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I. Introduction

Anticipating the rising sea level and the increasing rainfall, both attributed to climate changes, plans are made for the construction of a new, third discharge sluice in the Afsluitdijk. The design of this new sluice will be part of a Design and Construct contract. In this paper a preliminary design of the bed protection in the discharge channel is presented, which has been based on the experience gained after the construction of the two existing sluices that have been completed in 1932.

The Afsluitdijk is the dam that closes the IJsselmeer basin, the former Zuiderzee, in the northwest of The Netherlands and has a length of about 30 km (Fig. 1). Outside the dam lie the Waddenzee and the North Sea. The River IJssel and the River Vecht run into the IJsselmeer. Also, the excess rainwater from the surrounding lowlands, i.e. from the polders protected by dikes, is sluiced into the IJsselmeer. Now, in winter the target water level in the IJsselmeer is often exceeded, and is expected to be exceeded more and more often in the future. In the Afsluitdijk two discharge sluices have been built to maintain the water level at the target water level and to guarantee the safety of the surrounding polders. At the completion of these sluices the bed protection in the discharge channels consisted of a concrete apron with a stilling sill at the end. The total length of the bed protection was 18 m. The unprotected seabed at the end of the bed protection consisted of boulder clay or sand. However, in a process of lengthening the protection and monitoring the new scour at the end of the protection (trial and scour), which lasted to 1964, the bed protection had to be extended to a length of about 200 m. The scour holes reached a depth of 25 to nearly 30 m below sea level, with an original water depth of 5 m.

In the new sluice project one of the aims is to predict the scour more accurately and to design a bed protection that reduces the scour and keeps the scour away from the sluice. First, in this paper the extension of the bed protections of the existing sluices is reviewed, on the basis of [1] and [2]. Second, a preliminary design of the bed protection is presented. Third, the requirements for the new sluice are derived, on the basis of the review and the preliminary design.

II. Existing sluices

A. *Present Seabed Level*

The discharge sluice near to Kornwerderzand (KWZ) consists of two clusters, with five sluice channels in each cluster. The discharge sluice close to Den Oever (DO) consists of three clusters, also with five sluice channels per cluster. The situation of the sluices is shown in Fig. 1.

Recent depth measurements at the seaside of the Afsluitdijk show a large depression in the seabed next to the sluice of KWZ and three large depressions next to the sluice of DO. At KWZ the maximum depth in the depression is about 28 m below mean sea level (MSL), at a distance of about 200 m from the sluice structure. At DO the maximum depth in the depressions is about 26 m below mean sea level (MSL), at a distance of about 140 m from the sluice structure. At KWZ the steepest under water slopes, which are found at 125 m from the sluice structure, are 1:2 to 1:3. These slopes lie between depths of 14 m and 24 m below MSL. At DO the steepest under water slopes, which are found between 90 m and 140 m from the sluice clusters, are 1:2 to 1:3. These slopes lie between depths of 10 m and 24 m below MSL. Closer by and further away slopes are 1:4 or less [3,4].

Depth measurements at the IJsselmeer side of the Afsluitdijk show that the inflow channel at KWZ bends around the extremity of the western breakwater. This is explained by the fact that the inflowing water, particularly at higher discharges, flows through the deeper channels of the Middelgronden, original tidal channels at the west side of the sluice. The measurements also show that the inflow channel at DO lies south of Robbenplaat and is oblique to the flow direction through the sluice. This oblique direction is explained by, first, the location of the original tidal flow channels in the IJsselmeer and, second, the under water ridge of boulder clay that reaches to a height of 2 m below still water level (SWL). The steepest slopes, to the south of Robbenplaat, are about 1:2,5 and are found between 2 and 6 m below SWL [3,4].

B. *Bed Protection History*

At the completion of the discharge sluices in 1932 the total length of the bed protection in the discharge channel was 18 m. However, due to scour the bed protection had to be extended. A broad overview of these extensions behind two of the center sluices, which is derived from [1] and [2], is given in Table I [3,4].

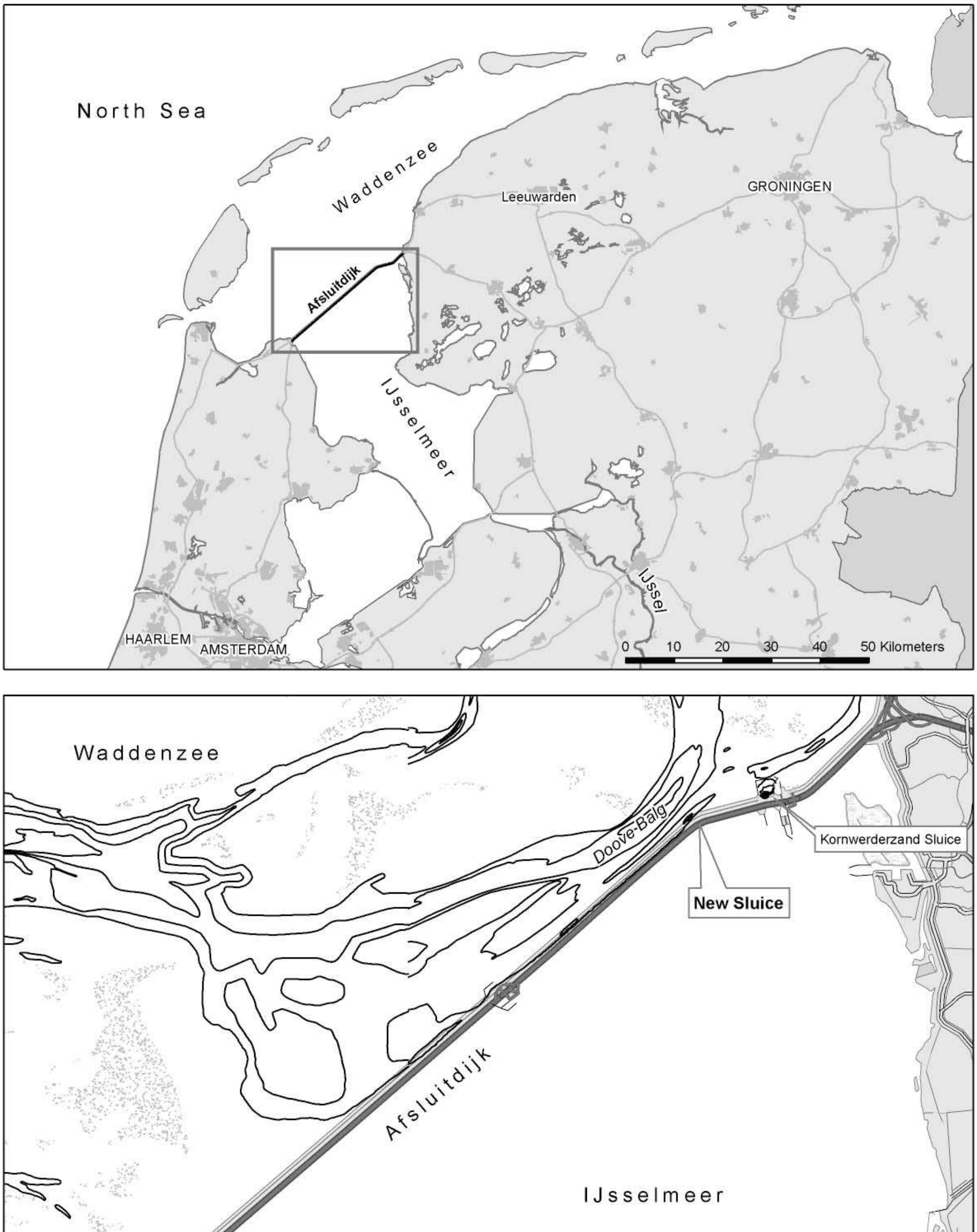

Figure 1. Situation Afsluitdijk, Den Oever sluice, Kornwerderzand sluice and new sluice

TABLE I.
BROAD OVERVIEW PROTECTION EXTENSION KWZ AND DO [3,4]

KWZ: Center Sluice Cluster 5		
Period	Distance between Sluice and Outer End Bed Protection	Bed Protection Extension
May 1932	18 m	Concrete apron with stilling sill
Dec. 1932	128 m	3 rock mattresses 80-200 kg
1933-1937	145 m	Rock mattress 80-200 kg + rock filled with concrete over 50 m from stilling sill
1945-1954	173 m	Rock mattress 80-200 kg
1955-1964	210 m	Rock mattress 80-200 kg
DO; Center Sluice Cluster 2		
May 1932	18 m	Concrete apron with stilling sill
Oct. 1932	128 m	3 rock mattresses 80-200 kg
1933-1937	140 m	Heavy rock 500-1000 kg over 25 m from stilling sill + light rock filled with concrete over 50 m from stilling sill + rock mattress 80-200 kg
1938-1944	160 m	Rock mattress 80-200 kg
1955-1964	205 m	Rock mattress 80-200 kg

The bed protection extensions were not made on the original seabed at 5 m below MSL. After the formation of a new scour hole at the end of the bed protection, this hole was partly filled with sand and a layer of boulder clay, on top of which a rock mattress was placed. The initial slope of the first three mattresses was 1:10 to 1:8. In 1964 the deepest part of the bed protection lay at a depth of 25 m below MSL.

The greater the distance is to the sluice and the deeper the bed protection lies, the lower are the flow velocities and turbulence above the seabed. At a distance of about 200 m from the sluice, the unprotected bottom seemed to resist the hydraulic loads exerted by the flow.

Fig. 2 and Fig. 3 are rough cross-sections of the seabed and the bed protection in the discharge channels behind two of the center sluices, at different points in time. From Fig. 2 and Fig. 3 it is concluded that the present level of the seabed roughly corresponds to the level of 1964. The bed protections, which have been placed before 1964 and the maintenance that has been carried out later seem to prevent subsequent scour. However, according to Fig. 3, it is possible that rock on the steep slopes between 10 m and 24 m below MSL has been transported by the flow. On the condition that maintenance will be carried out, any further scour will be limited.

In 1932 the first bed protection in the inflow channel consisted of a concrete floor, 20 m wide, and a willow mattress, also 20 m wide. After completion of the sluice the bed protection has been extended with a rock mattress, 25 m wide. In 1934 the willow mattress has been filled with concrete [1]. Now, at the end of the bed protections scour holes have been found 1 tot 3 m deep. It is possible that these scour holes will grow in the future.

C. *Safety Check*

In 2004 the stability of the sluice structures in the Afsluitdijk, given the design hydraulic conditions, has been tested according to VTV 2004 [5], a Dutch regulation to check the safety of the main dikes and other primary water-retaining structures. This test included a check of the risk of shear and flow slides in the scour holes, which can endanger the structures [3,4]. As the under water slopes close to the sluices are largely protected by bed protections, this aforementioned risk is sufficiently low.

At KWZ, at the location where one of the discharge channels touches the northeastern breakwater, the flow has caused steep under water slopes. The same holds for the inflow channel and the extremity of the southwestern breakwater. At these locations the risk of shear and slides is too high and measures should be taken. At DO, the inflow channel lies next to the south point of Robbenplaat, which is part of the Afsluitdijk. Also here, measures to prevent sliding have to be taken.

D. *Stability in Discharge Flow*

Using depth measurements, the area of the flow has been determined, perpendicular to the flow, at several cross-sections at different distances from the sluice structures. The maximum discharges have been estimated from measured discharges [6]. From those flow area's and maximum discharges the maximum averaged flow velocities at the cross-sections have been estimated. Then, using the stability formula of Pilarczyk, the required bed protection has been calculated. In Table II both the calculated and the existing bed protections are presented. From this table it is concluded that most of the existing protections are stable at the maximum flow conditions. However, locally at the breakwaters and at the edge of the protection in the IJsselmeer inspection and protection measures are necessary.

TABLE II.
CALCULATED AND EXISTING BED PROTECTION [3,4]

KWZ		
Location	Calculated	Existing
Waddenzee, distance to sluice piers (flow velocity): 0 m (6,6 m/s) 50 m (2,8 m/s) 100 m (1,5 m/s) 210 m (0,8 m/s)	 Concrete apron 60-300 kg 10-60 kg 30/60 mm	 Concrete apron Mattress and concrete 80-200 kg End of protection
Northeastern breakwater 1-1,5 m/s	80/200 mm	<u>No protection</u>
IJsselmeer, distance to sluice piers: 20 m (2,6 m/s) 90 m (1,9 m/s)	 5-40 kg 50/150 mm	 Concrete apron <u>No protection</u>
Extremity southwestern breakwater 1-2 m/s	80/200 mm	<u>No protection</u>
DO		
Waddenzee: 0 m (6,6 m/s) 50 m (2,8 m/s) 100 m (1,5 m/s) 210 m (0,8 m/s)	 Concrete apron 60-300 kg 10-60 kg 30/60 mm	 Concrete apron 500-1000 kg/mattress and concrete 80-200 kg End of protection
Northwestern breakwater 1-1,5 m/s	80/200 mm	80-200 kg
IJsselmeer: 20 m (2,7 m/s) 90 m (1,6 m/s)	 5-40 kg 40/100 mm	 Concrete apron <u>No protection</u>
South point Robbenplaat 1,7-2 m/s	80/200 mm	<u>Partly no protection</u>

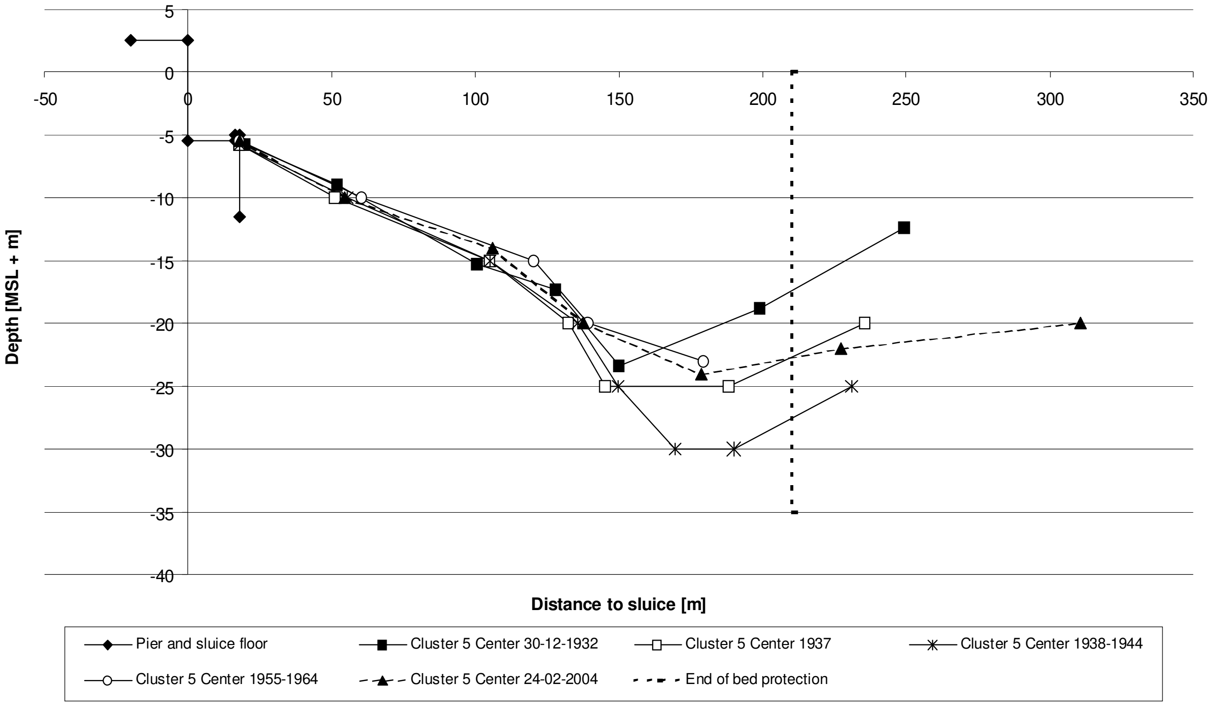

Figure 2. Cross-section of seabed and bed protection in discharge channel; Kornwerderzand

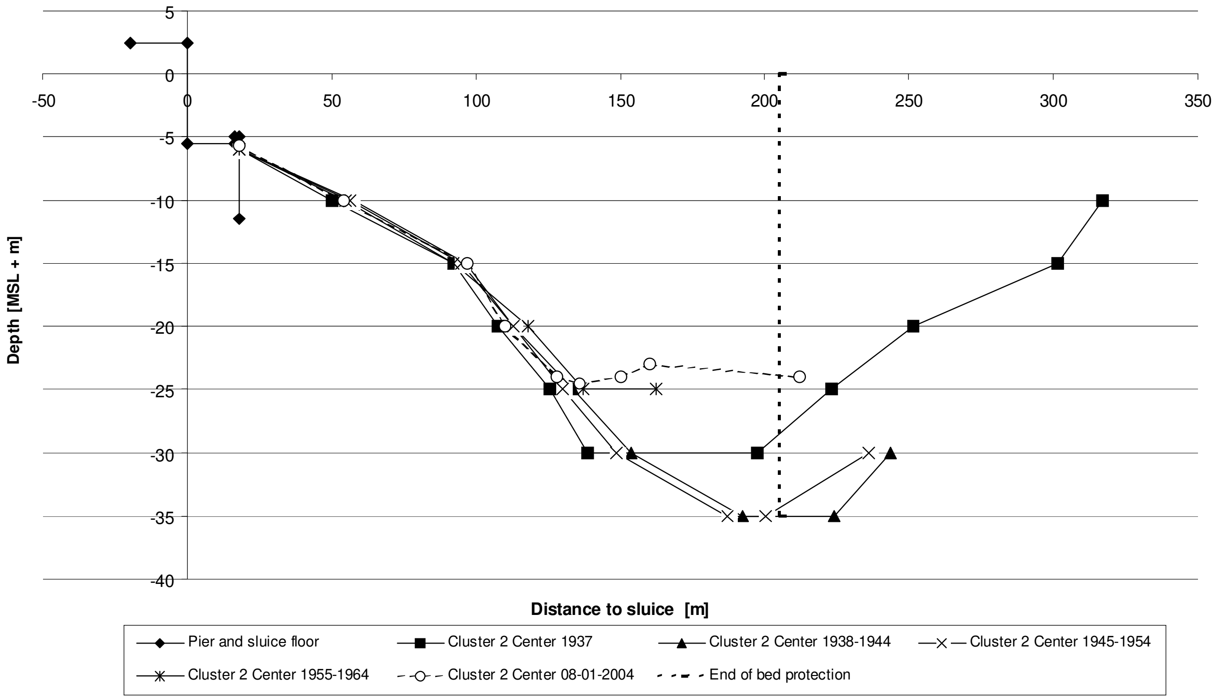

Figure 3. Cross-section of seabed and bed protection in discharge channel; Den Oever

E. Sluicegates Refuse to Close

If the sluice gates refuse to close and at high tide the flow direction turns towards the IJsselmeer, the flow velocities can become extremely high (Froude > 1), especially when it starts to storm and the wind is coming from the northwest. In this case the bed protection at the IJsselmeer side of the sluice is most probably insufficient. Large scour holes will form and part of the bed protection will be flushed away. The height of the risk that bed protection and sluice will be damaged depends on the chances of the gates refusing to close and of the Waddenzee rising to high levels simultaneously.

F. Recommendations Existing Sluices

With regard to the seabed next to the sluices, the following is recommended:

- The large bed protections on both sides of the sluice gates have to be maintained to prevent the formation of new scour holes and under water slope slides. Inspections at a maximum interval of one year.
- At the locations where the flow channels are close to the breakwaters measures have to be taken to prevent the shear and sliding of the steep under water slopes. For example, first, the under water slopes have to be measured. Then the steepening slopes have to be replenished with sand and/or boulder clay. Finally, rock mattresses have to be placed.

  Once the flow touches a rough surface, like a bed protection, the turbulence of the flow increases and this increases the transport capacity of the flow. This must be remembered if it is decided to protect the slopes only locally. In other words, protection can introduce scour.
- To maintain the bed protection at the IJsselmeer side, the scour at the edge of the protection has to be stopped. This means inspection and the aforementioned measures. It is emphasized that the speed of the erosion is limited as long as the seabed consists of boulder clay.

III. A NEW DISCHARGE SLUICE

A. Location and global features

For the present the new sluice will be built at the bend in the Afsluitdijk, less than two kilometers west of the existing sluice at KWZ (Fig. 1). At this location old tidal channels, in the IJsselmeer, and new tidal channels, in the Waddenzee, are close to the Afsluitdijk.

The preliminary design of the new sluice is an open concrete structure, 200 m wide (parallel to the Afsluitdijk). It has five channels, each of which is 30 m wide and 35 m long (perpendicular to the Afsluitdijk). In between the channels are piers, each of which is 10 m wide. Every channel is closed by a single sluice gate. The gate sill is at 6,5 m below MSL.

The new sluice will be built in the crest of the Afsluitdijk, i.e. at the seaside, which means that the inflow channel is closed in, at two sides, by the large inner berm. The seabed of the inflow channel, which is 200 m wide, lies 8 m below MSL. A discharge channel will be dug between the sluice structure and the tidal channel in the Waddenzee, the Doove Balg, to a depth level of 11 m below MSL. At the gate sill the seabed drops vertically to this depth. Given this relatively large depth, flow velocities will decrease significantly, before the flow reaches the seabed.

At the seaside, along the discharge channel, two breakwaters will be constructed, which must answer the following demands:

- Keep the flow and flow eddies away from the Afsluitdijk.
- Guide the flow to increase the efficiency of the sluice.
- Guide the flood currents away from the Afsluitdijk, leading to an enlargement of the shallow water area, east of the sluice, being beneficial for water animals and plants.

B. Scour Predictions and Protection Length

1) The Discharge Channel

The sea edge of the bed protection in the discharge channel has to lie at a minimum distance to the sluice structure. Then, when the flow reaches the unprotected seabed, flow velocities have already decreased and scour holes will be less deep. The distance has to be larger than the part of the bed protection, which possibly can slide down into the scour hole. Thus the functioning and the stability of the sluice are guaranteed.

The required length of the bed protection has been derived from the scour predictions, which are given in Table III [7]. The prediction formula of Breusers and the formula of Dietz [8] have been applied, and an average flow velocity of 1 m/s has been assumed.

TABLE III.
SCOUR PREDICTIONS, PRELIMINARY [7]

Distance between Sluice and Outer End Bed Protection [m]	Maximum Scour Depth, t = 1 year (Breusers) [m]	Maximum Scour Depth, t = 20 years (Breusers) [m]	Equilibrium Depth, t = ∞ (Dietz) [m]
100	7,7	25,7	26,2
150	6,9	22,8	24,2
200	6,3	21,0	22,9
250	6,1	20,1	22,2

The predictions in Table III say that the maximum scour depth, even at 200 m from the sluice, can be about 20 m below the original seabed, which is comparable to the scour depths at the existing sluices. As with the existing sluices, finally, the flow turbulence and the velocities in the scour hole will decrease and the scour hole will stop growing. The upstream slope of the scour hole will reach a value between about 1:2 and about 1:4, before parts of the slope start sliding down. The actual slope before sliding and the final slope after sliding strongly depend on the characteristics of the soil. Flow slides can be expected in natural sand layers, which have been deposited quickly, as a result of which the sand is less compact. Flow slides start occurring when slopes are about 1:4. The final slope after a flow slide will be 1:15-1:20. Shear will start at a steeper slopes, closer to 1:2. The final slope after a shear slide will be 1:6-1:8. The required length of the bed protection is calculated with (1) as in [8]:

$$L = \frac{1}{2} y(\cot(\gamma) - \cot(\beta)), \qquad (1)$$

in which: L = failure length (m),
y = maximum scour depth (m),
γ = upstream slope after sliding (°),
β = upstream slope before sliding (°).

The required length varies from about 60 m, in case of shear, to about 160 m, in case of flow slides. In the preliminary design, first, a protection length of 150 m has been chosen. However, in that case the scour holes at the end of the bed protection can lead to the sliding down of breakwater slopes at both sides of the discharge channel. Instability of the breakwater slopes has to be prevented by applying a toe protection, with a minimum length of about 60 m. As the scour will continue more rapidly in the small, unprotected area that is left, it has been decided to protect the entire seabed area in between the breakwaters.

The extremities of the breakwaters are at the edge of a flood channel, which lies parallel to the Afsluitdijk. At these extremities scour holes will develop as a result of both flood currents and discharge flows. Therefore, the seabed around the extremities has to be protected against sliding, by applying a bed protection, which is about 60 m wide. The total area of bed protection is shown in Fig. 4.

2) The Inflow Channel

The bed protection in the inflow channel has to withstand very high flow velocities, when the sluice gates refuse to close and the high water level of the Waddenzee rises high above the IJsselmeer level. A maximum head difference of 4 m has been assumed.

The flow over the sill will be supercritical (Froude > 1). There will be a hydraulic jump in the inflow channel, close to the sill, and the maximum flow velocities will be about 11 m/s. After the hydraulic jump velocities and hydraulic loads will be lower, but still comparable to the maximum velocities in the discharge channel. As the width of the flow increases only gradually, velocities remain high in the entire inflow channel. Scour holes at the end of the bed protection, given a hydraulic load lasting 12 hours, can reach a depth of 15 m below the seabed. The freeway on the Afsluitdijk, the A7, is guided over the inflow channel by a traffic bridge, of which the piers are standing in the inflow channel. It is concluded that the bed protection has to be extended about 75 m south of the traffic bridge. The total length of the bed protection on this side of the sluice is 170 m. The total area of bed protection is shown in Fig. 4.

C. Stability in Discharge Flow

First, the maximum averaged flow velocities have been estimated, for the maximum discharges, at several cross-sections at different distances from the sluice structures. Then, using the stability formula of Pilarczyk [9], the required bed protections have been calculated, of which the top layers are given in Table IV and shown in Fig. 4 and Fig. 5.

TABLE IV.
DISCHARGE FLOW: CALCULATED BED PROTECTION [7]

Location	Estimated Maximum Flow Velocity [m/s]	Required Top Layer (Pilarczyk)
Waddenzee, distance to sluice piers [m]		
0-40	4,7-4,3	Concrete apron / 300-1000 kg
40-70	4,3-3,5	300-1000 kg
70-150	3,5-2,8	60-300 kg / 40-200 kg
150-300	2,8-2,5	40-200 kg / 10-60 kg
IJsselmeer	3,5	5-40 kg

TABLE V.
GATES REFUSE TO CLOSE: CALCULATED BED PROTECTION [7]

Location	Required Top Layer (Pilarczyk)
IJsselmeer, distance to sluice piers [m]	
0-35	Concrete apron
35-125	1-3 ton / 300-1000 kg
125-155	300-1000 kg / 60-300 kg
155-170	60-300 kg

D. Sluice gates Refuse to Close

The bed protection in the inflow channel has to withstand the flow velocities caused by an estimated head difference of 4 m, at high tide on the Waddenzee. The top layers of the bed protection, based on estimated flow velocities, are given in Table V and shown in Fig. 4 and Fig. 5. In the discharge channel the flow velocities are maximal at the maximum discharge.

IV. Design and Construct

A. Introduction

The design of the new discharge sluice will be part of a Design and Construct contract. To prepare this contract, first, the principal has to define the objects, which are part of the sluice. The main object of the new sluice is the sluice structure in the crest of the Afsluitdijk. Other objects are the inflow and the discharge channel, the breakwaters along the discharge channel, and the traffic bridge across the inflow channel.

Second, the functional requirements of these objects have to be formulated. With the new sluice, it has to be possible to maintain the water level of the IJsselmeer at the summer and winter target levels. As the sluice will be part of the Afsluitdijk, the sluice has to retain the water of the Waddenzee. The flow channels have to provide space for the flows to pass through. The breakwaters have to answer the requirements, which are mentioned in paragraph III.A, and the traffic bridge has to maintain the traffic connection.

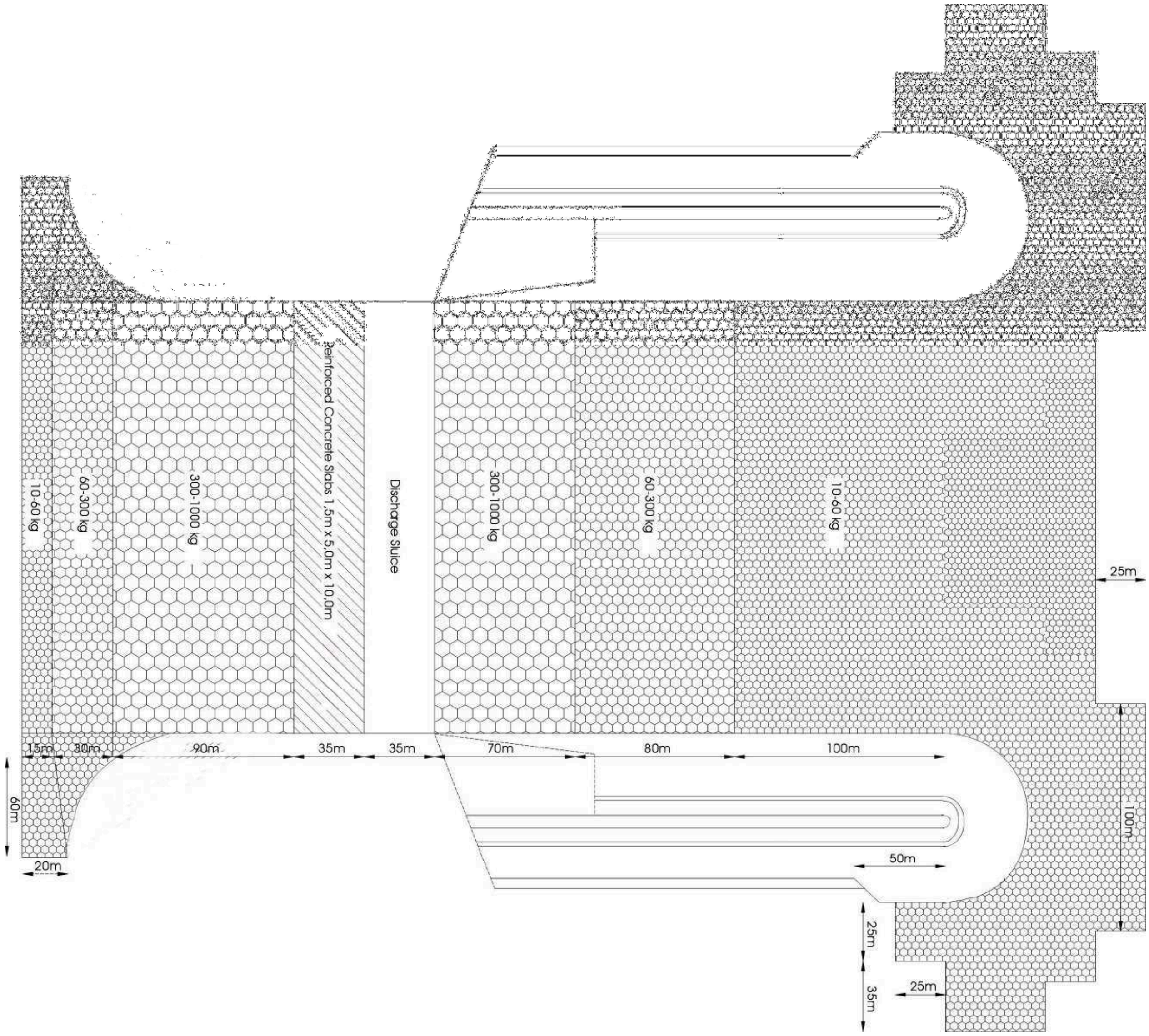

Figure 4. Upper view preliminary design bed protection

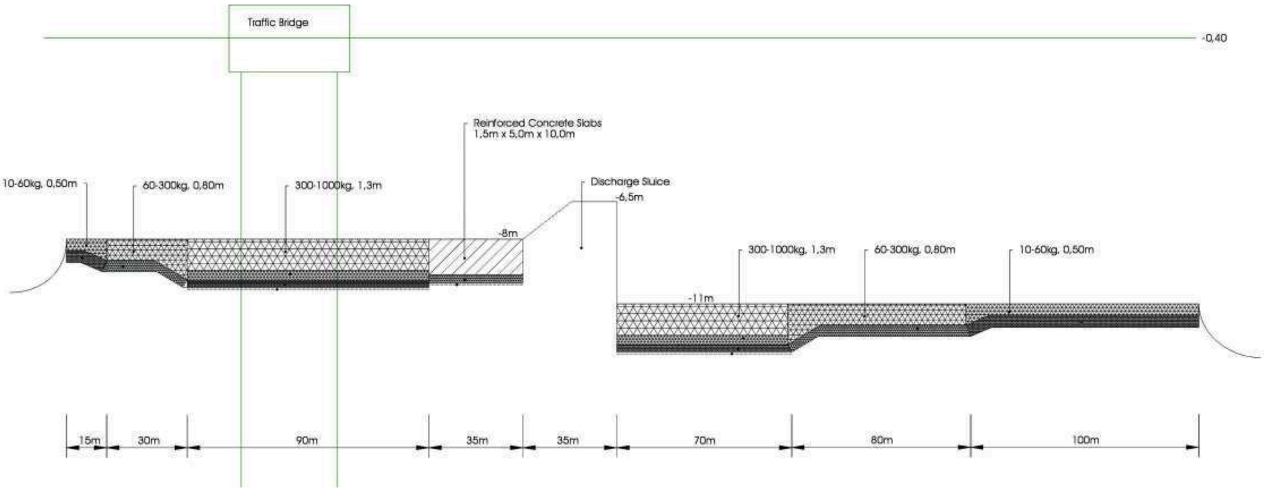

Figure 5. Cross-section preliminary design bed protection

Contrary to the usual Construct contracts, the principal does not provide the contractor with the design of the bed protections, including top layers, filter layers and protection lengths. Only the functional requirements are given, from which the contractor has to draw up the design. In the next paragraph the general requirements, which are related to scour and bed protection, have been summarized.

B. General Requirements Related to Scour

The general requirements in this paragraph have been derived from the experiences with the existing sluices and the preliminary design of the new sluice. The corresponding functions are given in the headings, between brackets.

1) Probability of Failure (To Retain Water)

The overall probability of failure of the new sluice is prescribed. From this the designer has to derive the allowed probabilities of failure for the individual objects, including any soil slope, bed protection or breakwater. These probabilities determine the measures which have to be taken to limit or to prevent scour and thus to maintain the stability of the structures.

2) Stability Afsluitdijk (To Retain Water)

The stability of the Afsluitdijk, i.e. the geotechnical stability of the foreshore and the dike body, is not allowed to decrease as a result of the new sluice structure and its morphological effects (erosion).

3) Temporary Structures (To Retain Water)

Temporary structures, which during realization take over the water-retaining function of the Afsluitdijk, have to be just as reliable as the Afsluitdijk. During the realization of any bed protection, the reliability has to be guaranteed.

4) Operating Conditions (To Retain Water, Target Water Levels)

The principal supplies the hydraulic conditions, i.e. water levels and waves, and the maximum discharges, which have to be realized. From this, the designer has to calculate the maximum hydraulic loads and flow velocities on the seabed. The designer has to determine whether measures are necessary to prevent scour and erosion, so that the sluice satisfies the maximum probability of failure and fulfills its functions. Hydraulic research in a laboratory is compulsory, to check hydraulic loads and any bed protection which has been designed.

5) The Discharge Channel (To Retain Water, Target Water Levels)

At the location where the protected part of the seabed ends and the unprotected part begins, scour holes will form, as a result of both the discharge flows and the tidal currents around the extremities of the breakwaters. It has to be prevented that shear or flow slides into the scour holes lead to the malfunctioning or even failure of the sluice and the breakwaters.

6) Inflow Channel (To Retain Water)

The designer has to determine the dimensions and the weight of the bed protections in the inflow channel from the following conditions:

- water level statistics concerning the IJsselmeer and the Waddenzee;
- the overall probability of failure;
- the chance that the sluice gates refuse to close.

The bed protection design has to be tested by hydraulic research in a laboratory.

7) The Discharge Channel (Target Water Levels, Mitigation of Morphological Effects)

A discharge channel has to be dug between the sluice structure and the large tidal channel in the Waddenzee, the Doove Balg. By prescribing this channel, it is expected that erosion and other morphological effects can be limited to the location of the channel.

8) Maintenance (Life, Maintenance)

As the design hydraulic conditions can occur in the first year of operation, any bed protections have to be robust. The amount of damage has to be very limited, i.e. without maintenance, which will hinder the operation of the sluice. Any bed protection has to be tested by hydraulic research in a laboratory.

9) Life (Life)

The new sluice has to fulfill the aforementioned requirements during the entire, prescribed life.

V. Recommendations

At the preparation of a new discharge sluice, the existing sluices are an important source of information, to draw up the requirements that are related to scour and bed protection.

The overall probability of failure of the new sluice has to be prescribed. From this the designer has to derive the allowed probabilities of failure for the individual objects, including any soil slope, bed protection or breakwater (reliability study).

The main hydraulic loads on the seabed of the inflow channel are caused by the inward flow from the Waddenzee. The height of these loads depends on the chances that the sluice gates refuse to close after the discharge period (reliability study).

If requirements lead to the construction of bed protections, these requirements have to imply robust designs, because large maintenance works will hinder operation of the sluice.

At the locations where the flows from the discharge sluice and/or tidal currents skirt the breakwaters, which are situated along the flow channels of the sluice, measures should be taken to prevent sliding down of the breakwater slopes. Under water slopes can become steep and scour holes can develop.

Shear and flow slides depend on the characteristics of the soil. A soil investigation has to be carried out to determine the probability of flow slides. Probably, flow slides are restricted to certain soil layers.

More effort has to be made to gain insight into the morphological consequences of the digging of a discharge channel towards the Doove Balg. This new channel can attract tidal currents. The combination of discharge flows and an increase of tidal currents, i.e. an increase of sediment transport capacities, can speed up scour and erosion, not only at the sluice, but also along the Afsluitdijk. In the new Design and Construct contract it has to be defined clearly how far the responsibilities of the principal and the contractor go.

Looking back at the existing sluices, it is clear that only when the unprotected seabed lies deep enough the soil can resist the hydraulic loads exerted by the flow. This is a missing element in the preliminary design. At the end of the bed protection flow velocities and turbulence are still high and scour is only shifted from the sluice to the end of the bed protections, where large scour holes will form that eventually will damage the protections. This is not a stable situation.

Acknowledgment

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