PERMANENT INTERNATIONAL ASSOCIATION OF NAVIGATION CONGRESSES

Edinburgh 1981

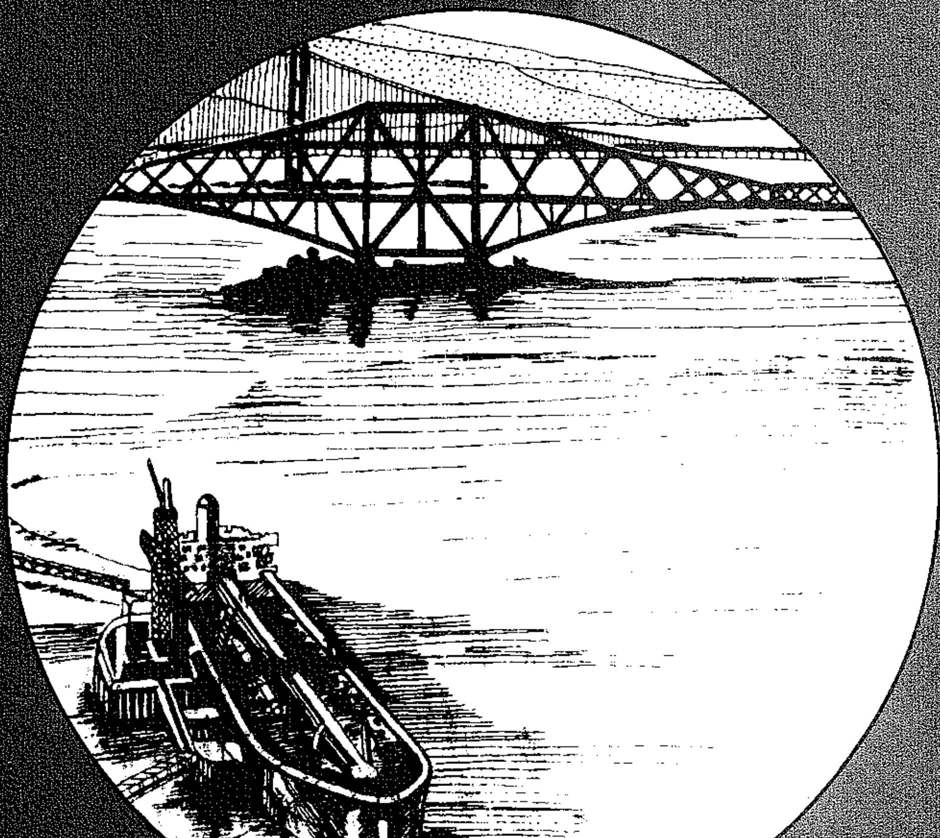
XXVth Congress — XXVe Congrès

INLAND & MARITIME WATERWAYS & PORTS

Design - Construction - Operation

Section II — Volume 5

Maritime Ports and Seaways
Ports et Accès Maritimes



VOIES NAVIGABLES ET PORTS INTERIEURS ET MARITIMES

Conception - Construction - Exploitation

ASSOCIATION INTERNATIONALE PERMANENTE DES CONGRES DE NAVIGATION

PERGAMON PRESS

Coastal Changes due to the Construction of Artificial Harbour Entrances and Practical Solutions, including Beach Replenishment

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INTRODUCTION

When longshore sediment transport is interrupted by a construction along a coast, e.g harbour moles or a dredged approach channel, the equilibrium of the coastline may be disturbed.

When the disruption is caused by breakwaters, the longshore transport that is held back will cause accretion updrift of the breakwaters and erosion downdrift of them. The updrift accretion may eventually result in the harbour entrance shoaling.

The downdrift erosion might cause difficulties when valuable areas are situated close to the coastline or when the coastline forms a coastal protection for land behind it.

When the disruption is caused by a dredged channel, no accretion updrift of the channel will occur since the material is trapped in the channel. This means, however, that here too there is a lack of material downdrift and erosion will again occur there.

The following means are available to overcome the problems:

(a) Artificial sand by-passing. The material is picked up at the updrift side of the harbour and transferred to the downdrift side. In the case of a dredged channel, this will also markedly reduce the shoaling in the most shoreward part of the channel.

(b) The sand can be also supplied to the eroding beach at intervals of some years. The material required can be found, for example, updrift of the harbour at the coastline or at another site such as an approach channel, a new harbour basin or an offshore source. In all cases, a dredged channel not protected by breakwaters will still have to be maintained.

(c) The eroding beach can be protected by groynes or some other form of coastal protection works. The principle of groynes is that the rate of longshore transport is decreased, whereas coastal protection works will simply prevent the coast being scoured. The decrease in the longshore transport means that less sand is transported from the coast and that erosion is therefore reduced.

In order to be able to plan the measures required, one requires a forecast of the longshore transport and the changes in the coastline due to changes in this transport.

METHODS OF FORECASTING COASTAL CHANGES

At the PIANC-Congress in Paris (1969), Bijker and Svasek (1) reported on possible ways of predicting morphological changes caused by man-made coastal structures.

Two lines of approach were indicated in their paper:

(a) A method for the determination of coastal changes using physical models with mobile beds. In order to determine the morphological time scale in such models, Bijker worked out a mathematical formula for the combined effect of waves and currents.

(b) A method for predicting the coastal changes based upon an empirical C.E.R.C.-relationship between the energy dissipation in the breaker zone and the longshore sediment transport. Svasek defined the method by a formula for transport inside the breaker zone and included the effects of the changing wave climate in a morphological computer program.

Physical models are particularly suitable for studies of complicated situations which cannot readily be simulated with a numerical approach. In the immediate neighbourhood of breakwaters or in cases of very irregular bed formations (rocky outcrops and islands in front of the beach) the physical models still give the most reliable results.

In the Netherlands, where the harbours are built on a normal sandy coast, the mathematical models devised by Svasek (modified C.E.R.C. approach) and Bijker have been further developed and applied for the purpose of forecasting the expected coastal changes.

BACKGROUND TO THE C.E.R.C.- APPROACH AND ITS LIMITATIONS

The so-called C.E.R.C. equation is the first attempt (2) to provide some basis for solutions to coastal problems with sandy coasts:

$$S = K_1 - E_b \cdot c_b \cdot \sin 2\phi_b$$

where S = total sediment transport along a coast within the breaker zone

E_b = the wave energy per unit of the surface area of the sea

c_b = the wave group velocity

ϕ_b = the angle between the group velocity vector and the orthogonal to the coastline

Subscript b indicates that all values of the variables have to be valid for the breaker zone.

K_1 = an empirical constant containing all processes that are either unknown or too complicated.

This empirical constant is similar to the well-known coefficient of Chezy, which remains a valuable aid in applied hydraulic engineering. The coefficient K_1 covers (and hides) all the complicated aspects of the sediment movement in the zones of breaking and wave run-up, averaging all systems of longshore and rip currents and their influence on the temporary shape of the coastal bars and throughs (3).

Svasek's extension of the C.E.R.C. equation to the area within the breaker zone (1;4) neglects the real processes as well. The main improvement that this extension offers is the introduction of a linear relation between the gradient of the energy-flux along a wave ray and the local depth within the breaker zone:

$$\Delta S(D_n, D_{n-1}) =$$

$$K_2 \left(E_n \cdot c_n \cdot \sin 2\gamma_n - E_{n-1} \cdot c_{n-1} \cdot \sin 2\gamma_{n-1}\right)$$

with D_n and D_{n-1} being the local average depths at the arbitrarily chosen depth contours. And K_2 is the local constant factor in which the computered refraction and shoaling coefficient as well as the above mentioned empirical coefficient K_1 are combined.

Neither the original C.E.R.C. equation nor the above mentioned extension of it, however, can solve the typical problems appearing in the immediate neighbourhood of capes or breakwaters. In that region, the rip current is stabilised and has a dominant influence upon the sediment transport perpendicular to the coastline. In addition, the diffraction effects of such capes or breakwaters have not yet been incorporated in the computer programs based upon this approach.

Consequently, the application of the C.E.R.C. equation and its extension are limited to undisturbed sandy coasts with gradually changing direction of depth contours along coasts and coastal inlets.

In such areas, the calculation results differ from the volumetric data on coastal changes by approximately 30% by hindcast. These results were obtained using a computer program (Figs. 1 and 2).

This program is equipped with the facility for input of the statistical distributions of wave heights in deep sea for all sectors from which the waves might reach the coast (4).

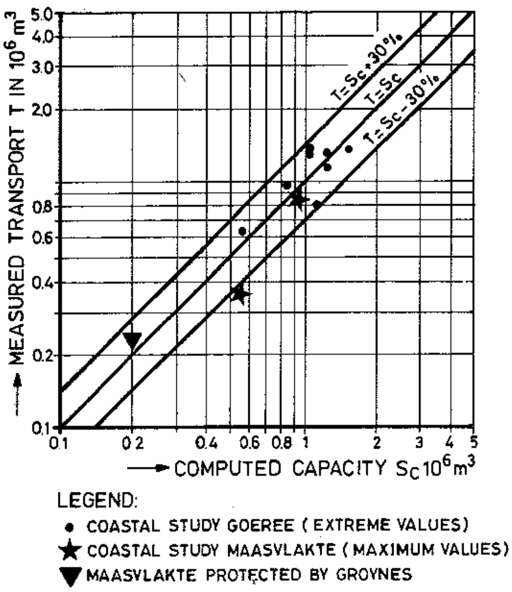

Fig. 1 Computated longshore transport vs measured transport

The average yearly wave climate has to be known in order to be able to estimate the future location of sedimentation and/or erosion along the coast. If, however, the expected morphological changes will cause a considerable reorientation of the depth contours, the initial schematisation of the topography of the bed has to be adapted in stages.

Coastal protection works such as groynes reduce the sediment transport considerably. The reduction caused by permeable (pile) groynes or low solid groynes which are frequently submerged can be computed using the following assumptions:

(a) The breaking of the waves is the dominant mechanism for stirring up the bed sediments into suspension, while the turbulence generated by the breakers is responsible for maintaining the fine sediment concentration in the breaker zone.

(b) Groynes built perpendicularly to the coast do not influence the gradient of the energy flux along the wave rays within the particular limits of the refraction computations (wave ray distances are of the same order of magnitude as the groyne divisions).

(c) Permeable or submerged groynes reduce the longshore currents in the fields between the groynes due to the local "Bernoulli" resistance which can be expressed in the local hydraulic head ΔZ over a groyne.

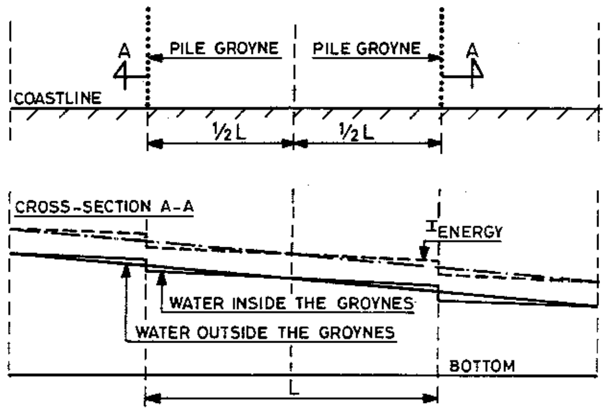

Fig. 2 The hydraulic gradient between permeable groins.

(d) The reduction of the longshore currents can be approximated by using a modified hydraulic gradient $I' = I - \frac{\Delta Z}{L}$ within the groyne fields (Fig. 2)

in which I' = longshore hydraulic gradient between the groynes

I = longshore hydraulic gradient at an undisturbed coast

Z = local energy loss in the longshore current due to the groynes

L = distance between 2 groynes of a groyne system

(e) The stabilisation of the circulation flow of the water masses as well as the sediments within the groynes is not allowed for (the approximation in all other longshore transport equations do not take account of the non-stabilised rip current).

(f) Transitional effects at the boundaries of a groyne may be expected. With the assumptions mentioned above, the correction for the influence of the groynes in reducing the longshore transport has been incorporated into a mathematical model as follows:

The refracted waves defined by the local wave parameters: significant height H_{sb} of the breaking waves and the local angle ϕ_{sb}, both determining the transport according to the C.E.R.C. equation, are replaced by imaginary waves with local parameters H_{sa} and ϕ_{sa} which are designed to represent the conditions, including the groyne resistance:

(1) The loss of the local energy flux remains the same:

$$H^2_{sa} \cdot C_s \cdot \cos \phi_{sa} = H^2_{sb} \cdot C_s \cdot \cos \phi_{sb}$$

(2) Longshore current is reduced by a local resistance factor A:

$$\overline{U}_{sa} = A \cdot \overline{U}_{sb}$$

The longshore current velocity $\overline{U}_{sb}$ is a function f_{us}:

$$U_{sb} = f_{us}(H_{sb}, \phi_{sb}, \Upsilon_s)$$

where Υ_s represents the locally bounded influence of some other factors like the representative period $\overline{T}$ of the wave field, the local bed resistance coefficient f_{sw}, local depth ds, tidal flow velocity and any other local quantities. All these factors, however, do not change for a given location $S(\Upsilon_{sa} = \Upsilon_{sb} = \Upsilon_s)$

Consequently, the local imaginary parameters H_{sa} and ϕ_{sa} can be determined from the two equations:

$$H^2_{sa} \cdot \cos \phi_{sa} = H^2_{sb} \cdot \cos \phi_{sb}$$

and

$$f_{us}(H_{sa}, \phi_{sa}) = A \cdot f_{us}(H_{sb}, \phi_{sb})$$

This method has been checked on an eroding (artificial) coastline (reclaimed land at the Europoort) and the results of the volumetric data correlated reasonably well with the computations (Fig. 3).

THE METHOD FOR NON-UNIFORM LONGSHORE TRANSPORT

In cases where transport is not semi-uniform i.e. where there are important longshore changes, a more sophisticated method has to be used.

The more refined solution of longshore transport computation, i.e. computing a longshore current followed by a transport formula for waves and currents, is used under the following circumstances:

(i) In cases where there is a combined effect of wave-induced transport and transport caused by tidal or wind-driven currents. Normally, however, the latter is small compared with the transport generated in the breaker zone. Approximate calculations have revealed that the influence of wind-driven and

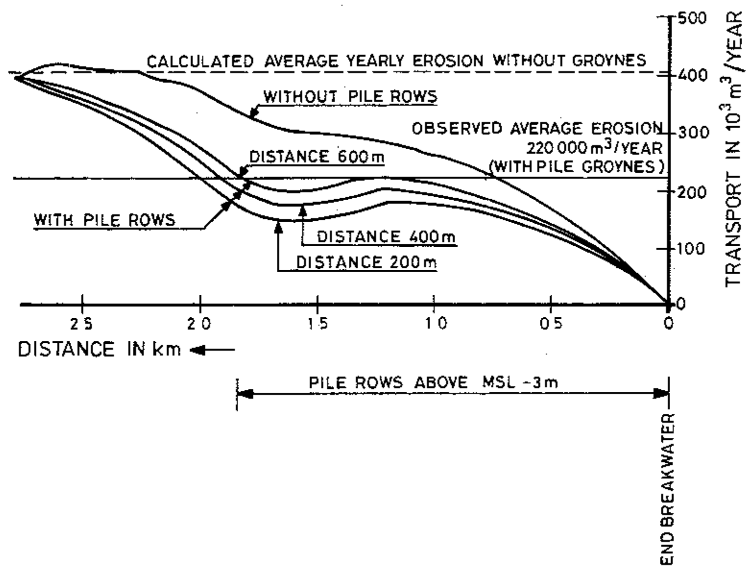

Fig. 3 Comparison between computed and observed erosion at a coast protected by pile groynes.

tidal currents within this breaker zone is normally negligible in comparison with the wave-induced currents.

(ii) In cases where the wave height along the coast changes so much that the gradient of the longshore normal component of the radiation stress dS_{xx}/dx cannot be neglected. In that case, the effect of the gradient in wave set-up along the coast has also to be taken into account. This situation is often found in the lee of breakwaters and other structures interrupting longshore transport.

(iii) In cases where the longshore transport changes so much that fairly extensive coastal changes can be expected. In such quasi uniform situations the gradient of dS_{xx}/dx could possibly be neglected. However, due to the change in the longshore current, the continuity of the water has to be compensated for by transverse water transport, which also carries sediment. This transport of sediment cannot be neglected in the equation of continuity determining the coastal changes.

Van Overeem developed a model in 1978 (5) in which he calculated the longshore transport by computing the longshore current. His basis comprised the radiation stress components in the breaker zone and the approximation for the bed friction as suggested by Bijker in 1967 (6) and 1971 (7). He followed the method of Battjes 1974(8) for determining the final form of the current distribution (see v.d. Graaff and Van Overeem 1979 (9).

The result of such a velocity profile is given in Fig. 3. The procedure as suggested by Bijker in 1971 (7) and discussed by v.d. Graaff and Van Overeem in 1979 (9) is used for the longshore transport.

The influence of variations in the wave height along the coast, resulting in a variation of the wave set-up and a gradient of the longshore component of the radiation stress, can easily be introduced into this model.

In this so-called NL program the coastal area is schematized into series of cross-sections at equal distances Δx and depth contours with equal depth intervals. The distance of the depth contours is measured from a reference line lying somewhere near the coastline. The transport of water through the profile boundaries of the grids is calculated by way of the computed longshore velocity and the same is done for the transverse water transport through the grid boundaries formed by the depth contours using the equation of continuity. The water transport through the actual coastline y(ik,o) is by definition zero.

The transport is computed from the currents. Since this NL program is in principle one-dimensional, the longshore transports are computed first. The transverse transport through the grid boundaries formed by the depth contours is determined from the product of the water transport and sediment concentration. This concentration is determined in the longshore transport calculation. An extra transverse transport occurs in those cases where the slopes of the profile change substantially. This transport can be assumed to be proportional to the deviation of the actual slope from the equilibrium slope (Bakker, 1968 (10) and can be calculated according to the procedure suggested by Swart in 1974 (11). With these transport equations, the equation of continuity for every grid and subsequently the changes in bed level can be determined.

This procedure has the advantage that it is possible to include all possible effects on the longshore transport and therefore of the coastline changes.

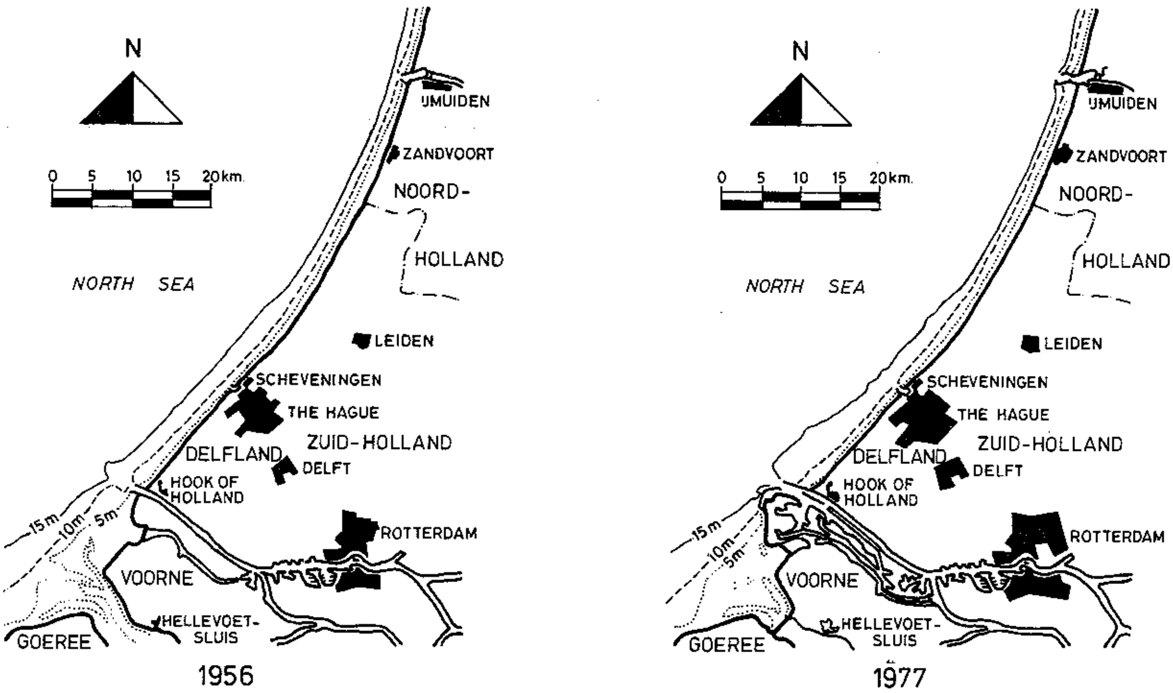

Fig. 4 Changes at the coast of Holland

The limitations and difficulties with the approach are as follows:

(i) The longshore transport formula. The formula applied in this procedure has by no means found widespread acceptance nor been fully tested. The fact that this is also true of the longshore current formula is self-evident. Sediment transport is still not fully understood and it is masked only in the direct transport formula like that of the C.E.R.C.

(ii) In nature the waves approach the coast from varying directions. To determine the equilibrium position of the coastline, it is possible to apply the various wave directions and heights according to their total distribution of occurrence. The sequence and duration of the various wave fields have also to be taken into account in order to predict the development. However, this, too, applies to all coastline computations.

(iii) The method is basically one-dimensional which means that the effect of rip currents travelling in the same direction will have to be developed for this.

PRACTICAL SOLUTIONS

GROYNES

In the last quarter of the 19th century harbours were constructed along the Dutch coast at Scheveningen, the Hook of Holland and IJmuiden. Two latter harbours were connected with the existing inland ports of Rotterdam and Amsterdam; the harbour of Scheveningen is mainly a fishing harbour.

All three were constructed on a sandy coast.

Even prior to their construction, the coast between the Hook of Holland and Kijkduin (Fig.4) was protected by groynes to combat the constant erosion of the coast. The first groynes were constructed here in 1776. The harbour of Scheveningen was situated at a stretch of beach that had been protected by groynes since 1885. The coast near IJmuiden was undefended.

Groynes are stone constructions, perpendicular to the shoreline with protection against erosion at both sides. The groynes were constructed from the toe of the dunes up to approximately 50 m outside the L.W. mark. The height is approximately 0.5 m below the toe of the dunes, extending to approximately 0.50 m below low water. Mattresses were laid around the heads of the groynes in order to secure them.

The distance between the groynes is equal to once or twice their length. The heads have to be situated along an even line. Groynes can only be used on gently shelving beaches where the erosion is mainly caused by longshore transport, which they then help to reduce.

The construction of the three harbours also had an impact on the adjacent beaches. Near the Hook of Holland and IJmuiden it took about 25 years before the coast adapted to the new situation. The influence of the breakwaters at Scheveningen was less, because they extended only 100 m further into the sea than the existing groynes.

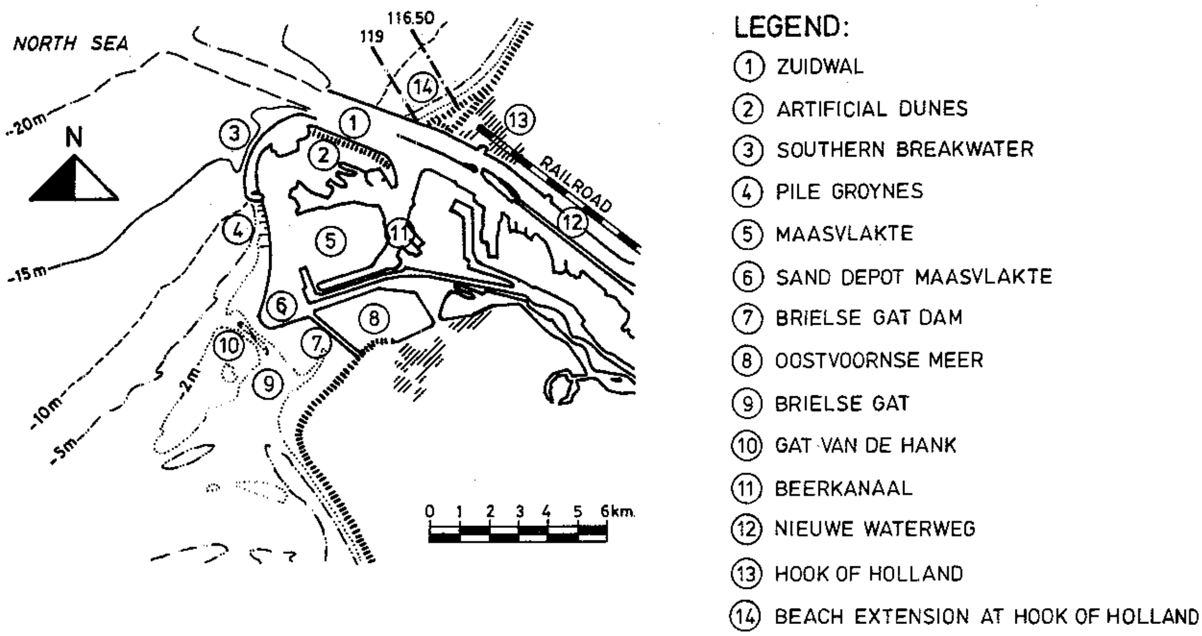

Fig. 5 Europoort

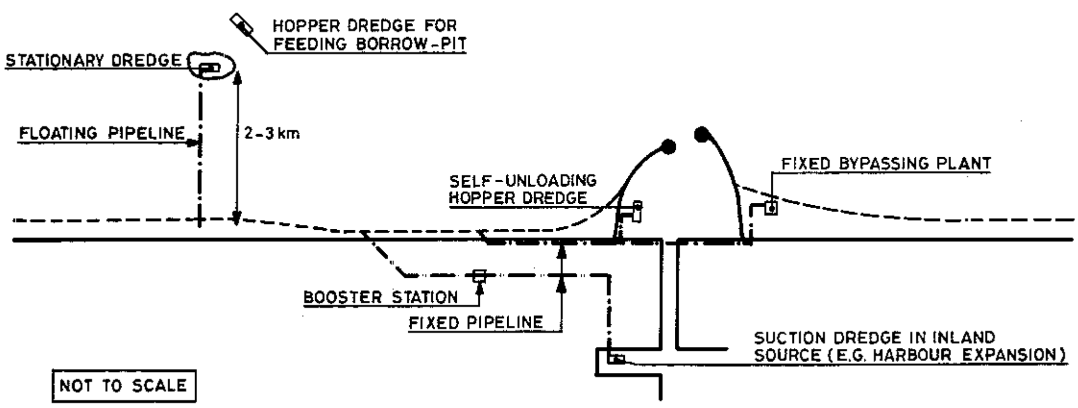

Fig. 6 Various suppletion systems

After a state of equilibrium had been reached, it could be observed that the M.S.L. line was moved about 500 m in seaward direction at the northern breakwater at the Hook of Holland as well as at IJmuiden. At IJmuiden the accretion south of the harbour entrance was about one third of the accretion at the north.

Due to the accretion north of the Hook of Holland, some 10 groynes had to be extended in the period from 1890 to 1910. The heads of these groynes were made heavier between 1919 and 1939, while the groynes themselves were lowered.

After the extension of the breakwaters a new adaption process had to be expected. Drawing on the available experience from former extensions and recently developed calculation methods the future location of the M.S.L. line and the toe of the dunes was determined. The new adaption process was accelerated by artificial beach fill. Only minor modifications were made to the existing groyne system near Scheveningen.

In general, no new groynes are under construction at present. The main reasons are that they are very expensive (construction US $ 5000 per metre and annual maintenance

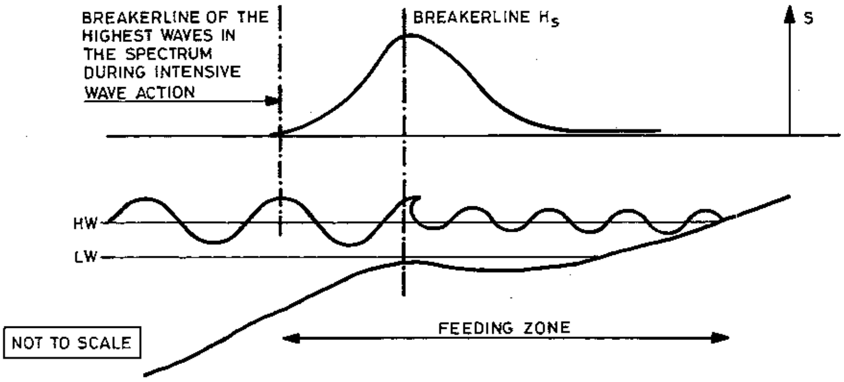

Fig. 7 Location of the Feeding zone

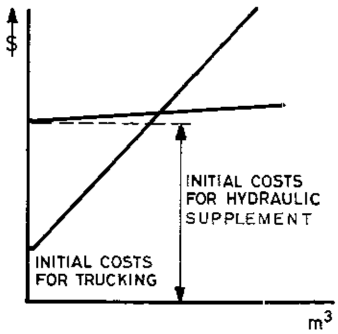

Fig. 8 Costs as a function of cubic metres to be handled

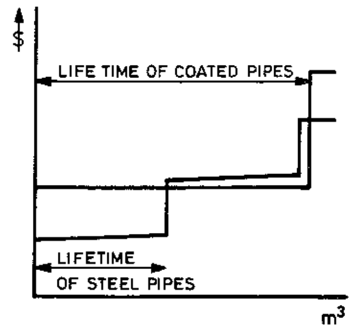

Fig. 9 Costs as a function of cubic metres to be handled

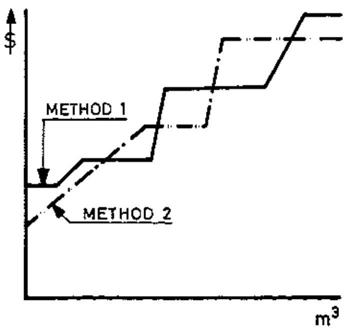

Fig. 10 Costs as a function of cubic metres to be handled

US $ 5000 per groyne) and that it is not easy to follow changes in the morphological process. Groynes lack the flexibility of sand supplemental methods.

PERMEABLE GROYNES (PILE GROYNES)

A disadvantage of impermeable groynes, especially in regions with strong currents along the coast, is the initial scour at the groyne heads. The flow contraction, which increases the local flow velocities by some 30%, together with the stabilised rip currents along the groynes are the direct reason for such scouring.

Regular maintenance of the groynes is usually necessary at the base of the groynes in deeper water.

Moreover, in areas with tidal channels along the coast, the series of groynes tend to stabilize the channels. In consequence, such channels usually deepen and the groynes have to be extended in depth in order to prevent undermining and finally disintegration.

This problem was recognised in the Southwestern part of the Netherlands (Zeeland) some 200 years ago. Rows of wooden piles were incorporated into the crests of low, impermeable, groynes in order to reduce the flow gradient during the maximum tidal flow and prevent the strong contraction at the groyne heads.

It seems evident that large tidal ranges (up to 4 m) and the existence of tidal channels and banks were the reason for this traditional construction which was not taken over in the area north of the Hook of Holland.

Experiments were started with pile groynes at the beach on the island of Walcheren in the years up to 1968 and 1969.

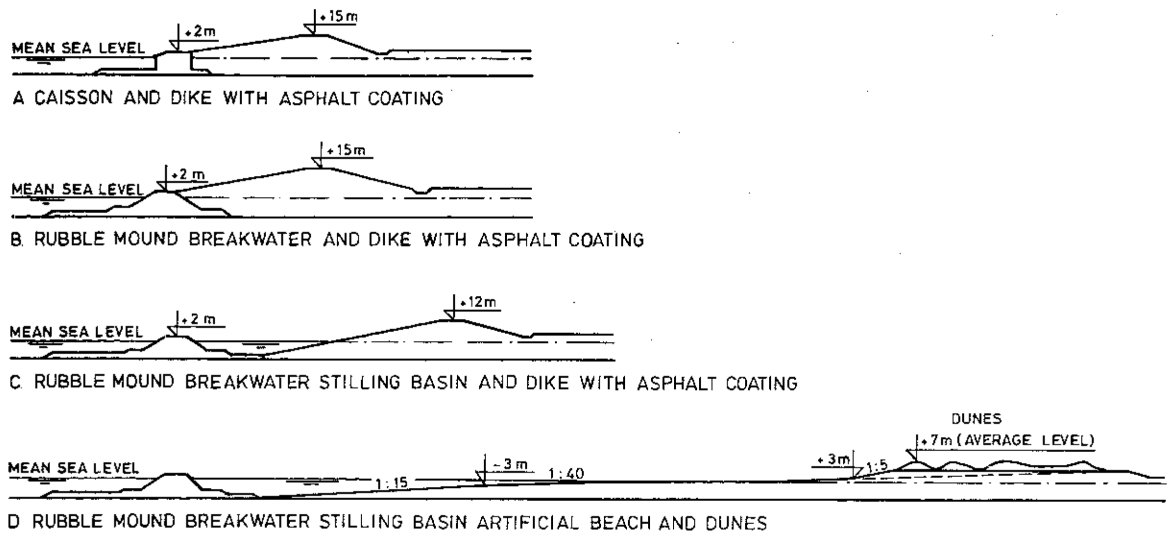

Fig. 11 Cross-sections at Europoort

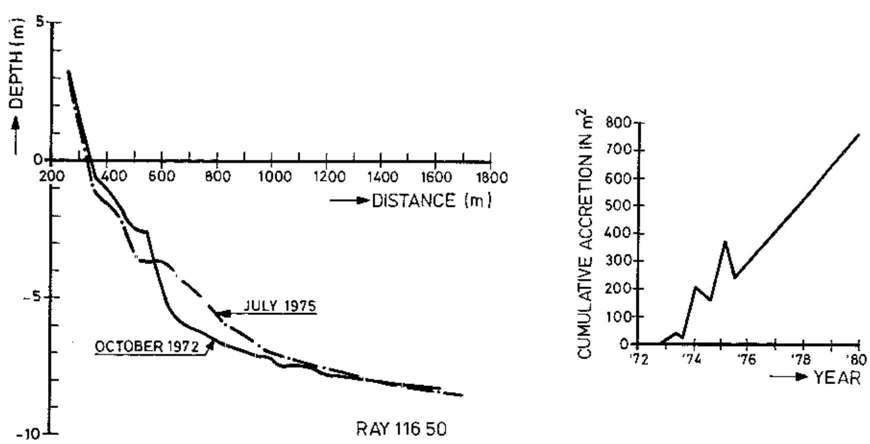

Fig. 12 Profile variations in ray 116.50 (Europoort)

This time the impermeable groyne foundation was omitted which simplified the construction and significantly reduced the costs.

The effect of permeable groynes has now been incorporated into the morphological computer programs and it is now possible to determine the dimensions of the groynes; the groyne length and the distance between them as well as the spacing between the piles.

The length of the individual piles is still determined empirically on the basis of the local depth: 55% of the length of the piles should always be embedded. If a channel lies near the groynes, the outer piles should be sunk deeper. The sinking of piles in gravel is more difficult, and in addition they have to be placed much deeper.

Often and mainly for practical reasons, two rows of piles are jetted into the bottom to form one groyne (Figs. 18 and 19). The piles are jetted either from a temporary jetty, walking construction platform or directly from the shore, while the jet-installation is moved over a temporary deck laid over the two rows of the piles. The piles should be rammed home for the final metre by hammering or vibration.

The final crest of pile groynes is usually 1.5 to 1.7 m above the highest observed beach profile, and in deeper water approximately 0.5m above the mean sea level.

The costs of the double pile groynes in the Netherlands are approximately 15% to 20% of those for the traditional impermeable groynes.

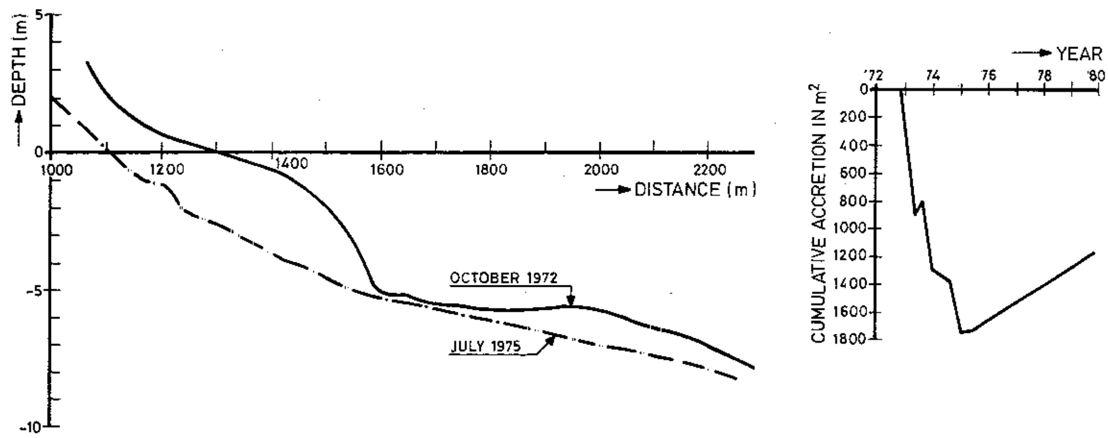

Fig. 13 Profile variations in ray 119 (Europoort)

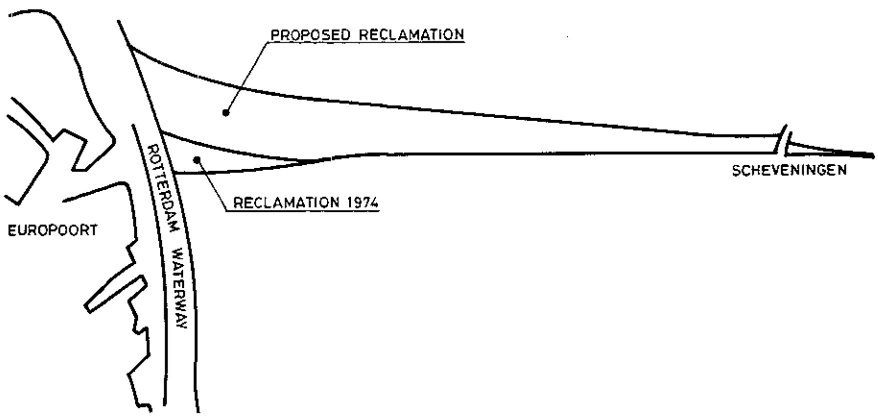

Fig. 14 Proposal for reclamation

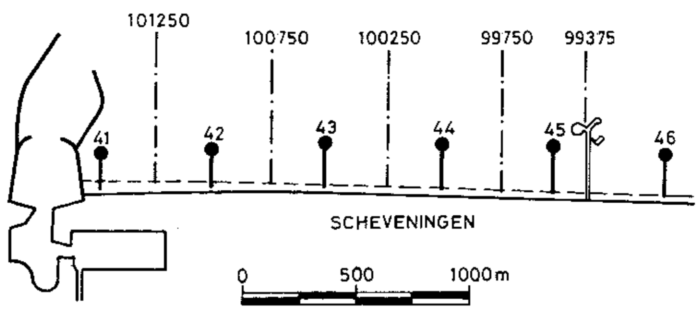

Fig. 15 Scheveningen

SAND FILL

Sediment properties. The sediment for the fill has to satisfy several conditions. It should preferably be clean and odourless material, have dominant granulometric characteristics corresponding to the existing or designed beach slope; and the fines content should not be too great. Fine particles are washed away very quickly and therefore increase the total quantity of fill material to be handled and may temporarily give both the sea area and the beach a polluted appearance.

In most cases it will be desirable to use a rather coarse sand, because coarse sediment

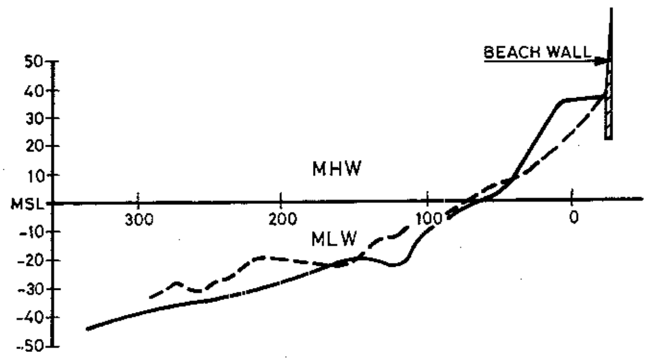

Fig. 16 Profile variations in ray 99.750
(Scheveningen)

settles very quickly and allows for rapid drainage of the fill area. This is advantageous when the supplemental works are carried out on beaches used for recreational purposes and to which the public wants access as soon as possible (Fig. 20). This also results in a very clean sand, free of smaller clay particles, which is an advantage when the beach is used for recreational purposes.

Experience in Scheveningen (near The Hague) has shown that replenishment with a medium grain-size of 350 micron sand allowed the public access to the filled section directly after the filling was completed. On the other hand, the grain-size should not differ too much from that of the original beach as this has an effect on the beach slope. The overall beach stability may then be jeopardized as well. The borrowing area should not be located near sewage-outfalls and dredged material from maintenance dredging in harbours is consequently seldom suitable.

In general, two types of locations for sand-borrow pits can be distinguished: sand-pits in the open area and 'inland' sources. 'Inland' sources are all sources where sand can be dredged under protected conditions, e.g. in an estuary, behind an island, or in a harbour. If the borrowing area is located in the open sea, there may be a minor impact on marine life on the sea bottom. It is therefore advisable to have an expert in marine life study the expected effects in advance.

Nourishment methods. In the preceding sections it has been clearly demonstrated that each beach nourishment scheme is unique and has to be tailored to the locally prevailing conditions.

No two schemes are exactly alike, but all share one essential feature: only sand placed shoreward of the surfzone, which corresponds to moderate or severe sea conditions, will effectively be fed into the process that governs beach erosion or beach restoration. This is called the Feeding Zone.

There is one exception to this rule: the sand can be used to construct an offshore submerged breakwater - an artificial sandbar - which effectively changes the wave climate and thus the entire sand transport mechanism of the beach.

Construction of such a bar is relatively simple by comparison with actual beach nourishment, where the sand has to be dropped in the Feeding Zone. The offshore boundary of this zone is seaward of the area of major littoral transport during intensive wave action (Fig. 7) The onshore boundary would normally be the M.H.W.-line, but could be higher, above the H.H.W.-line if needed.

The beach nourishment would then only become effective after further erosion of the existing beach.

How can sand be fed into the Feeding Zone? Three basic methods can be identified:

Trucking sand onto the beach. This requires an onshore source of sand of satisfactory quality and available in adequate quantities. These conditions hardly ever occur at beaches requiring replenishment and the method can be disregarded here.

Direct dumping. Direct dumping into the Feeding Zone. This is a special case, which occurs only when the Feeding Zone extends to depths sufficient to allow shallow draft vessels to discharge a load of sand there. The method has been applied in several projects using shallow-draft, trailing hopper-suction dredgers equipped with sliding bottom doors, or dredgers of the split-hull type (Fig. 21). These vessels run very close inshore, even on to the beach and dump their load. During unloading they float up and back off the beach. The sea conditions can impose a limitation on this sort of operation, but it is effective and economical. Fig. 22 shows an operation of this type at the Hook of Holland beach replenishment scheme, near Rotterdam.

Hydraulic fill. A sand/water mixture is pumped on to the beach and into the surfzone through a pipeline system on the beach. The method of operating the fill area is very much like any other hydraulic fill, except for the fact that no precise profiling is required: that can be left to nature itself.

Care should be taken that the excess water used in transporting the sand is allowed to run off freely into the sea and that no impounded areas can be formed that would cause sedimentation of the silt and clay fractions. Special care should be taken that any runnels in the foreshore are not closed. Fine fractions

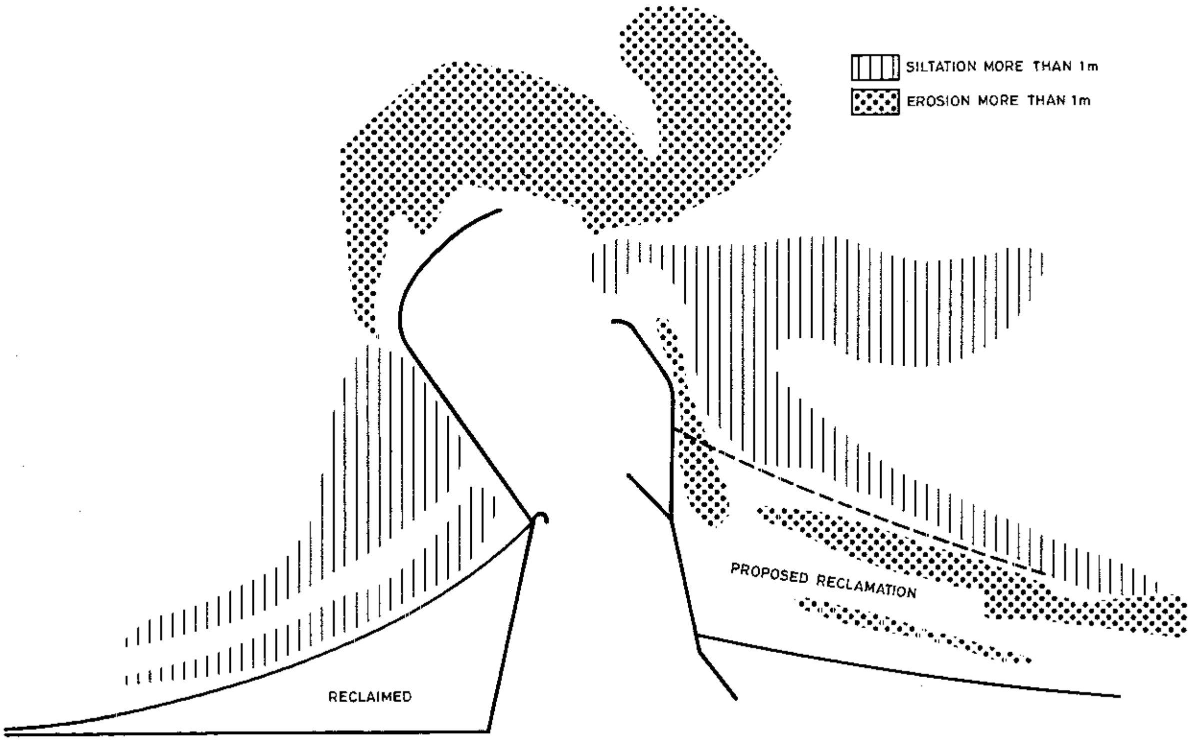

Fig. 17 Sedimentation and erosion near IJmuiden

sedimentating in these impounded areas or in runnels form a silt layer which may be dangerous to children. If the method is carried out properly, fine particles are washed out and a sandy beach remains.

With this method all the sand is fed into the Feeding Zone.

Movement out to sea is limited largely by the surfzone, so the sand will travel parallel to the beach. Consequently, no major sand losses as such need be expected.

Another advantage is that fill operations need only be stopped in extreme weather conditions.

An important factor regarding the weather is that in general beaches are used for recreation during good weather. Consequently, the nourishment work should preferably be carried out in the poor weather period (winter season) which may exclude some of the methods. Overall weather limitations are set by the actual revovery and transport of this sand and resort can be made to a variety of solutions (Fig. 6).

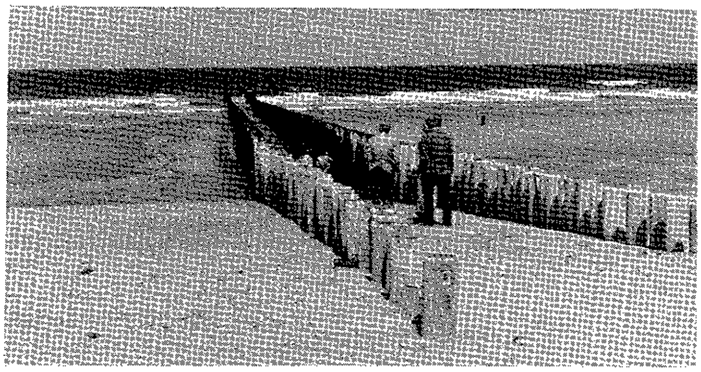

Fig. 18 Permeable groyne at Europoort

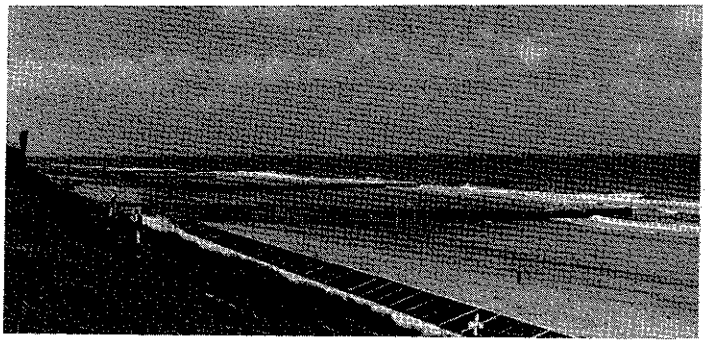

Fig. 19

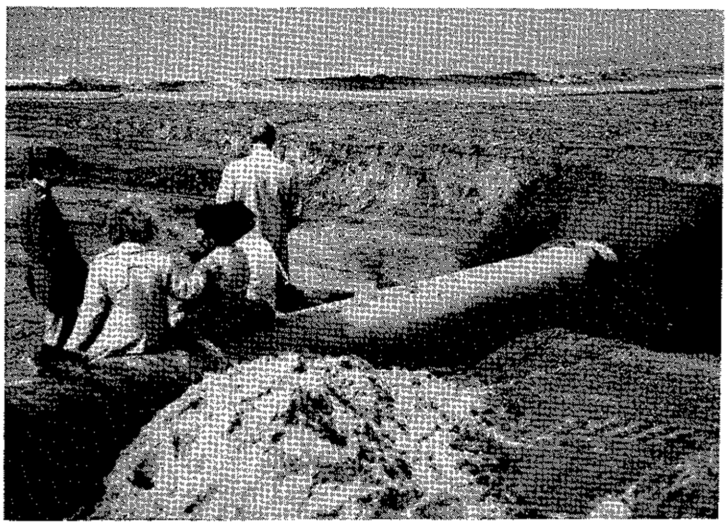

Fig. 20

<u>Hydraulic fill from a dredge pit in sheltered waters.</u> This could be a lake behind the dunes, or a sheltered sea inlet. The recent replenishment at the German island of Sylt was of this type. The equipment used is of the type commonly used in inland waters, lakes, or estuarine areas: a stationary floating dredger discharging through a floating pipeline which is connected to a land-based pipeline which discharges on the beach. As the material to be dredged is essentially non-cohesive, no cutter-head is required to cut the soil and a straightforward suction dredger, operating in a relatively shallow pit, is a logical choice. In densely packed sand layers, water jet-nozzles around the suction-mouth would be used to fluidize the sand to maintain the high production rates associated with this type of

Fig. 21

equipment. A typical dredge of this type would be able to dredge to depths of 40 metres, produce 3000 m^3 of sand per hour and deliver at distances up to 5 kilometres (with or without intermediate booster stations, depending on the delivery pump horsepower installed).

For large dredger in this category these figures could rise to 60 metres and 4000 m^3/hour.

Hydraulic fill via port. In this case seabed sand is dredged with a trailing hopper suction dredger (Fig. 23) which enters port and either discharges directly by pumping its cargo into the hydraulic fill pipeline system, or dumps it in front of a rehandling suction dredger which operates in the sheltered port area. The latter method is attractive in as much as it incorporates a buffer stock which helps to avoid the seagoing trailer suffering weather downtime.

However, this buffer, in the form of an underwater dump, requires a substantial harbour area which, due to the presence of the rehandling dredger, is inaccessible to other shipping.

Hydraulic fill directly from sea. In this

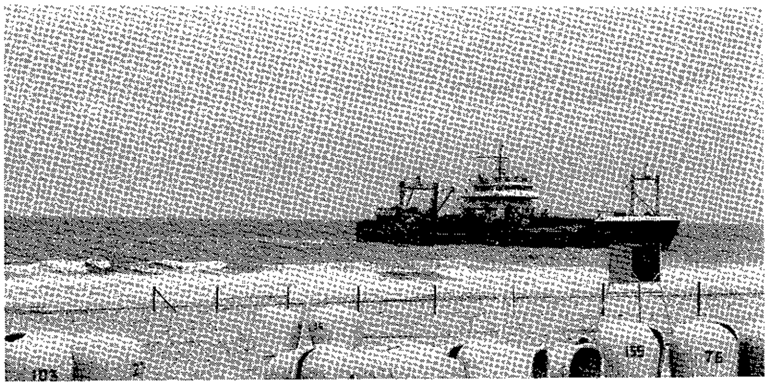

Fig. 22

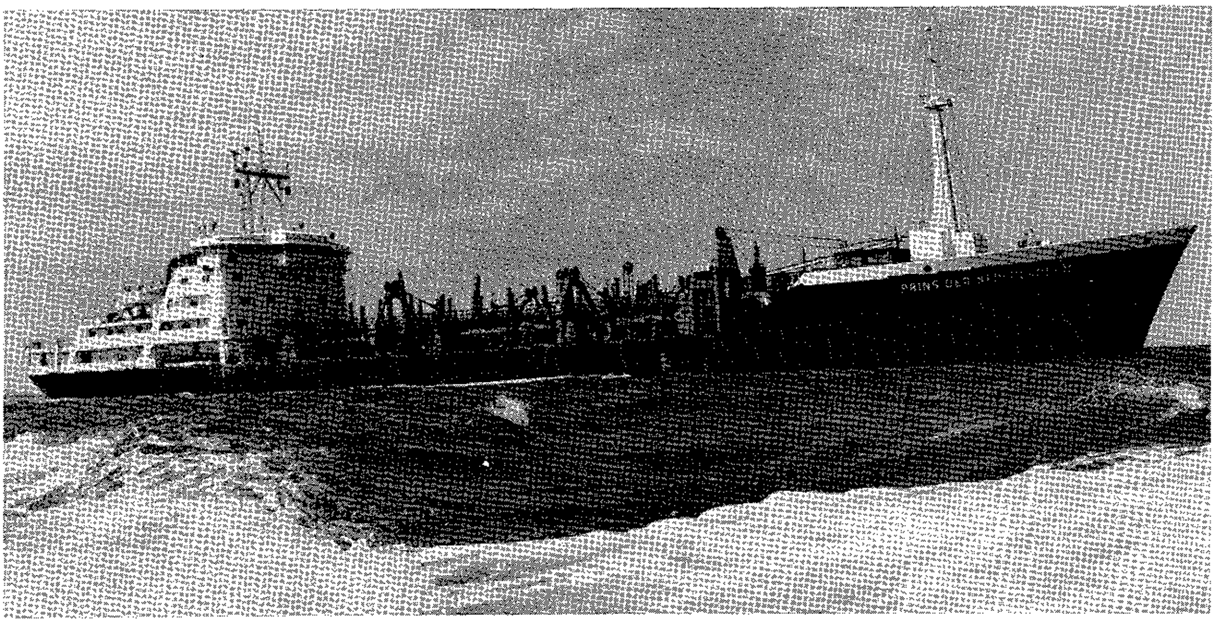

Fig. 23

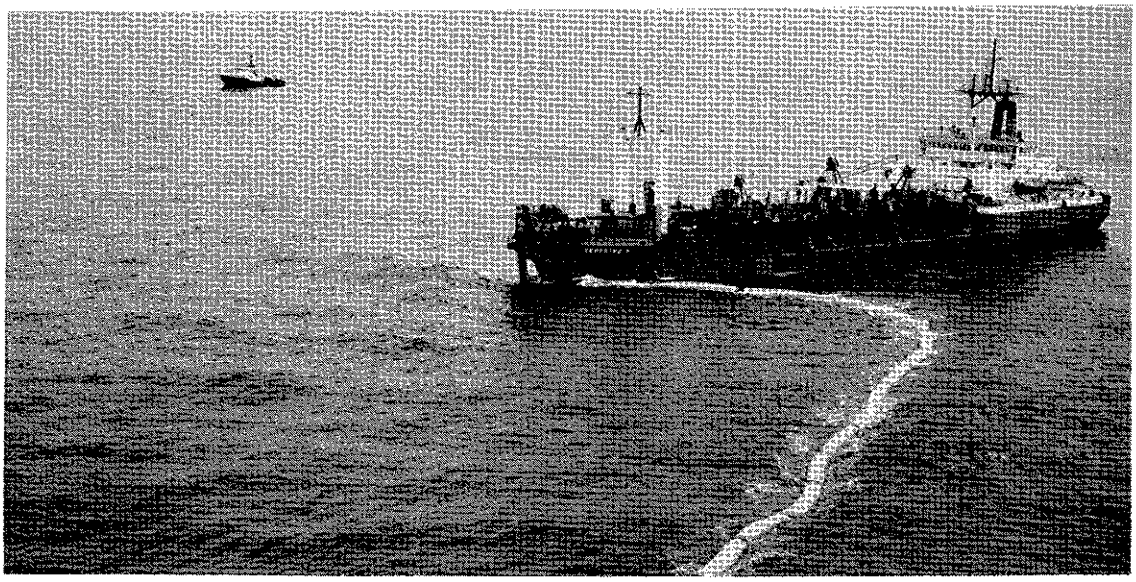

Fig. 24.

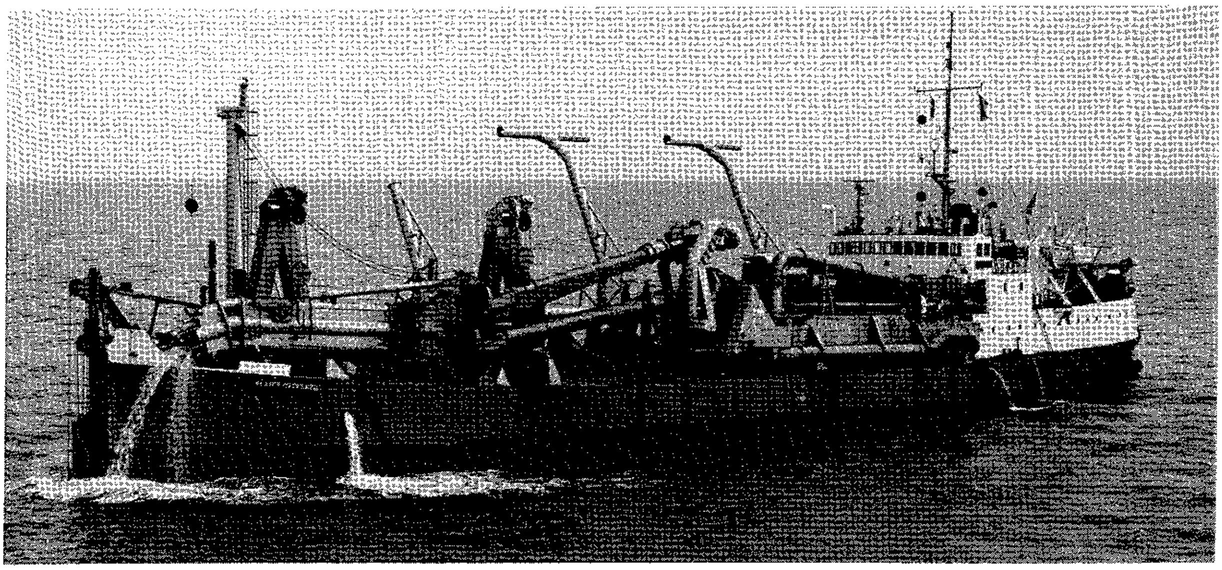

Fig. 25

case, the onshore hydraulic fill pipeline system is fed by an offshore dredger through a pipeline which runs out to sea. This pipeline is either of the submerged steel type that surfaces offshore at a mooring buoy, or of the flexible floating type, or a combination of the two.

These floating pipelines have been used for a number of years now and have gained full acceptance; nevertheless, it is evident that in a fully sea-borne operation, the connection between the vessel and the pipeline and the connection between the floating and the fixed pipeline, or the surfzone crossing section, are extra vulnerable points which require careful engineering.

An attractive solution for the surfzone crossing consists of a floating flexible hose, which is towed offshore to enable it to remain intact during adverse conditions. The solution is a new one, but all the components have already been tested in other operations.

An operation incorporating many of these elements was carried out in the middle of the northern North Sea, covering a 36-inch gas line in 200 ft of water with dredged seabed gravel.

The end of a floating pipeline was picked up by the dredger and locked into an automatic coupling with the dredger discharge pumping system. Fig. 24 shows this system in operation.

The floating discharge hose consists of 100 m rubber pipe sections with flotation collars.

The pipeline length seaward of the beach should be as short as possible, but certainly not longer than, say, 2000 - 3000 metres.

In the case of large-scale replenishment schemes a single pipe may be worn out before the scheme is finished, and a second line may be needed. In most cases this would be installed at the same time as the first one. The dredger can be a stationary floating dredger which either dredges the local seabed directly, or rehandles sand dumped on the seabed by a trailing hopper suction dredger.

The majority of these stationary dredgers, however, are built for inland use and are not particularly suitable for sea-borne operations. In the first place most of them have rigid suction pipes which do not allow for much pitching and heaving of the dredger; secondly, they mostly lack the necessary freeboard for survival conditions at sea, which requires a return-harbour nearby. Consequently, only specially designed stationary dredgers can be used for this work (Fig. 25).

Another solution is to operate a trailing hopper suction dredge which moors at the buoy, connects to the pipeline and discharges through the pipeline directly onto the beach and into the Feeding Zone.

Weather downtime susceptibility and storm-survival capability are very much improved in a system using a platform type dredging unit. Two of these are in operation now, both jack-up offshore platforms equipped with a dredging system. The largest, the US $ 100 million 'Simon Stevin', is equipped with 8 legs enabling it to walk and turn. The discharge pipeline can be accommodated on a stinger or suspended (Fig. 26).

Buffer. In any scheme involving rehandling by a second dredger, a buffer is automatically formed. Particularly if situated in sheltered waters, this enables delays due to the weather or breakdowns as well as differences in production capacity between dredger to be bridged. If sufficient room is available, a large-size sea-going dredger can be selected which creates a large buffer volume within a short time, allowing a rehandling dredger to be selected which matches delivery requirements and possibly takes more time to rehandle the sand.

Continuous by-passing. A solution related to the methods discussed in the preceding sections is to trap the sand in the accretion zone at one side of the harbour entrance, transport it to the other side, and dump it in the Feeding Zone. From a fundamental point of

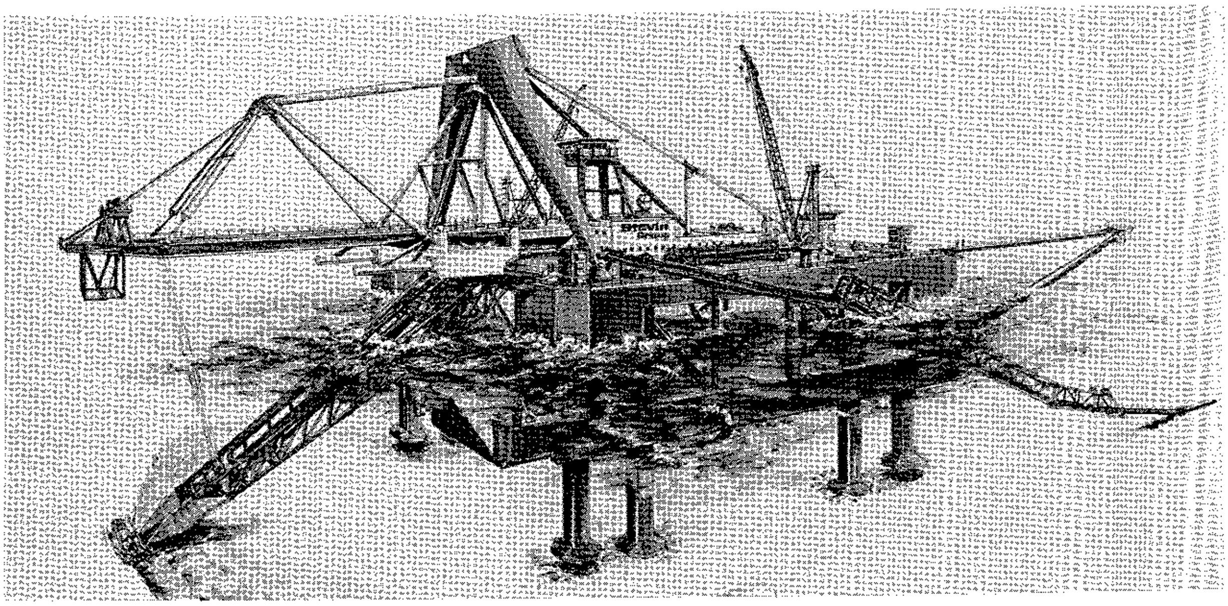

Fig. 26

view this is a very attractive solution, but there are some practical problems:

- often there is no accretion zone because of the topography of the coast, or the accretion cannot be used in a simple way.
- the efficiency of a fixed by-passing plant is limited by the volume of sand flowing into the borrow pit of the suction plant.

Some of these systems are in operation, but they cannot be regarded as a universal solution to the disturbance of the coastal regime created by a harbour.

Costs. The main costs of a beach nourishment scheme can be divided into two parts:

- start-up costs

- operational costs

Some working methods (like trucking) have very low start-up costs, but high operational costs (Fig. 8). This method is attractive for small quantities. For large quantities the relative importance of the start-up costs decreases and the emphasis is on low operational costs. This is yet another factor favouring hydraulic fill schemes.

Cost diagrams can be assembled for the operation as a whole as well as each element in the chain. The diagram for pipeline is presented in Fig. 9. This diagram shows that steel pipes are much cheaper than coated pipes, but that for certain quantities coated pipes may be more economical. When such diagrams have been compiled for all the elements, diagrams for the various working methods can be drawn up (Fig. 10).

One can then read off directly which method has to be used for a given quantity of sand.

It will be clear that these diagrams vary for each particular job.

Other aspects affecting the overall costs are:

- frequency of undertaking
- losses during operation
- combinations with other work (effectively decreasing either start-up or operational costs, or both).

Sand replenishment can be carried out at different intervals (once a year, once every five years, etc.) with corresponding varying overall volumes. This frequency has a major impact on the price as the start-up costs are a direct function of the number of operations. Consequently, a one-off operation on a large scale is, in general, cheaper. In practice the main limitation to this type of replenishment is not a technical one but the fact that the beach is owned by the public authorities which do not always possess the proper means of budgetting for a number of years ahead.

Two types of 'losses' occur during suppletion. Some finer particles are washed away by wave and currents in the same way as 'losses' occur in the period after the completion. These 'losses' during the operations have to be regarded as the beginning of the process of feeding the littoral transport, and it is therefore incorrect to call them losses.

Other losses are the fine particles, which are also washed away by waves, but go into suspension and do not feed the littoral transport. It is therefore sound practice to use sediment without a high fine particle content in order to prevent such losses. In Scheveningen approximately 7% of the sand was lost in this way.

Combining a beach-fill operation with the initial dredging of harbour basins can prove very attractive, for the replenishment sand then comes free. Some fine particles or pollutants in the sand are washed away, and a very clean beach remains.

The use of sediment from maintenance dredging in harbour basins is not usually possible, because such sediment generally has a very high fines content. This limitation does not apply to the same extent in the case of access channel maintenance.

Scheduling. When the sediment is dredged at sea, the operations period is mostly restricted to the calm weather season. This, however, is also the period when the beach is most heavily used for recreational purposes. Planning the work is therefore very difficult in most cases and a short operations period with large-scale equipment is preferable. This makes it a distinct advantage to use high-capacity dredgers to minimize the time needed; moreover, if the sand does not have too high a fines content, the beach may be accessible immediately (Fig. 20).

THE MORPHOLOGICAL CONSEQUENCES OF EXTENSIONS TO 3 HARBOURS IN THE NETHERLANDS

EUROPOORT

The morphological aspects were significant constraints on the design of this deep-water port at Rotterdam (Fig. 5).

The low breakwaters protect the exposed part of the reclaimed land against erosion by tidal flow and reduce the energy of overtopping waves. A lagoon has been created behind the southern breakwater; the border of the reclaimed land is formed by an artificial beach and dunes (12).

It has been calculated that an average by-pass of the order of 40,000 m^3/year will be necessary to maintain this beach.

This solution, including the capital costs of the maintenance by-pass, proved to be only 25% of the initial costs of an asphalt dike, which in turn was the cheapest option among the so-called hard constructions behind the breakwater (Fig. 11).

In the five years after the construction was completed, the beach erosion remained within the figure mentioned above.

The area south of this breakwater was designed to be bordered by an artificial beach and dunes only. An average by-pass of approximately 200,000 m^3/year combined with 6 permeable groynes was chosen here as the most economical solution (Figs. 5 and 18). The groynes are designed to reduce the sediment transport capacity by 50%.

The volumetric check on the calculation has shown an actual reduction of 45% and total loss of sand of 440,000 m^3 over two years (1977-1979)

The northern breakwater has been elongated in order to optimize the tidal flow in the harbour entrance for shipping purposes. The waves generated by north-western storms are reduced and reach a gravel beach on the other side of the harbour entrance. This gravel beach is constructed as a 2 m-thick layer on sand and positioned above the mean sea level.

It proved inadequate because of the high maintenance costs and has been replaced by a revetment along its full length.

It has been calculated that the natural beach of the Hook of Holland north of the entrance will accumulate a great deal of the southward longshore transport. Consequently, the northward transport capacity cannot be saturated and erosion at a distance of approximately 5 km had to be expected. This erosion would continue until the orientation of the beach next to the northern breakwater allowed for an equilibrium to be restored.

In order to speed up the process, approximately 14 million m3 of sand that had been dredged in the approach channel was pumped into the accumulation area and a new recreation area was created for the heavily populated area in and around Rotterdam.

Further studies have shown that approximately 300,000 m^3 accumulate in front of this new beach each year (Figs. 5 and 12). There has been some initial erosion next to the northern breakwater which is caused by the waves overtopping the breakwater and by the stabilized rip-current along this breakwater (Fig. 13).

Proposals for large-scale reclamation (Fig. 14) for the whole stretch of the coast between the Hook of Holland and Scheveningen are now under discussion (13). The principle of this plan is to reclaim approximately $20 \cdot 10^6 m^2$ in a shape which will minimize future maintenance.

SCHEVENINGEN

The breakwaters of the harbour of Scheveningen were extended by approximately 500 m in order to reach the depth of approximately 7 m (Fig. 15). The original entrance was situated at a depth of approximately 4 m and in consequence was facing the breaker zone too often.

The major part of the longshore sediment transport was able to pass this entrance due to the limited depth and the contracted tidal flow in front of the harbour.

This transport across the harbour entrance has been considerably reduced by the extension of the breakwater. Breaking waves occur rarely at a depth of 7 m and the effect of non-breaking waves on the sediment content of the tidal flow is not sufficient to guide the longshore transport from one side of the harbour entrance towards the other.

In 1971 and 1975 a by-pass on the beach was created by using fairly coarse sand. The initial slope of the by-pass beach was rather steep. The waves were not able to carry the sand distributed along the beach during a relatively calm period to greater depths. Consequently, the adaption of the beach slopes to the equilibrium stage showed a large apparent loss of the beach material above the low-water-contour (Fig. 16).

Most of the lost sand, however, was deposited below L.W. by waves. The annual erosion in the area north of the old groynes system did not increase. The total losses due to longshore transport, however, were of the same order of magnitude as the calculated losses.

The by-pass obviously neutralized the negative influence of the elongated breakwater.

On both sides of the harbour, sedimentation took place as expected next to the breakwaters.

These calculations did not include the losses due to the landward transport of beach sand caused by the wind action upon the exposed beach. The unquantified amounts of wind-blown sand were removed from the "Boulevard" of Scheveningen back to the beach.

The sediment transport by wind, however, can be included in forecasts of future morphological developments on sections of beach using a computer-program according to the equations of Bagnold (14, 15).

IJMUIDEN

The 100-year old port of Ijmuiden was built in order to provide a new fairway to the harbour of Amsterdam.

The coastal development after the construction of the breakwaters formed a test case for the development of the mathematical morphological model. The extension of the breakwaters towards the 15 m depth contour was completed in 1967 (Fig. 17).

As in the case of Europoort, the morphological aspects were included in the studies for the purposes of the design.

The area south of the breakwaters was filled with approximately 2 million m^3 of sand dredged in the entrance channel to the port. The dual purpose of combining an improvement in recreational facilities with a reduction in the danger of coastal erosion was the basis for this decision.

The northern beach and the dune area landward of it border on the largest steel plant in the Netherlands. This area, too, is suitable for reclamation as it is expected that sand from the southern drift will accumulate in the breaker zone.

Although a study on the optimum shape for the reclaimed land has been completed, the economic trend in the country and other more technical aspects will determine the feasibility of such a plan.

Feeding of the eroding beach north of the harbour will finally lead to the natural growth of the accumulation area and the phasing of investment on such a maintenance by-pass might prove a more economical solution than investments in a one-off reclamation operation.

ENVIRONMENTAL ASPECTS

BEACH REPLENISHMENT

When sand supplementation work is being carried out, the environment in the vicinity of the source of the sand and the beach to be replenished is temporarily disturbed.

The sand itself should comprise clean and odourless material, so that the beach can continue to be used for recreational purposes and does not pose any danger to public health. In view of this, a sand source at sea should not be located in the vicinity of a sewage outfall. The spoil from maintenance dredging in harbours will as a rule be unsuitable for use as sand for suppletion purposes, unlike the sand obtained when deepening a harbour.

A borrowing area located in the open sea might have a temporary minor impact on marine life on the sea bed at that point and in the surrounding area. In the case of inland sources, the presence of pipelines and machinery during the breeding season or in the vicinity of colonies of birds need not be an insurmountable objection. The laying of pressurized pipelines through nature reserves should, however, be avoided as much as possible; this is crucial to areas with a vulnerable pioneer vegetation. Once damaged, this vegetation can no longer protect the soil against erosion by water and/or wind.

The beaches along the Dutch coast where replenishment work has been carried out have a shelving foreshore of sand or a steep foreshore running into a channel, sometimes with mud on the bed.

A great deal of sand ends up shoreward of the surf zone during beach replenishment. The effect of this on marine life, if there is any at all, is probably minimal, because the marine life in this area is used to turbulence and the changing state of the water.

In a channel with a muddy bed adjacent to the beach, there will be relatively large quantities of molluscs such as mussels, etc. The lower the temperature of the water, the lower the capacity of these creatures to react, so that they are vulnerable when sand importation is carried out in the spring or autumn. These shell fish are not agile enough to work their way up through the sand which engulfs them and so they die. Later, these decomposing creatures are washed up and give off a penetrating and distasteful odour. This phenomenon was observed after the beach replenishment on Voorne between October and December 1977.

RECREATION

Radical social changes took place during the construction of the new harbour entrance. These included the growing interest in living conditions and the living environment as a result of greater affluence and the growing significance of leisure time since the introduction of the five-day week around 1960 as well as the change in attitudes towards nature, especially since 1970 which was Nature Conservation Year.

The significance of this becomes all the more apparent when one realizes that the Randstad agglomeration of Holland in which half of the population live and work is located behind the coast between IJmuiden and the Hook of Holland.

It is scarcely remarkable therefore that these social changes have affected and continue to exercise an influence on the purpose, layout and design of the transitional areas between the harbour's industrial areas on the one hand and the residential, recreational and nature areas on the other. The largest project, the new harbour entrance at the Hook of Holland, is a prime example (Fig. 5).

The new harbour entrances attracted a great deal of public attention during their construction, a fact which was used to good advantage in the design of the information centres and resulted in their becoming temporary recreation areas.

Despite the fact that the jetties are a major attraction for marine anglers, it is a pastime which is prohibited because of the real dangers to the fisherman and the fact that the government would be responsible in the case of accidents. The Zuidwal, which forms the northern boundary of the Maasvlakte and is covered with shingle, proved to be a reasonable alternative and right from its construction the Zuidwal became an ideal spot for anglers.

The floods in the autumn of 1973 resulted in the beach at Scheveningen being submerged over a length of 500 metres. The beach cafe proprietors were thenceforth forced to construct their cafes on stilts to ensure that they would not be swept away during high water in the summer months. Clearly, therefore, the beach replenishment at Scheveningen in 1975 was not only in the interests of the coastline but also served recreational ends.

Sightseers' parking areas have been constructed near to the harbour entrance at Scheveningen and the Hook of Holland so that people can enjoy the view of the incoming and outgoing ships and of the waves breaking during storms in the comfort of their cars. It need scarcely be added that these are popular with the public throughout the year.

The implementation of the 'beach plan' north of the new harbour entrance at the Hook of Holland in 1971/1972 meant that the beach could continue to act as a recreation site along with the accompanying facilities such as access roads, beach cafes and a parking area of more than 3 hectares behind the new coastal ridge. The area between the old coastal ridge and the new one was planned as a recreation area. The original idea was to have a long irregularly shaped shallow lagoon but the plan was abandoned because of the problems of periodic changing or topping up of the water and for reasons of hygiene. In 1979 the area was made into an artificial dune area by means of earthmoving works and access was later provided by paths. The plans for the vegetation in this area were carried out in 1980.
The railway line between Rotterdam and the Hook of Holland is to be extended in the near future so that this area will be accessible by train as the old beach was in the past. After the

Fig. 27

sand dam along the southwest side of the Maasvlakte was completed, the Beer canal was extended to the Maasvlakte, later opening into the Mississippi harbour. So much sand became available that the sand dam was widened 200 metres seawards but even this was not sufficient to absorb all the sand. After much discussion, the sand was dumped in an area extending along the northern side of the Brielse Gat to 1½ kilometres beyond the sand dam gradually running in a concave arc 200 metres from the sand dam at the point where the Zuiderdam starts (Caisson dam). This extensive area of dumping covering approximately 200 hectares was later made accessible by roads with parking areas. Since then, according to counts, more than 25,000 visitors have started spending their summer weekends on this new stretch of North Sea beach which extends for more than 4 kilometres.

During the sand borrowing for the Maasvlakte in the Oostvoornse Lake, water from the Beer canal regularly had to be let in through a lock so that the ground water level of the dune area in the vicinity did not drop to inadmissible levels. In 1973 the Government decided that the Oostvoornse Lake would no longer be connected with the sea; the enclosure dam on the western side, the BrielseGat dam, became permanent. This Government measure has opened up the way for a nature area to be created here outside the dikes.

The Oostvoornse Lake itself was considered to be unsuitable for recreational purposes because of its great depth of 40 metres. Nevertheless, once the suction dredgers have departed, the area proved to be a great attraction to visitors from nearby (Oostvoorne) and further afield. Once the Government decision had been taken, its development for recreational purposes was not far behind. Along the shores angling and beach leisure activities were in full swing which meant that safety measures had to be taken. To this end a gravel threshold was dumped along the outer edge of the shallow water zone and protruding above the water to cordon off the deep water area. Since motorboats are not admitted, it provided a unique opportunity for surfing. Divers were attracted by the clear, calm water and the lake is now a training ground for deepsea diving.

An area south of the Oostvoornse Lake in the former Brielse Gat has been designated as a nature reserve.

VISUAL SCREENING AND VEGETATION

The Maasvlakte protrudes approximately 5 kilometres beyond the former coastline. It was decided at an early stage that the rather unattractive sight of the typical industrial port complex with 20-metre high oil tanks must not be allowed to spoil the landscape for inhabitants and visitors to the old coastal area of the Hook of Holland and Oostvoorne. To screen off the industrial area, it was decided to construct a row of artificial dunes along the Zuidwal as well as the northern edge of the Oostvoornse Lake. The Zuidwal dunes have in fact now been created (Fig. 27). It was calculated in advance that the creation of this line of dunes would be accompanied by an extra dust load of 50 mg/m^3 at the Hook of Holland in the event of a west-southwesterly wind. The Hook of Holland local authority considered this to be unacceptable, since the maximum of 80 mg/m^3 air was already exceeded there several times a year. For this reason the dune ridge, which was 2 kilometres in length, 100 metres at its base and 18 metres high, was constructed in four stages. The first three entailed pumping in hydraulic fill of a 4- to 5-metre layer of sand (wet sand does not blow away). The first layer was covered with a ground layer containing clay, while the second and third layers were covered with Sandfix, a bitumen product made by Shell. After the fourth layer had been applied in the dry state, the entire line of dunes was covered with sand containing silt and a 75- to 100-cm clay layer. In anticipation of the planting of saltresistant shrubs - sea buckthorn, tamarish, dog rose, boxthorn, gorse, hawthorn, common barberry, creeping willow, elder, Japanese rose, Russian olive - the upper layer was seeded with 'Europort' mix. This is the result of tests and is used for consolidating hydraulically filled sites in the Europoort and on the Maasvlakte. It comprises a mix of approximately 50% rapidly growing crops (rye/barley), 50% grass species which grow more slowly (perennial ryegrass, red fescue and hard fescue (Festuca ovina subsp. cineria)).

In the harbour area itself, an attempt is being made to create an environmentally attractive area by means of vegetation. In fact, since 1974 it has been a condition of site allocations in the harbour area that a minimum of 1% of the surface area must be provided with vegetation. The present design for the vegetation provides greater variety both in a spatial sense and in the choice of types of vegetation, by contrast to the original rectilinear planting alongside the straight, geometrical sites and buildings.

NATURE AREAS

Seawards of the Brielse Gat dam there is an extensive area which is largely uncovered at low water. A nature area of considerable proportions could be created here especially if the plans to close the Gat van de Hawk and to construct a ridge of dunes over the Hinderplaat are put into effect. The short estuary breaking through the natural line of outer dunes which is thus formed will come to be rich in a great variety of bio-communities in the course of time. A nature area of this kind would be more than adequate compensation for the loss of the De Beer nature reserve (1300 hectares) which was lost in 1962 as a result of construction of the Europoort/Massvlakte harbour area.

CONCLUSIONS

Harbours have long been in use along the Dutch coast. Originally, they were situated at natural inlets and therefore posed no problems to the stability of the coastline. However, since the entrances did not provide adequate depth for the larger ships which began calling at the ports at the end of the 19th century, measures had to be taken to provide deeper entrances.

This resulted in the construction of artificial entrances protected by moles and maintained by dredging. This is specifically the case with the harbour entrances at the Hook of Holland, Scheveningen and IJmuiden.

In order to guarantee the safety of the dune coast protecting the low lying land behind it, sand supplement is required at various coastal sections.

Computational procedures for longshore transport and the coastline changes are discussed to ensure that such projects are properly evaluated. It is demonstrated that these methods can provide a reliable forecast of the effects of measures, and the methods of implementing them while taking the environmental aspects into account, are discussed. It is demonstrated that sand supplementation is to be regarded as a valuable tool for stabilizing coastlines.

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RESUME

A l'origine, les ports néerlandais étaient, comme la plupart des ports du monde, situés le long de chenaux naturels de marée ou à l'embouchure de fleuves.

Mais l'emploi de navires de plus en plus grands depuis la fin du XIXe siècle imposa de chercher d'autres solutions pour assurer des accès portuaires plus profonds. C'est dans cette perspective que les Pays-Bas ont créé les entrées artificielles de Hoek van Holland, de Scheveningen et d'Ijmuiden. Ces entrées portuaires ont gravement perturbé l'équilibre de la côte.

Cette perturbation provoquée par l'interruption du charriage longitudinal est, d'une part, l'accroissement de la zone littorale du côté amont du port et, d'autre part, l'érosion du côté aval. Il est possible de remédier à ce déséquilibre en charriant en permanence du sable d'un côté à l'autre de l'entrée portuaire à l'aide d'une installation fixe. Mais on peut aussi, à des intervalles de quelques années, remblayer la côte qui s'érode par des apports de grandes quantités de sable. Si le remblayage n'est pas possible ou si la côte ne peut être stabilisée, on peut prévoir des ouvrages de protection de la côte. Il peut s'agir de jetées qui ont principalement pour but de réduire le charriage longitudinal. Ainsi, le déplacement de sable est réduit et l'érosion côtière diminue. Signalons comme autre solution la protection de la rive sous-marine à l'aide de matelas de fascinages, par exemple, pour prévenir le retrait de la côte.

Afin de bien planifier de telles mesures, il faut mettre au point des méthodes de calcul du charriage longitudinal et des conséquences des changements de charriage pour la ligne côtière. Nous pouvons en principe distinguer deux situations.

1. Les charriages à évolution lente qui peuvent être calculés à l'aide d'une formule connue, la formule CERC.

2. Les charriages à évolution rapide, par exemple par suite de la diffraction près des digues de port ou d'abrupts changements de l'orientation de la ligne côtière. Dans ce cas, il faut appliquer une méthode plus précise permettant de calculer d'abord le courant longitudinal dû à l'action des vagues, puis le charriage provoqué par le courant longitudinal et les vagues.

Après avoir ainsi calculé les charriages, il est possible de prévoir, à l'aide de modèles mathématiques, l'évolution de la ligne côtière. En s'aidant des résultats ainsi obtenus, on peut localiser les endroits où il faut intervenir.

Nous étudierons dans un premier temps les différentes mesures, c'est-à-dire la construction des jetées étanches ou partiellement étanches. Puis, nous examinerons en détail les méthodes modernes de remblayage artificiel des plages avec du sable extrait à d'autres endroits. En principe, nous disposons des méthodes suivantes:

(i) Amenée par voie terrestre depuis les lieux d'extraction situés sur la terre ferme.

(ii) Amenée du sable depuis un lieu d'extraction sur la terre ferme; le sable est extrait par drague suceuse, puis transporté jusqu'à la plage par canalisation.

(iii) Amenée du sable depuis un lieu d'extraction en mer où le sable est dragué par un "trailer". Puis, le sable est directement transporté vers le lieu de dépôt par la drague suceuse ou encore par barges. Ce dernier mode de transport n'est en principe possible que si les chalands à clapets peuvent parvenir dans la zone des brisants, sinon le sable ne pourrait pas atteindre la côte. Si la ligne côtière doit être remodelée sur une grande distance en mer - et uniquement dans ce cas-là - il est possible, dans un premier temps, de déverser le sable directement en dehors de la zone de ressac.

En outre, le sable extrait en mer ("off shore") doit être transporté vers la plage selon l'une des méthodes suivantes.

(a) Le sable est déversé dans un puits en eaux protégées, puis à l'aide d'une pompe aspirante il est amené sur la plage par canalisation.

(b) Les bateaux de dragage s'amarrent à une bouée à un seul point et extraient par pompage le sable qui est transporté vers la plage par une canalisation flottante ou immergée.

(iv) Extraction du sable par une pompe aspirante en mer et refoulement direct du sable vers la côte par canalisation immergée si la distance n'est pas trop grande ou par barges automotrices si la distance est grande. Ces barges peuvent être déchargées comme indiqué au point iii.

Lors de l'exécution de ces travaux, il faut évidemment tenir compte des effets sur le milieu naturel, et tout d'abord sur le lieu d'extraction. Lorsque le sable est extrait sur la terre ferme ou en mer, il faut tenir compte de l'éventuelle pollution par des matériaux fins qui sont charriés ou déversés par-dessus bord. Dans le cas d'extraction en mer, il faut en outre étudier dans quelle mesure la couche superficielle peut être gravement perturbée. Lors du déversement du sable sur la plage, il faut aussi considérer les dangers de la pollution par des matériaux fins et préserver les possibilités de loisirs sur la plage.

Dans bien des cas, il faut sacrifier de précieuses zones de loisirs et des zones naturelles. Il faut mettre en balance ces inconvénients et les avantages du projet envisagé.

Dans cette étude, nous approfondirons les points exposés ci-dessus et nous les illustrerons par des études de cas.

Nous pouvons conclure que, bien souvent, le remblayage par du sable des plages qui s'érodent est le procédé le plus économique et le plus acceptable.