The Institution of Civil Engineers.

SPECIAL LECTURE ON

"THE ENCLOSURE OF THE ZUYDER ZEE."

BY

VICTOR JEAN PIERRE DE BLOCQ VAN KUFFELER

LONDON:

Published by the Institution,

GREAT GEORGE STREET, WESTMINSTER, S.W.1.

1934.

The Institution of Civil Engineers.

SPECIAL LECTURE ON

"THE ENCLOSURE OF THE ZUYDER ZEE."

BY

VICTOR JEAN PIERRE DE BLOCQ VAN KUFFELER.

LONDON:
Published by the Institution,
GREAT GEORGE STREET, WESTMINSTER, S.W.1.
1934.

ADVERTISEMENT.

PRINTED IN GREAT BRITAIN BY
WILLIAM CLOWES AND SONS, LIMITED, LONDON AND BECCLES.

EXTRA MEETING.

2 March, 1933.

SIR MURDOCH MACDONALD, K.C.M.G., C.B., M.P., President, in the Chair.

SPECIAL LECTURE ON

"The Enclosure of the Zuyder Zee."

By VICTOR JEAN PIERRE DE BLOCQ VAN KUFFELER.

THE GENERAL SCHEME OF THE ZUYDER ZEE WORKS.

THE enclosure of the Zuyder Zee is the most important part of the Zuyder Zee works from the point of view of the engineer, and, an hour being too short to deal with the main features of the work, I shall speak chiefly about that. I shall begin, however, with a short description of the general scheme.

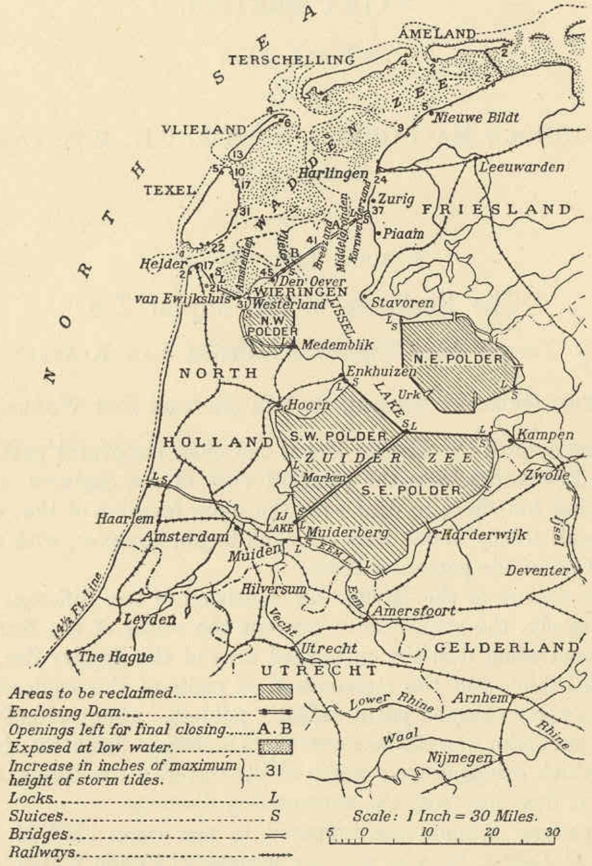
The enclosure of the Zuyder Zee consisted of two different operations, namely, the enclosure to prevent the water of the North Sea from penetrating into the embanked area of the Zuyder Zee, called the Ijssel lake, and the reclamation of parts of this enclosed area. Between the reclaimed parts, called "polders," about 270,000 acres of the Ijssel lake were to be reserved as a storage basin for the river Ijssel, which brings down a ninth of the water of the Rhine, and for the water draining from the surrounding districts.

The general scheme was prepared in the years 1887–91 by the late Dr. C. Lely, C.E., who was our Minister of Public Works in 1918, and later the president of the Zuyder Zee Board, and who died in 1929, when the bill authorising the execution of the Zuyder Zee works passed the legislature.

The enclosing dam runs from the coast of the province of North Holland to the west side of Wieringen, and from the east point of that island to the Frisian coast near Zurig (*Fig. 1*). The main dam, which is about 20 miles long, encloses the Ijssel lake, an area of about 915,000 acres.

The partial reclamation of the Zuyder Zee was to take place by embanking and separately draining four parts of the Ijssel lake, comprising a total area of about 550,000 acres, which is about one-third of the area of Lincolnshire. The total area to be reclaimed

Fig. 1.



MAP OF THE NORTH-WESTERN NETHERLANDS SHOWING THE PARTIAL RECLAMATION OF THE ZUYDER ZEE.

was approximately 7 per cent. of the whole, and about 10 per cent. of the arable area of the Netherlands.

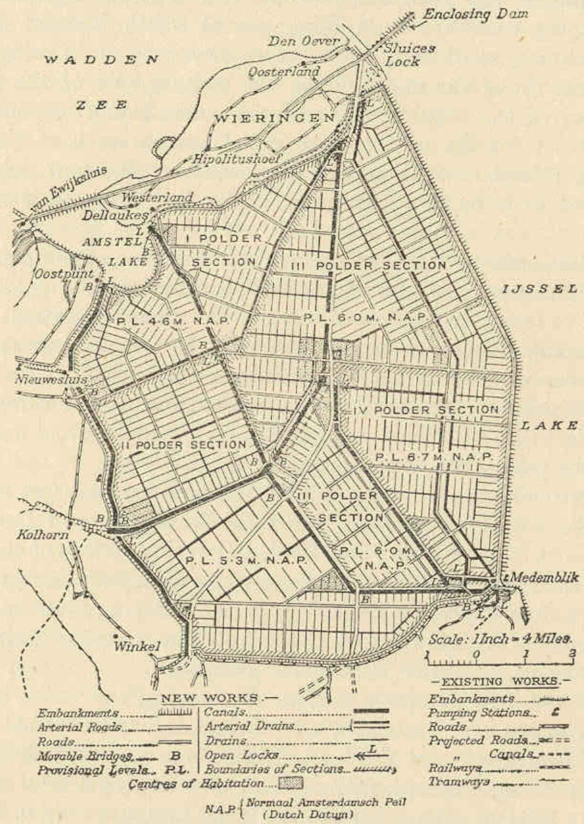
Plans were drawn up so that the open tidal basin would be enclosed first, thus enabling the making of the polders in the Ijssel lake to be carried out without tidal interference.

In June, 1920, the construction of the main dam started with

the dumping of clay from the first hopper-barge into the Amsteldiep, the deep channel between North Holland and Wieringen. Owing to the financial crisis the programme was limited from 1922 to 1926, and only the enclosing of the Amsteldiep was completed in that period.

As the shortage of arable land was strongly felt in Holland at that

Fig. 2.



THE WIERINGERMEER POLDER.

time, a bill was passed in 1926 authorising the enclosing, during the next period, of the Zuyder Zee between Wieringen and Friesland, and the reclamation of the north-western polder, called Wieringermeer (*Fig. 2*). These works are now finished.

The north-eastern polder was the next to be reclaimed, and here the Government decided on the improvement during that year of some harbours in the vicinity, in order to facilitate the execution of work on the polder.

The Reclamation of the North-Western Polder.—The reclamation of the Wieringermeer has now advanced so far that the first colonists, living in two recently-built villages, are cultivating a part of the land. The total area of the polder, about 50,000 acres, is nearly 9 per cent. of the whole reclamation scheme.

The polder has been enclosed by two separate embankments, one running westward from Wieringen to North Holland, and the other running southward from the eastern side of Wieringen. A canal runs along the mainland on the western side of the polder; this receives the surplus water of the surrounding districts, and discharges it to the north. This canal has to serve at the same time for inland navigation, and the canals of the new polder are connected to it by two locks, and to the Ijssel lake by two other locks.

Simultaneously with the construction of the embankments, the main drainage canals and the collecting drains in the polder were dredged to facilitate the flow of water to the pumping stations during the pumping-out of the enclosed polder. To reduce excavation the polder was divided into four sections, each with its own water-level, according to the level of the sea-bottom, which varied from 2 to 16 feet below datum; each section had its main canal leading to one of the pumps of the pumping stations.

The normal water-level in each section is fixed at 4 feet 8 inches below the lowest arable land. In future the outlets of the drain-pipes will be 8 inches above that level, and during periods of abundant rainfall the water-level should not rise more than this 8 inches. This condition determined the capacities of the pumping stations, which were powerful enough to exhaust the water from the embanked area in a period of 6 months' continuous pumping.

There are two pumping stations discharging the water into the Ijssel lake, one in the south called "Lely," and another in the north called "Leemans." At the Lely station there are three electrically-driven centrifugal pumps, with vertical axes, having a total capacity of nearly 260,000 gallons per minute; the Leemans station has two centrifugal pumps with horizontal axes, driven by diesel motors, with a total capacity of more than 120,000 gallons per minute.

In the parcelling of the polder special attention was paid to the connection of the roads and the canals with those in the adjacent districts, cheap transport, both by land and by water, being of great importance to its development. It was only after a careful investigation of the requirements of modern agriculture that the parcelling of the polder was fixed. The normal parcel of 50 acres has a length of 880 yards and a width of 275 yards, although for experiment some parcels were given other dimensions. A road was made along one of the short sides of each parcel, and a collecting-drain, accessible to small barges, along the other.

As the sea-bed gradually dried the digging of ditches and the construction of roads and bridges, and of locks between the various sections was started.

At the beginning of 1927 the reclamation works commenced: on the 10th February, 1930, the pumping plants of the first Zuyder Zee polder were formally started, and on the 21st August of that year the provisional water level in that polder was reached; the remaining works will probably be completed next year (1934). The total cost of the reclamation works was estimated at about £5,000,000.

An agricultural administration is now in action, and a superficial drainage of the land was completed by the middle of 1932, enabling the rain water to leach out the salt in the soil, thus preparing it for cultivation, the sandy soil losing its salt quicker than the clay. The first rye was reaped in 1931, and an area of about 11,000 acres is now under cultivation.

As cultivation went on, provision was made for the habitation of the polder, and up to the present two villages and numerous sheds have been built, while the social settlement of the polder develops quickly.

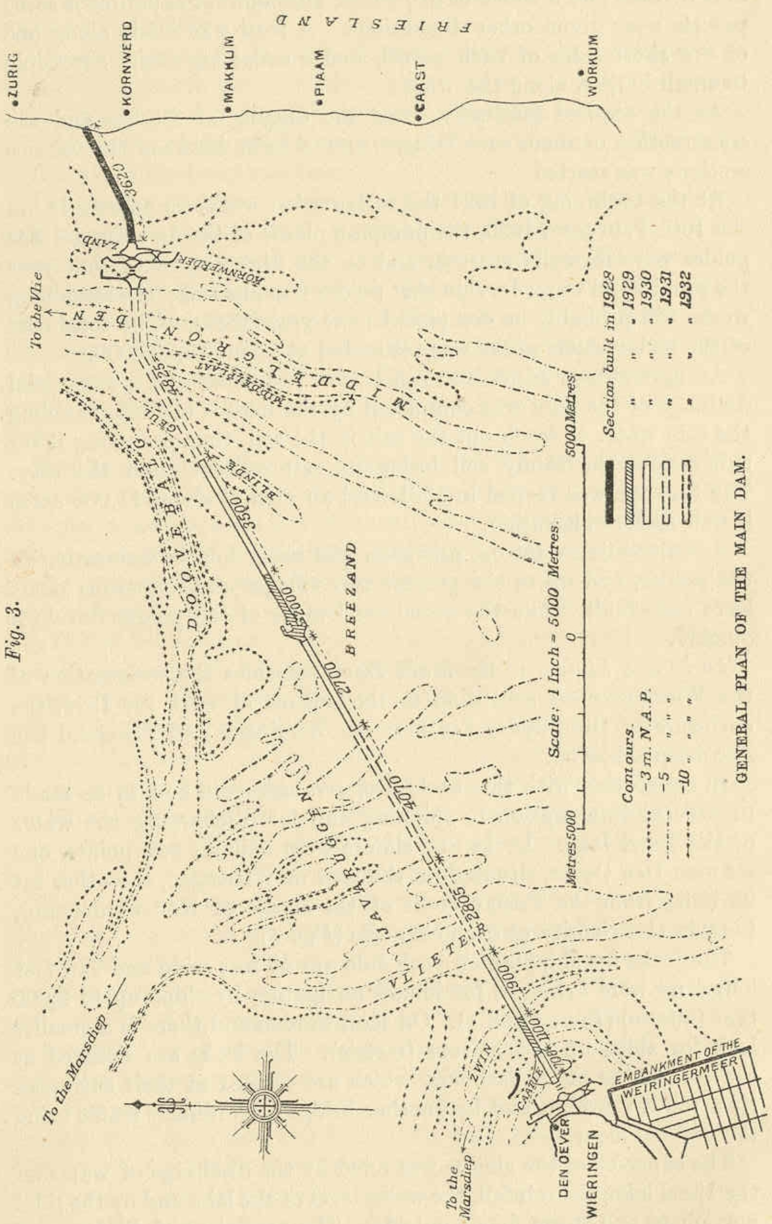
Locks and Sluices in the Main Dam.—Besides the reclamation of the Wieringermeer according to the scheme of work for 1926, the enclosure of the Zuyder Zee between Wieringen and Friesland has also been achieved.

In connection with this enclosure, arrangements had to be made to prevent interruption to shipping and for discharging the water of the Ijssel lake. Locks and sluices were built at two points, one set near Den Oever, situated on the east of Wieringen, the other set $2\frac{1}{2}$ miles from the Frisian coast on the shoals of Kornwerderzand, both in the vicinity of deep channels (*Fig. 3*).

The locks for shipping on each side are 46 feet wide and 470 feet long, and were arranged for inland navigation by ships up to 2,000 tons (metric) (*Figs. 4* and *5*). On Kornwerderzand there is a smaller lock for ships up to 600 tons (metric). The locks are situated at the end of the outer harbours, which are crossed at their entrances by a railway bridge, and by another bridge for ordinary traffic using the embankment.

The capacity of the sluices was fixed by the discharge of water on the Ijssel lake, the rainfall, the water level of the lake and by the tidal movement and storm floods outside. The coefficient of discharge of the sluices was investigated in hydraulic laboratories, and twenty-five

Fig. 3.



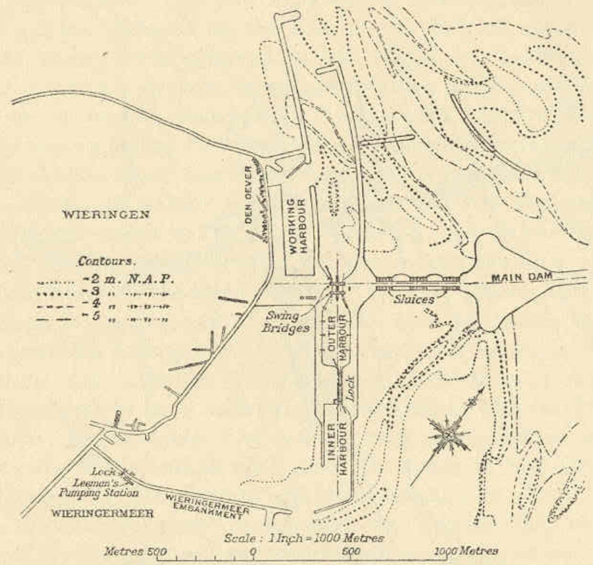
GENERAL PLAN OF THE MAIN DAM.

sluices were built, each with a width of 40 feet and a depth over the sill of 12 feet at low water; fifteen of these are near Den Oever, the others at Kornwerderzand, both groups of locks and sluices being built in pits in the open sea.

The Enclosure: Changes in the Tidal Movements.—I come now to the main point of my lecture, namely the construction of the enclosing dam between Wieringen and Friesland, which was started only after a careful investigation of the problem had been made.

During the construction of the embankment the tidal movement

Fig. 4.

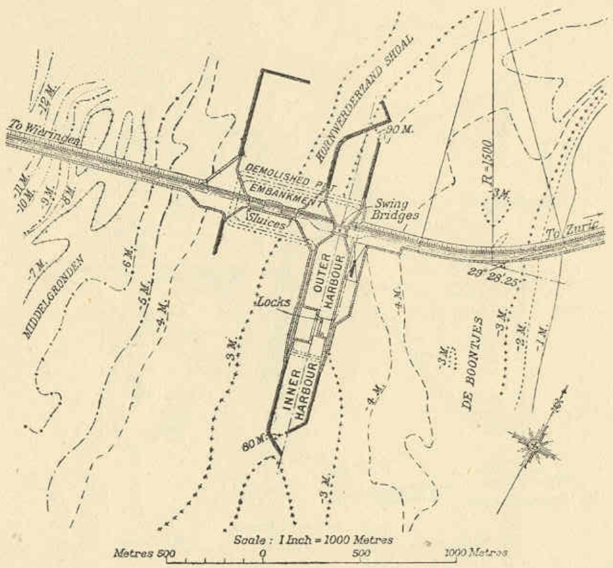


PLAN OF THE LOCKS AT WIERINGEN.

would gradually change; a clear insight into this question was therefore necessary, the height of the subsequent storm-floods and the fall in the last gaps of the enclosing dam being of paramount importance in the organisation of the construction programme.

I shall begin by giving you a rather popular explanation of the changes in the tidal movements, which enter the Zuyder Zee from the North Sea through two straits, one between North Holland and the island of Texel, called Marsdiep, and the other between the islands of Vlieland and Terschelling, called Vlie. The length of the Zuyder Zee from these straits to its southern end was more than half the length of the tidal wave, and consequently the tidal flows on the two sides were opposite in direction; thus the Zuyder Zee was not a basin filled by flood and emptied by ebb. On the site of the projected dam there was a flow to the south at high water, which reduced its level, and when this flow was cut off by the dam the high-water level was forced to rise. The fall of the low-water level can be explained in the same way. The tidal range outside would gradually increase during the construction of the dam, while inside it would decrease, the flow through the gaps diminishing. As stretches of the dam were built an increasing difference of level at the gaps was to be expected.

Fig. 5.



PLAN OF THE LOCKS AT KORNWERDERZAND.

The Zuyder Zee was so large that it was never quite filled by storm-floods, which did not last long enough for this; there was, therefore, always a flow to the south along the planned line of the dam which diminished the storm-flood level. When this flow was cut off by the dam, the storm-flood level had to rise. This phenomenon had to be considered in determining the heights of the crest of the enclosing dam and of the existing embankments surrounding.

It was not sufficient to have a qualitative insight only into the question of the tidal change after enclosure; a quantitative one was also necessary. The investigation of this question was very complicated and difficult: a Royal Commission under the presidency of the well-known physicist and mathematician, Professor H. A. Lorentz, was in charge of it. The Commission first investigated the existing conditions, collecting numerous observations of the tidal movement, especially in the North Sea, of flows and of the effect of wind. It was found that as soon as the tidal-waves had passed the straits leading to the Zuyder Zee, the tidal range decreased rather quickly, and the time of high-water determining the phase occurred later. At the south end the tidal-wave was reflected, this causing an acceleration throughout the range. The tidal flows followed the deep channels, and the flows in the shallows were of little importance. The two tidal-waves entering the Zuyder Zee had a phase-difference on the line of the dam of about 3 hours, so that when floods occurred in the system of western channels at the points where they crossed the dam, a further ebb-flow took place in the eastern channels for 3 hours, the rotatory flows in the middle shallow, called Breezand (*Fig. 3*), being explained in this way; on this shallow there was hardly any flow to and from the south.

The data collected by the Commission was sufficient to deduce the tidal movement in the Zuyder Zee from that in the North Sea, the Zuyder Zee being divided for this purpose into a system of channels following the main channel. In every channel the ordinary equations of motion and of continuity were applicable, and these two equations determined the whole flow. The integration of the equations was, however, a very difficult problem, and several disturbances had to be considered, the rotation of the earth being an example. Nevertheless, Professor Lorentz succeeded in computing exactly the whole complicated tidal movement in the Zuyder Zee. Considering the peculiarities and complications of the tidal movement in what formerly constituted the Zuyder Zee, the results attained in the computations were very successful, and consequently predictions of the changes that took place after the enclosure could be made with a high degree of probability. Not only the normal tide but the storm-tide was also investigated; the problem was then solved by computing the influence of the south-going flow during storm-tides on the water-level at the site of the dam after the increase of the tidal range.

The Commission concluded that there would be an increase in the tidal range outside the main dam of about 90 per cent.; the level of high water was expected to rise about as much as the low-water level would fall; and the storm-flood height near the dam would increase by about 3½ feet. The tidal range outside the dam was originally nearly 3 feet, and so the fall of the ordinary low-water level had an important effect upon the discharge through the sluices.

The dam was closed in May, 1932, and the present changes in the ordinary tidal movement agree exactly with the conclusions of the Commission: up to the present there has been no real storm-flood, but stormy weather has, however, given indications that there can only be small disagreement with the expected storm-flood level.

Following up the work of the Commission, the expected fall at the gaps, occurring while the dam was under construction, was investigated under the supervision of Professor Lorentz. It appeared that it was only after the total length of the gaps had been reduced to less than $3\frac{3}{4}$ miles that the fall began to increase rapidly from $3\frac{1}{2}$ inches to 28 inches for a normal tide unaffected by wind; concurrently with this fall, the average maximum velocity in the gaps rose to 12 feet per second. The greatest velocity to be expected for storm-tides depended upon the length of the gaps; under certain circumstances it might exceed 20 feet per second.

I can only give the main features of the theoretical improvement; a more complete treatise on the subject would take a great deal of time. The information, however, will be sufficient to explain the scheme of execution.

The Construction of the Embankment.—I come now to the project for the embankment, which had to be built in the open sea with an average depth of 10 feet, increasing to 25 and even to 40 feet in the channels.

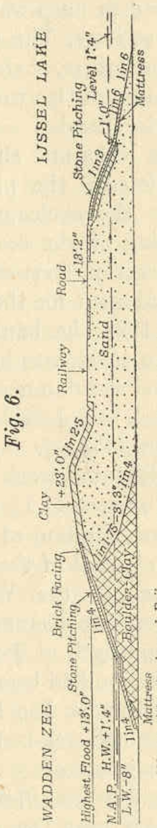
The sea-bed generally was adequate for carrying the bank; over a small stretch, however, layers of a softer subsoil had to be replaced with sand. A layer of boulder-clay occurs in the subsoil between Wieringen and the Frisian coast at a depth of 25 to 50 feet below datum.[1] Boulder-clay is a firm, tough loam of glacial origin; in a fresh, plastic state it resists the scour of flowing water extremely well, and waves have little action upon it. Although boulder-clay varies in quality, it is a material that has been of the greatest importance in the enclosure of the Zuyder Zee. The boulder-clay rests on a thick layer of sand, and is covered by sand more or less muddy, and varied by small layers of clay and peat.

The materials for the earthwork of the embankment had to be found in the vicinity, and consequently boulder-clay and sand were used. On the outer side there is a dam of boulder-clay with its crest at the level of the highest storm-floods, and backed by sand covered with a layer of clay or boulder-clay. The boulder-clay dam gives a real guarantee against rupture.

[1] Datum in the Netherlands is the former half-tide level at Amsterdam, and is denoted by N.A.P.

Below the water-line the earthwork is protected by mattresses of brush-wood, weighted with rip-rap (*Fig. 6*). Above the water-line the slopes are protected against wave action by stone-pitching and brick-facing, rising on the outer side to half the height between the storm-tide level and the crest, and on the inner side to the berm. Basalt from the Rhine and Belgian limestone were used for the stone slopes and the rip-rap, while above the stone slopes the bank is protected by turfing. The height of the crest of the bank is sufficient to prevent it from being overtopped by the storm-waves, and it ranges from 22 feet 4 inches to 25 feet above datum. Under water the boulder-clay and sand slope at 1 in 4 and 1 in 6 respectively; above the water-line the outer slope is 1 in 4·3, and the inner slopes are 1 in 3 and 1 in $2\frac{1}{2}$ respectively. On the inner berm a road 13 feet wide for ordinary traffic has been constructed, and a double-track railway is planned. The outer side of the berm is at a height of 12 feet above datum to keep it free from the wash of waves from the Ijssel lake during southern storms.

Fig. 6.



Scale: 1 Inch = 100 Feet.

TYPICAL CROSS SECTION OF THE MAIN DAM.

The Construction Scheme.—The scheme of construction was based mainly upon the results of the investigations on the tidal movement. As the flows chiefly followed the main channels, the currents in the shoals were of little importance; it was decided, therefore, to build the dam in the shallows first and to close it in the deep channels; in that way the least change was produced in the flow of water during the construction of the dam, the channels remaining open until the dam was finally closed. Had any other method been adopted there would always have been strong currents along the end of the dam during construction, which would have caused loss of material and deepening of the sea-bed. Long stretches of the bank could now be built without a serious increase in the flow through the gaps.

There was still another part of the enclosure to be effected, namely the building of the sill-dams in the deep channels, which had also to be kept free from this effect. A great deal of the cross section of these channels could be cut off by building these sill-dams without inconveniently decreasing the capacity. The purpose of these sill-dams was to prevent the sea-bed from being scoured as soon as the currents became stronger, and to form the base of the last part of the enclosing dam, which had not, therefore, to be dumped in deep water; otherwise the loss of material would have been serious. The sill-dams had to be built in the early stages of the enclosure, before the currents had increased notably. The execution of this work was in accordance with the programme drawn up beforehand.

The locks and sluices had to be in use before the enclosure was completed; the pit for these works near Den Oever was built before the enclosure of the Amsteldiep, in order to prevent the scouring of the sea-bed, and the first earthwork that came under construction between Wieringen and Friesland, in 1927, was the embankment for the sluice-pit on Kornwerderzand.

In 1928 the bank, $2\frac{1}{2}$ miles long, connecting this pit with the Frisian coast, was built in the shoals along that coast; only a small channel was dammed here, after it had been connected with the deep channel, called Middelgronden, which lies to the west of Kornwerderzand (*Fig. 3*).

In 1929 the work started in the middle on the shoal of Breezand, and a stretch of $1\frac{1}{4}$ miles of dam, the service harbours on each side, the first sill-dam of $1\frac{1}{2}$ miles in the Middelgronden, which was the main channel of the eastern group, and a small part of the western sill-dam in the Vlieter channel were completed. On a shoal between two channels east of Wieringen another stretch of bank, over a length of $\frac{3}{4}$ mile was built. Up to that time no channel of importance had been dammed, and, although 5 miles of the entrance to the Zuyder Zee had been closed, there was no danger that the unprotected sea-bed would be scoured by storm-tides during the following winter.

The western sill-dam was finished in 1930. The bank from the sluice-pit near Den Oever to this dam was then constructed, thus closing the channels east of Wieringen; an extension of this stretch over a length of about 2 miles, on the eastern side of Breezand to the Blinde Geul channel, and a section on the western side over a length of about $2\frac{1}{2}$ miles, were completed in the same year.

During the winter of 1930–31 there was only a gap 3 miles long to the east, and another nearly $4\frac{1}{2}$ miles long to the west, while several channels had already been dammed; consequently scour of the unprotected sea-bed during storm-tides was feared. To obviate this a low boulder-clay dam, 3 to 6 feet in height, was dumped in each gap except the Blinde Geul to prevent too serious a loss of capacity, and an inconvenient increase in the velocity of the currents.

This precaution was justified, and the extension of the middle stretch of bank up to both sill-dams could be started in the spring of 1931 without the occurrence of any deepening in the sea-bed.

During the construction of both sections scouring of the sea-bed, which was protected by a small dumping of boulder-clay only, would be caused by the increase in the velocities of the currents; the building of a temporary boulder-clay dam as soon as possible up to the level of ordinary high-water, to shorten the time of the scouring action, was therefore of the greatest importance. In the east the dam on the shoal was built before the damming of the Blinde Geul, a layer of boulder-clay only being at first dumped into this channel. In both sections the work started from the two ends; the $2\frac{1}{2}$-mile boulder-clay dam on the western section was closed in $15\frac{1}{2}$ weeks, and that on the eastern section, which was $1\frac{1}{2}$ miles long, in 14 weeks, without the currents deepening the sea-bed more than 7 to 10 feet near the closing points. This proved that preliminary protection of the sea-bed with mattresses would have been uneconomic.

Up to now the work had proceeded very successfully, and the building of the bank through the Blinde Geul, which was about $\frac{1}{2}$ mile in length, seemed simple, no deepening having taken place during the construction of the connecting stretch of the bank. After the dumping of boulder-clay from both ends of the gap, the scouring action of the currents considerably deepened the unprotected sea-bed; this necessitated the dumping of large quantities of boulder-clay, and retarded progress. This was annoying, as according to the working scheme the bank over the sill-dams was to be built in the following year; damage to the embankment in the Middelgronden, however, necessitated the completion of that stretch before the following winter, although this would have been dangerous before the Blinde Geul was closed, as an increase in the velocity of the currents would have made the damming of this channel very difficult. Notwithstanding these temporary difficulties, the Blinde Geul and the Middelgronden were closed before Christmas. I shall give some more details about this part of the work later.

During the winter of 1931–32 there remained only one gap, with a sill-dam, $1\frac{3}{4}$ miles long, which protected the sea-bed sufficiently; and thanks to the experience gained in the preceding year, the damming of the last channel went on very quickly, so that by the 28th May, 1932, the whole embankment being completed, the Zuyder Zee was finally enclosed.

The Construction.—I come now to the interesting question of how the embankment between Wieringen and Friesland was constructed in the open sea.

The four big Dutch contractors[1] for dredging work founded a subsidiary company, the "Maatschappij tot Uitvoering van Zuiderzeewerken" (M.U.Z. Company for the execution of the Zuyder Zee works), which was commissioned by the State to carry out the enclosure according to the programme following the fixed scheme of work. Each year the cost of the work to be executed was fixed by mutual arrangement between the M.U.Z. and the State Service of the Zuyder Zee works, subject to the approval of the Minister for Public Works. Competition being excluded, the State participated in the profit of the enterprise on an increasing scale. If agreement were not possible (this was never actually the case), the work was to be carried out to the instructions of the State Service, the companies' profit being limited to 5 per cent. of the cost. The State in this way secured the guarantee that, under all circumstances, there would be a reliable concern available for the work, provided with capital, experience and first-class equipment. This was the reason for this arrangement, which is uncommon in Holland.

The M.U.Z. once founded, the work started. The boulder-clay and some of the sand was dredged by bucket-dredgers, suction-dredgers also being used for the sand. The material to be dumped was towed into place in hopper-barges by tugs, and dumping went on up to 6 or 7 feet below datum, the boulder-clay dam being placed first to protect the sand from being washed away by the flows. As the depth decreased dumping became impracticable, and the boulder-clay was then discharged from plain barges by floating cranes with grab buckets and long jibs (up to 80 feet). The upper layer of sand was deposited through pipes by suction-dredgers which discharged it from plain barges; *Fig. 7* shows this taking place. The boulder-clay and clay protecting the sand were discharged by floating belt-conveyors. As soon as the boulder-clay dam was no longer submerged, the brushwood mattresses were towed into place and sunk with rip-rap, these preventing the dam from being washed away during stormy weather. The lower part of the stone pitching followed immediately; the blocks were placed as a rule by hand, but gyns were used for the heavier ones.

An idea of the plant used is given by the fact that during the construction of the bank in the Middelgronden twenty-seven large dredgers, thirteen floating cranes and belt-conveyors, one hundred and thirty-two barges and sixty tug-boats were at work, the value of which was nearly 2 million pounds, and the material used was about 20 million cubic yards of boulder-clay and 35 million cubic

[1] M. J. van Hattum's Havenwerken, Ltd., Beverwijk; Hollandsche Aanneming Maatschappij, Ltd., the Hague; Mr. A. Bos, Pz., Dordrecht; and Mr. L. Volker, Az., Sliedrecht.

Fig. 7

M. L. D. Vliegkamp "De Kooy."

VIEW DURING CONSTRUCTION OF THE MAIN DAM.

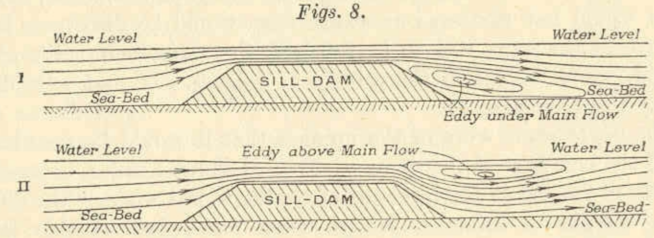
Fig. 10.

FALL IN THE LAST GAP.

yards of sand. This immense plant was of paramount importance, as it enabled the contractors to dominate the situation under all circumstances, and to prevent the scouring action of the currents from becoming too serious. Notwithstanding the use of large quantities of material in the Blinde Geul and in a part of the Middelgronden, the general result was quite satisfactory, the ratio of the quantity discharged from the barges to that remaining in the banks being 1·515 to 1; for boulder-clay this ratio was 1·97 to 1, and for sand 1·34 to 1.

The Sill-Dams, and the Closure of the Last Gaps.—Following the above general description of the work, I propose to give details of the construction of the sill-dams, and of the closure of the Blinde Geul and the Middelgronden: the sill-dams were the most important

Figs. 8.



STREAM-LINES NEAR THE SILL-DAM.

item in the closure of those channels, and their construction was the most interesting portion of the work.

It was known from investigation of the tidal movement that the velocities of the flows would increase rapidly only when the total length of the gaps had been reduced to less than 4 miles. At first the total length of the sill-dams was planned for that length, and in planning the sill-dams it was not sufficient to know merely the average velocity of the current in the gap, the velocity at the surface of the sill-dams was of chief importance; computation being impracticable here, an investigation of the problem in a hydraulic laboratory was necessary.

The stream-lines of the current over the sill-dams showed two different systems of flow, which depended upon the fall, the depth over the sill-dam and its roughness (*Figs. 8*). Above the dam the stream-lines were parallel to the sea-bed, becoming concentrated above the crest, while below the dam the stream-lines either went straight on, dividing themselves gradually over the whole cross-section, and reaching the sea-bed after a great distance, or they curved down, leaving the crest, and followed the slope of the dam, reaching the sea-bed near the toe of the dam. In the first case an eddy occurred with its axis horizontal under the main flow; in the second case with its axis above it. The second case was, of course, much more dangerous than the first, the sloping face of the dam and the sea-bed in the vicinity being attacked as a result of the great velocity of the main current. In the first case, however, the sloping face and the sea-bed near it are only exposed to the smaller velocity of the secondary current or eddy, which is unable to cause damage. It was necessary to ensure that even under the severest storm-tide the sill-dams would never be exposed to the second case. This problem was conscientiously investigated in the laboratory, and the conclusion reached was that, the total length of the gaps being about 4 miles, the computed fall might be exceeded by 60 per cent. before the second case could arise. During the construction of the last stretches of the dam, as the length of the gaps decreased, normal tides would not matter, but storm-tides would be disastrous; the closure of the gaps had to be finished, therefore, before the storm period, which begins in the middle of August. If that were done, safety would be assured.

The contractors were of the opinion that it would be possible to build the last part of the dam, a length of about 4 miles, before the middle of August in the last year of the work, but without the 60 per cent. margin of safety, although they were glad of this later. However, as they were considered right, the total length of the sill-dams was reduced to 2½ miles, it being sufficient to build one sill-dam at each end, the main tidal flows crossing the dam in the west and in the east.

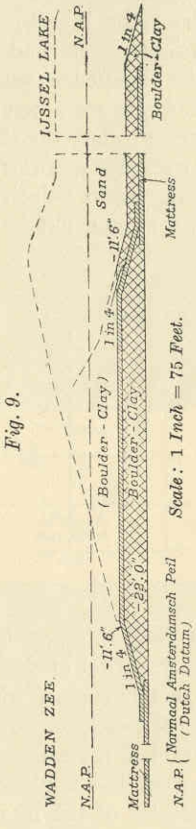
Regarding the construction of the sill-dams two questions had to be taken into account, namely, the depth expected on both sides, and the protection of the surface from attack by the currents. Apart from the scouring action on the sea-bed in the vicinity of the down-stream side of the dam, the depth near the dam depended on the upward flow, and was computed at 37 feet below datum: an empirical relation between the velocity and the depth in the channels of the northern part of the Zuyder Zee had been fixed.

The sill-dam formed part of the boulder-clay dam, and was the foundation of the enclosing dam (*Fig. 9*). It consisted of boulder-clay, protected against the current by brushwood mattresses and rip-rap, the boulder-clay alone being unable to withstand the attack of the current. The crest of the sill-dam was 130 feet broad to facilitate the construction upon it of the main boulder-clay dam.

The safety of the sill-dam was of paramount importance, as a rupture in it during the last period of the closure would have caused an enormous deepening of the sea-bed, and would have endangered the whole enterprise.

Experience of dam protection under similar cirumstances being lacking, investigation in the laboratory again had to be undertaken. It was found that even stones of 5 tons weight were scoured by the currents, and that protection of the dam with heavy stones was impracticable. The problem was solved by charging the mattresses with smaller rip-rap (1½ to 4 cwt.), protected against the direct attack of the currents by thick *wiepen* (bundles of brushwood strongly bound) connected with the mattresses; the diameter and necessary spacing of the *wiepen*, as well as the quantity and weight of the stones, had been carefully investigated. To compare the results of the laboratory experiments with actual conditions, a small mattress was exposed to high-velocity currents near one of the weirs in the river Meuse: the results were quite satisfactory.

Fig. 9.



Scale: 1 Inch = 75 Feet.

TYPICAL CROSS SECTION OF A SILL-DAM.

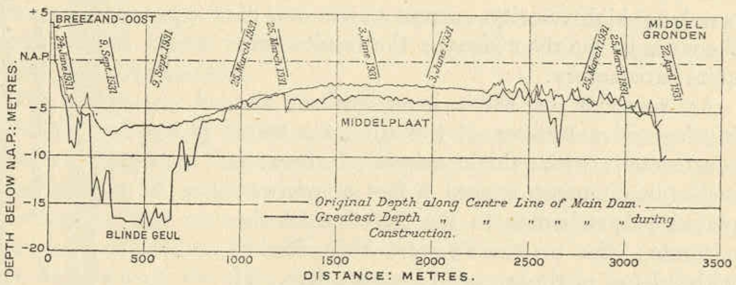
As a result of these investigations the brushwood mattresses of the sill-dams were constructed with thick *wiepen* 1 foot 4 inches in diameter, spaced 9 feet apart, and placed perpendicular to the direction of the currents; the mattresses were then loaded with 0·7 ton of rip-rap per 11 square feet. If the expected fall were now exceeded by 60 per cent. it would cause hardly any movement in the rip-rap. The solidity of the mattresses, and especially of the *wiepen*, being of great importance, they were bound with galvanised-iron wire and rope.

After the many experiments made, we felt no anxiety with regard to the safety of the sill-dams; but in the spring of 1931 investigations on the older parts of the sill-dams, namely those in the Middelgronden, showed that the wire and rope had been attacked by rust to such an extent that the thick *wiepen* would be no longer safe when, in the coming winter, strong currents passed the dam.

The mattresses of the sill-dam in the Vlieter, which were of more recent date, were still in good condition. A rupture of the sill-dam in the Middelgronden had to be prevented at all costs, and the damming of this channel in 1931 was absolutely necessary. This greatly enlarged the task of the M.U.Z. for that year, but at first it seemed possible to finish it before the winter.

In the meantime the difficulties in the Blinde Geul began to influence the progress of the work: these call for explanation. I have already said that the currents in the final gaps were carefully investigated in a vertical plane, this being the main consideration affecting the construction of the sill-dams; in a horizontal plane the investigations had been somewhat neglected, as no injurious effects had been expected from the eddies beside the gaps. The experience gained during the last period of the closure showed that we were wrong. The current, after passing the gap, was concentrated on the down-stream side, and the smaller the gap the greater was the contraction; this was of practical importance, as the greatest velocity was found in the smallest cross section of the current and not in the gap itself. The main current caused eddies

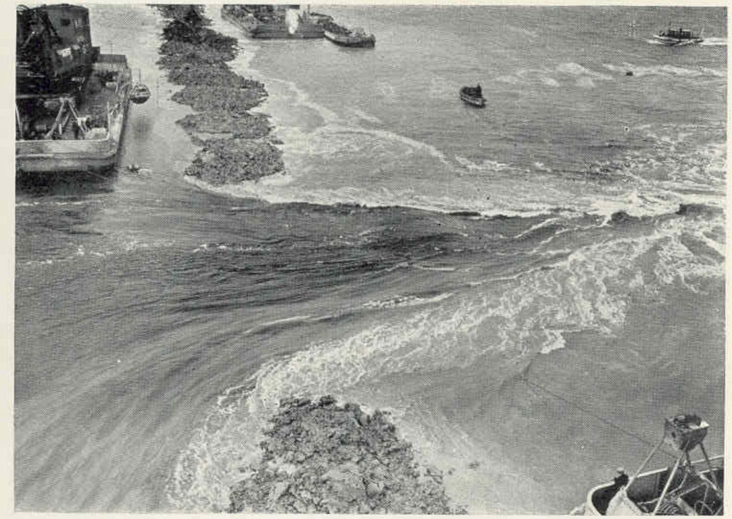
Fig. 13.



on both sides, with vertical axes and much smaller velocities. At the junction of the two currents the water was in extremely turbulent movement, which caused vortexes during the periods when the fall of level through the gaps was considerable. These vortexes attacked the sea-bed, forming craters on both sides of the gap at the end of the boulder-clay dam, which increased in depth with the velocity of the main current, and continued to deepen as long as this phenomenon took place. *Figs. 10, 11* and *12* illustrate the conditions of flow at the gaps.

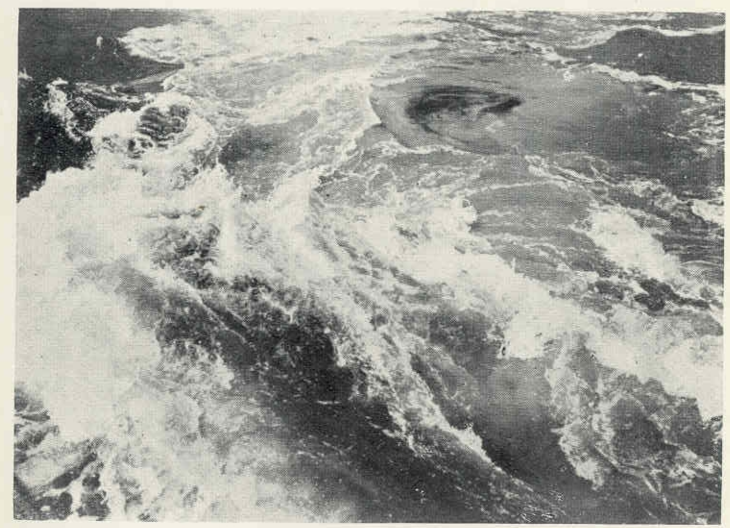
The quick building of the boulder-clay dam by the M.U.Z. was an important preventative, which failed however in the Blinde Geul, where the layer of boulder-clay, dumped before the damming of that channel, was too small to protect the sea-bed against the scouring action of the main current. At this place the depth along the line of the dam soon increased from 20 to 37 feet, and nearly the whole fleet of hopper-barges used for dumping boulder-clay was put in use to prevent further deepening. *Fig. 13* gives a longitudinal section along the line of the dam between Breezand-Oost and the

Fig. 11.



CONTRACTION IN A SMALL GAP.

Fig. 12.

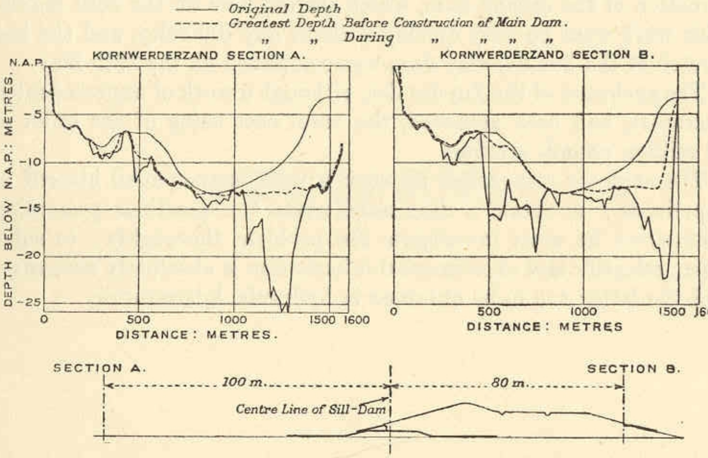


TURBULENT WATER IN THE SIDE OF THE MAIN STREAM.

Middelgronden. The deepening that took place in the Kornwerderzand channel during closure is shown in *Figs. 14.* The construction of the boulder-clay dam proceeded slowly, and turbulence occurred in full, causing the depth around the ends of the boulder-clay dams to increase to 55 feet below datum. The capacity of the working-plant of the M.U.Z. being sufficient, the gap was gradually reduced, and damming was only a question of time and a large quantity of boulder-clay and sand.

This experience showed that a stronger boulder-clay dam should have been built here. The effect of this mistake would not have been so annoying if the bank in the Middelgronden had not had to be built after the enclosure of the Blinde Geul, and it was only towards

Figs. 14.



the end of September that this part of the work could proceed at full speed ; the expectation of storm-tides, as well as the disastrous action of the vortexes observed in the Blinde Geul, made this the most unfavourable season for this work. To prevent vortex action brushwood mattresses 170 feet broad were sunk along the sides of the sill-dam.

Meanwhile the construction of the dam had to go on, and mattresses could only be sunk over a length of 1,700 feet. Before the mattresses were reached the well-known craters were formed, especially where the regular progress of the boulder-clay dam had been stopped by stormy weather. At one time the depth on the northern side of the boulder-clay dam increased to 90 feet below datum, and the outside of the dam slipped. Fortunately the dam was already sufficiently backed, and the enclosing dam could be brought back around the crater for a distance of 65 feet without being submerged; the outer slope did not slip any further. This was a dangerous accident, but fortunately the only one that occurred in effecting the enclosure.

As soon as the mattresses at the sides of the sill-dam were reached, damming went on quickly without any inconvenient deepening of the sea-bed, and the boulder-clay dam was closed on the 22nd November. In two months a gap of 3,350 feet was dammed; the working capacity was enormous, especially for this time of the year, the maximum of material removed in one week being 125,000 cubic yards of boulder-clay and 440,000 cubic yards of sand.

In accordance with the improved method, mattresses were sunk along the sides of the sill-dam in the Vlieter before the construction of the closing dam, which started here on the 23rd March. This work went on very quickly without any difficulty, and the last stretch of the boulder-clay dam was completed on the 28th May.

The enclosure of the Zuyder Zee, although a work of unprecedented character, had been achieved, the total cost being of the order of 12 million pounds sterling.

The engineer responsible for such a work cannot avail himself of experience: to obtain a clear insight into the questions presenting themselves he must investigate the problem thoroughly; to solve them, scientific and experimental information is absolutely necessary, and the latter has to be obtained in hydraulic laboratories.

PRINTED IN GREAT BRITAIN BY
WILLIAM CLOWES AND SONS, LIMITED,
LONDON AND BECCLES.