORM SURGE LEVELS AS A CONSEQUENCE OF THE DELTAWORKS

Storm surge levels will also decrease in the northern region after the execution of the Deltaworks. The further inland one goes the greater will be the lowering effect on storm surge levels. In fig. 3 this lowering effect is shown for a very big storm surge. It appears that along the Rotterdam Waterway up to Rotterdam the decrease is relatively small so that the dikes in this region must still be heightened. As has been remarked in the introduction the frequency of the occurrence of storm surge levels like 1953, must be considered as too high in relation to the possible loss of life and damage to property. Because of this, the statistics of the highwater levels have been exhaustively studied by various institutes, the Rijkswaterstaat (see the paper: P.J.Wemelsfelder, On the use of frequency curves to determine the design stormflood), the Mathematical Centre in Amsterdam and the Meteorological Institute. Finally it has been decided, the storm surge level of 16,5 ft above mean sealevel at Hook of Holland, which has a frequency of excess of about once in 10.000 years, to adept as a design value for the dikes in the northern Delta area. In fig. 3 the decrease of the storm surge levels are shown for inland places. These levels also depend on the shape of the storm surge curve at Hook of Holland, for which a hypothetical curve has been constructed on the basis of curves for storm surges which occurred in the past (fig. 4). With the help of statistical researches it has been shown, that in the case of very high storm surge levels it is reasonable to suppose that the simultaneous upland discharge does not differ much from the mean upland discharge. The probability of the simultaneous occurrence of very high storm surges at Hook of Holland and important upland discharge is much lower than the accepted frequency of excess of once in 10.000 years as an average.

On the other hand, for inland places like Dordrecht, the levels depend also on the upland discharge so that a certain level may occur here under various circumstances for stormflood levels and upland discharges. A high level at Hook of Holland and a low upland discharge may cause the same highwater level at Dordrecht as a lower storm surge level and a higher upland discharge. It may not be concluded, therefore, that the storm surge level for Dordrecht, shown in fig. 3, has a frequency of excess of once in 10.000 years. For the determination of the statistical occurrence of the storm surge levels the statistics of the upland discharges have to be taken into account. This problem will not be dealt with in detail; only the most important points are mentioned.

The stormflood levels to be experienced at various places in the Deltaregion when various stormflood levels occur at Hook of Holland in conjunction with certain upland discharges, have been determined by model tests.

In virtue of the independence of storm surges and upland discharges the probability of occurrence of a storm surge level at Hook of Holland, situated in a certain interval, together with the probability of occurrence of an upland discharge also situated in an interval, equals the product of the probability of occurrence of each factor As a stormflood level at Hook of Holland and an upland discharge cause

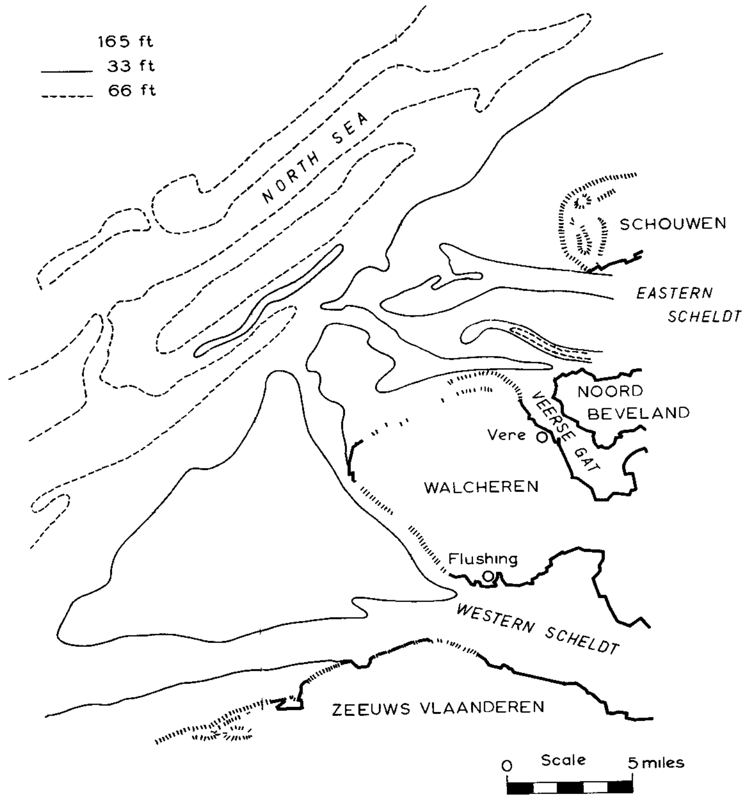

Fig. 6. The contour lines of 16.5 ft, 33 ft and 66 ft below mean sea level in the coastal area.

Fig. 7. The scheme of the sections outside the dam in the Eastern Scheldt and the island of Walcheren.

a determined stormflood level at any place in the Deltaregion e.g. at Dordrecht, the probability of occurrence of a stormflood level, situated in an interval at Dordrecht equals the sum of these probabilities mentioned above for which the storm surge levels at Hook of Holland and upland discharges cause stormflood levels in the considered interval at Dordrecht. Furthermore, the frequency of excess of a certain stormflood level at Dordrecht is the sum of the probabilities for the various intervals higher than the value of which the frequency of excess has been determined. In fig. 5 as an example the frequencies of excess of the stormflood levels at Hook of Holland are shown and for Dordrecht these corresponding to the present situation and after the execution of the Deltaplan. The decrease of the stormflood levels at Dordrecht can be determined from these graphs.

INVESTIGATIONS INTO THE TIDAL CURRENTS AND H.W.LEVELS IN THE COASTAL AREA

When the inlets of the Eastern Scheldt, Brouwershavense Gat and Haringvliet are closed, considerable changes will take place in the tidal currents of the coastal waters. The strong currents running to and from the estuaries will disappear and currents parallel to the coast will prevail. As a consequence the fan shaped gullies, directed to the estuaries, will gradually disappear and the coastline will be flattened out. Furthermore a regression of the sandy coastline of the islands may be expected. In the future therefore, protection works may become necessary. For the planning of these works detailed studies have to be made, taking into account the tidal mechanism, the action of waves and currents and their influence on the movement of sediments.

The process of reshaping the coastline may take a very long time, but it is possible that this development may cause dangerous effects of erosion even in the first stage. It is in fact, very difficult to forecast what will happen in detail.

Further investigations concern the determination of the increase of the stormflood levels after the closure. These are especially relevant to the height of the dams and the existing dikes.

The basis of the investigations consists of the study of the tidal motion in the coastal areas at present. The pattern of the tidal currents in the inlets of the estuaries is very complicated, due to the interference of currents directed to the estuaries with the tidal currents parallel to the general trend of the coast. These latter currents are caused by the general tidal motion in the North Sea, and as the distance from the coastline increases so does the influence of the North Sea tide. Complications are also caused by the important difference in phase between the North Sea currents and the estuary currents. If the currents in the North Sea region are maximum, the currents directed to the estuaries are small and vice versa.

In fig. 6 a review is shown of the banks and gullies at the inlets and outside the coastal line of the southern part of the Deltaregion. The shoals outside the coastal line have a width of about 12 miles.

In the coastal area at various points the vertical tidal motion has been recorded by using an instrument which determines the pressure of the watercolumn above the instrument.

With the help of these data and the observations at various places on the coast, the course of the tidal motion at other places in the coastal area has been derived by interpolation.

Furthermore velocity measurements have been taken for some years at various places, especially in the outermouth of the estuaries and at some points in the gullies in front of the islands. Then the relation with respect to the vertical tide can be derived.

While the tidal movement in the coastal waters is influenoed by the Coriolis forces, in the estuaries the influence of this force is limited by the restricted width.

As a consequence of the Coriolis forces the tides near the coast are stronger than in the area of the North Sea off the coast. It appears that at a distance of 15 miles from the coast the highwater level is about 2/3 ft lower than at the coast.

The tidal motion in the sea is determined by the two equations of motion, the equation of continuity and boundary conditions.

Equations of motion:

$$\frac{\partial u}{\partial t} - \Omega v + g \frac{s\,u}{C^2 a} = - g \frac{\partial h}{\partial x} ,$$

$$\frac{\partial v}{\partial t} + \Omega u + g \frac{s\,v}{C^2 a} = - g \frac{\partial h}{\partial y} .$$

Equation of continuity:

$$\frac{\partial h}{\partial t} + \frac{\partial a u}{\partial x} + \frac{\partial a v}{\partial y} = 0 .$$

t = time; x and y are plane coordinates; u = velocity component in x-direction and v in y-direction; h = height of waterlevel with respect to datum; g = acceleration of gravity; Ω = coefficient of Coriolis; C = coefficient of friction; a = depth. The value of the density of the water ρ is supposed to be one; s = magnitude of the velocity vector:

$$s = (u^2 + v^2)^{1/2}$$

The mean sea depth in the coastal area is low in comparison with the mean depth of the North Sea itself. In the gullies between the banks, the depth varies from 25 ft to 60 ft. In the adjacent part of the North Sea, outside the coastal region, the depth varies between 70 ft and 90 ft. As a consequence the resistance force in the equations of motion is much more important in the coastal area than in the North Sea, so that in tidal calculations especial care must be taken in considering the influence of this force.

The value of the resistance coefficient C has to be determined from tidal computations for the existing situation in the coastal area of which the tidal motion is known from the observations.

The computations are carried out in the following way.

An important reduction may be made by taking the abscis x in the length direction of a gully, in which the velocity has been observed at two or more points and the curve of the vertical tide is known. At first the differences between the measured velocities in various points of the gullies are verified with the aid of the equation of continuity.

Then $\frac{\Delta h}{\Delta t}$ and $\frac{\Delta a u}{\Delta x}$ are determined from the vertical tide and the velocity measurements. Further from the velocity observations the mean values of $\frac{g s u}{a}$ and $\frac{\Delta u}{\Delta t}$ are determined; the value of $-\Omega v$ also can be estimated from the observations in the gully itself and in neighbouring gullies. By reason of the assumption that the velocity is mainly directed in the gully, the value of $-\Omega v$ is mostly small in comparison with the other ones. If, moreover, the value of $\frac{\Delta h}{\Delta x}$ is known, the value of C for the gully can be computed from the first equation. The computation of C can be carried out for various moments during the tide, analogous to the corresponding computation in the rivers. Then it appears that the value of C as an average equals about 110 $ft^{\frac{1}{2}}$/sec. Because of the supposition that the value of C will not change importantly during a tide, these computations also give an impression of the exactness of the measurements and the various interpolations for the determination of the values of $\frac{\Delta h}{\Delta x}$ and the mean values of u. From the second equation the values of $\frac{\Delta h}{\Delta y}$, perpendicular to the gully, can be computed. They depend mainly on the values of Ωu.

Such computations are important for the knowledge of the tidal motion of the coastal area. Further information is obtained in order to verify the method by which the coastal region may be schematized for further tidal computations. The very shallow regions are then separated from the deeper gullies. The gullies are further divided into sections, which have comparable depth and width with lengths of 2 or 3 miles. Then the depth is considered constant. In fig. 7 an example of such a schematization for the area outside the dam in the mouth of the Eastern Scheldt and the island of Walcheren is shown.

For this area a complete tidal computation has been carried out in the following way. Only the most important steps are described. Firstly, the tide in individual gullies was computed by using the available measurements, as described above. After that, the tides in the various gullies were compared to ascertain the continuity of currents and vertical tides at the points where one section of the schema meets its neighbour. Differences at these meeting points have to be eliminated by modifying the computed tides in adjacent gullies. This is done by trial and error on account of the non-linear equations (quadratic resistance terms). These computations take much time and often show that the sohematization of the gully system has to be changed.

After studying the tidal motion in the present situation, tidal computations are executed for the situation after the estuaries have been closed.

Then the pattern of the currents along the coast is less complicated, running mainly parallel to the coast. In the inlets of the closed estuaries, however, the tidal motion propagates to the dams. Because of the short distance the propagation of this tidal wave can easily be computed. At first then it is supposed that the vertical tide at the seawardside of the inlet does not change, so that the currents directed to the dams can be computed approximately. After that the tidal motion outside the coastline of the Deltaregion can be calculated, supposing that the currents which are parallel to the coast are predominant with respect to the perpendicularly directed currents. In a strip with a width of about 12 miles, this tidal motion can be considered as a propagation of Kelvinwaves, in which case the currents are directed in one direction. The propagation of such waves can be computed in a similar way as the propagation of the tides in a river. The differences in level in the transverse direction can be computed from the equation $\Omega u = -g \frac{\Delta h}{\Delta y}$. Finally, the influence of the tidal motion to the inlets of the estuaries can be taken into acoount more fully.

On the seaside borders of the region for which the computations are carried out, the observed tide graphs are the boundary conditions. Along the coast the perpendicularly directed velocities are zero.

Some results of the computations are:

The H.W.levels in the neighbourhood of the dams will increase by 2/3 ft and the L.W.levels decrease by an equal amount. The stormflood levels will increase by 1· 1/3 ft. The H.W.levels at the capes of the islands, however, will only increase by a few inches.

The velocities in the outermouths of the estuaries, which will be closed, will decrease by about 30%, while this percentage will increase in the direction of the dams, where the currents completely disappear.

In the mouth of the Haringvliet, however, the determination of the changes of the currents is very complicated due to the discharge programme of the sluices.

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