DESIGN OF BEACH REPLENISHMENT

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1. INTRODUCTION

In the Netherlands much land was captured from the sea. At the same time however along the coast severe losses of land occurred. The main reasons were sea level rise and effects of decreasing tidal volumes of estuaries. Besides there were the local effects of shifting tidal channels and periodical movements of the coastline. Building of groynes, dune-foot revetments and dikes did not stop the loss of sand.

On behalf of the increased interests in the coastal area the Dutch government decided in 1990 to stop the coastal erosion. The main measure to achieve this purpose will be artificial beach nourishment. This coastal defense method is in harmony with nature, flexible and cost-effective.

This paper deals with the technical aspects of the new coastal policy.

2. PRESERVATION OF THE COAST

Some sections of the Dutch coast are continuously loosing sand. Figure 1a shows the calculated sand balance in the last 20 years, within a zone of appr. 1 kilometer (van Vesse, 1990). Fluctuations of the coastline position may cause local erosion periods of several decades. In figure 1b the present eroding coastal sections are given. In the future the compensation of the structural loss of sand from the coastal zone is the task of the Dutch government (Rijkswaterstaat, 1990). The principle is that the coastline will be maintained at its position in 1990. "Coastline" in this context can be read as the line of Low Water. In practice however, as a result of short-term morphological processes (such as profile fluctuations during storm surges) this line varies in time and space. Therefore the determination of the 1990 coastline is not based on a single measurement. For each of the yearly coastal measurements the position is calculated from the volume of the "wet" part of the profile (figure 2). The 1990 level of the trend-line through the time-series of the instantaneous coastline is the "average coastline" that must be preserved, the so called "Basal coastline" (figure 3). If in the future the trendline exceeds the basal coastline, the structural erosion will be combated by sand replenishment.

Besides the basal coastline a margin is determined. If the landward boundary of the margin is exceeded, nourishment must definitely be carried out. On behalf of the natural value of a dynamic coastal behaviour a rigid application of the basal coastline is not always desirable. In consultation with local authorities some fluctuations can be accepted.

b. Erosion areas

Figure 1. Erosion along the Dutch coast.

Figure 2. Definition of coastline.
Figure 3. Determination of required moment of beach nourishment.

3. COASTAL PROCESSES AND THE CHOICE FOR BEACH REPLENISHMENT

In the Netherlands there is a lot of experience with solid coastal protection works. About 40% (130 km) of the coast is protected by groynes. In sections, where the dunes became very narrow by erosion, dikes, sea-walls and dunefoot revetments were build (about 60 km). On a long-term these constructions are no adequate solutions, because they cannot influence the large scale morphological coastal behaviour, which implies net loss of sand in a significant part of the Dutch coast (figure 1).

Long-term and short-term erosion

Characteristic of a sandy coast is the continuous movement of sand in the near-shore zone. Currents and waves move the sand on the shore in cross-shore and longshore direction. This process may cause a loss of sand from the sea-defence zone to adjacent coastal sections or to neighbouring inlets. Because of these processes there is a continuous movement of the borderline between land and water. Short-term erosion and accretion alternate each other. Sometimes, during storm surges in a relatively short time the dunes are eroded.

So two major types of erosion can be distinguished:
- A fast, big erosion of dunes and beaches caused by wave attack during storm surges;
- A slowly, chronic erosion, which is not striking, caused by sea-level rise and other morphological phenomena.

During storm-induced dune erosion the sand is transported to the beach and a part of the shoreface. Afterwards under mild wave conditions it will be transported in landward direction by hydraulic forces and wind action. The coastal profile will be restored. Figure 4 shows that even the influence of the 1953 storm-surge was temporary.

The chronic erosion moves sand out of the sea-defence zone. An increasing sea-level rise may cause an increased chronic erosion. In that case also the coastal profile will adapt to the new water-level by moving in landward direction. The result of chronic erosion is a long-term withdrawal of the coastline. This causes a narrow and low beach, which makes the dunes vulnerable for wave attack under storm conditions. Because of the net loss of sand
complete restoration of the profile by nature is not possible. The conclusion is that storms play only a minor role in coastal erosion. The main cause is the large scale morphological development. This sometimes contradict the public opinion, which often indicates the visible short-term processes as the main cause of coastal problems.

![Diagram showing the effect of the 1953 storm on the dune foot position.]

**Effectiveness of shore defences**

Dune foot revetments and seawalls on a beach do not influence the daily coastal processes. So in case of a negative sand budget, the shoreline keeps retreating and the beach will disappear. Considering the increased interests in the coastal zone this will be unacceptable. On the other hand groynes reduce the longshore sand transport in the breaker zone. By building groynes the distribution of the sand can be controlled. Trapping sand in one section however means erosion in the adjacent sections. In coastal sections with a tidal channel near to the shore, groynes can keep the strong currents away from the beach and prevent landward shifting of the channel.

On behalf of the coastal policy analyses in 1989 an evaluation of the Dutch groyne-systems was made. From the analysis followed that on those locations where groynes kept the tidal current away from the coastline (thus acting like a river groyne), they functioned generally very well. These groynes are quite costly, because deep scouring holes are formed in front of the groynes, which require on their turn a heavy stone protection of the head of the groynes. Maintaining these groynes is compulsory. Removal of the groynes will automatically cause withdrawal of the coastline.

On locations where groynes act as resistance elements to the longshore current, their effectiveness is less clear. In those cases where the resulting longshore transport is small (e.g. because of wave impact from various directions) groynes were not able to influence the coastal erosion. Perhaps the coastal profile became somewhat more steep. Removal of these groynes will therefore cause a somewhat more gentle profile, causing some temporary extra erosion at the upper part of the beach. At most coastal sections where these kind of groynes exists, this temporary extra erosion cannot be allowed, because the dune-rows is already very narrow. Removal of the groynes is therefore only possible after a thorough and detailed study of the local morphology.

In those cases where a clearly dominant wave direction occurs, groynes decrease the erosion, especially above the low-water line. Generally this causes lee-erosion. Lee-erosion can be combated by building more groynes. The object of decreasing the erosion-rate is attained, but the costs are quite high, because of the necessity to construct more "lee-groynes". Removal of these groynes is dissuaded, because the coastal profile has been adapted to the new situation (is steeper). Removal will always led to increased erosion.

Hardly any new groynes will have to be constructed in the Netherlands. Con-
struction of new groynes can be considered along sections with heavy attack of tidal currents. But all coastlines in the Netherlands with such an attack are already protected by groynes-fields.

In case of surf-induced longshore currents the construction of new groynes should only be considered if a clearly dominant wave direction exists. However in those cases periodically beach nourishment might be economically more attractive, especially along longer (straight) coastal sections.

In those cases where no dominant wave direction exists (waves enter the coast more or less perpendicular) groynes should not be considered.

A general problem of groynes is that they are quite static and cannot follow the dynamic movements of the coastline, especially in cases of long-periodical fluctuations.

The effectiveness of pile-groynes proved to be minimal. Only in those cases with a clearly dominant wave direction, they had some influence on the erosion, mainly by decreasing the effects of lee-erosion after a groyne-field. The effects of the field are distributed over a longer distance. The general conclusion is that pile-groynes should hardly be considered as a means to prevent erosion.

Considering the other advantages such as flexibility and harmony with nature, in the future beach replenishment will be the main coastal defence measure. In spite of that defence systems seaward of the present coastline are not excluded. For two locations pilot studies are carried out.

4. DESIGN OF A BEACH NOURISHMENT SCHEME

4.1 General
An appropriate coastal measure can only be selected after a clear definition of the coastal problem. Therefore studies of the morphological processes and of the interests involved have to be carried out.

The design of a nourishment scheme mainly depends on the objective(s) and the coastal processes. In addition there are the local circumstances for execution, the available kind of sand, the aspects of landscape and the costs and benefits.

4.2 Types of beach nourishment
To select the appropriate type of a sandfill the objective of the project will be decisive. At the Dutch coast the interests to protect are:

- safety of the low laying polders behind the dunes;
- safety of settlements (housing, industry, drinking water production) in the dunes;
- natural values of the dune area itself;
- beach recreation.

By preserving the coastline generally these interests will be protected. Still the designer of preservation sandfills has to take into account the interests.

We can distinguish types in cross-shore direction and in longshore direction. Figure 5 shows some types of sandfills in cross-shore direction. The main objectives are:

- in the dune area.................safety of the polder, protection interests in the dunes;
- against the duneface............natural values, safety of polder and dune settlements, compensation of erosion;
- on the beach..................beach recreation, compensation of erosion;
- on the shoreface...............compensation of erosion.
Figure 5. Types of sandfills in cross-shore direction.

Recently studies are started on types of replenishment, that are new for the Dutch coast:
- beach fill protected by an artificial reef (perched beaches);
- sand dams on the shoreface to decrease wave attack and to compensate erosion.

In longshore direction the design depends on the local interests and on the longshore coastal processes, induced by waves and tide. Two major types can be distinguished:
- the elongated planform, by which the longshore sand transport is only less (at both ends) influenced; this type can be applied to compensate erosion in long stretches;
- a stock-pile of sand, from which the sand is transported and distributed along the coast by natural hydraulic forces.

The second type is suitable to compensate local erosion, for instance next to a groyne-system or a harbour entrance, where the longshore transport is interrupted. For safety or recreational purposes a local widening of the beach can be attractive. By means of continuous or periodical nourishment an unnatural coastline can be maintained.

4.3 Design methods
The design of a nourishment scheme contains two major elements:
- calculations of the required conditions with regard to the objectives;
- prediction of coastal development after the replenishment.

The design models can be based on trend extrapolation, equilibrium profile development or process calculations. In the following for some objectives examples of models are given.

In cross-shore direction profile changes due to storm-surges and structural erosion are the main causes of coastal problems.

Safety of interests in and behind the dunes
Based on field measurements before and after storm surges and on investigations with physical models Delft Hydraulics developed a dune erosion model (Vellinga, 1986). This model gives the equilibrium profile at the end of a
storm surge (figure 6 a).
In the Netherlands the defence system of the Holland coast must be able to resist a storm with a water-level frequency of 1/10 000 per year. For the Delta and Wadden coasts the frequencies are respectively 1/4000 and 1/2000 per year. During such a storm the probability of failure must be less than 10%. Therefore a quasi-probabilistic version of the Vellinga-model is made, taken into account the uncertainties of the hydraulic and physical conditions (figure 6 b). In this model the storm-surge level is 0.5 meter heightened and extra dune erosion is calculated. A minimum dune profile has to remain to prevent dune failure by overtopping waves.

![Diagram of storm surge and erosion profile]

**a. Principle of dune erosion prediction model (after Vellinga, 1986).**

![Diagram of computational and limit profile with calculations]

- A = calculated amount of dune erosion above computational level
- t = surcharge on A for duration of storm surge
- - gust surges and gust oscillations
- - inaccuracy computational model
- g = extra erosion due to a gradient in the longshore transport

**b. Quasi-probabilistic testing model for dunes as sea-defences.**

Figure 6. Dune erosion models.
Recently a process model for dune erosion is developed (Steatze, 1990), which calculates the profile development during a storm-surge. This model has the advantage that the effects of solid elements, such as dune foot revetments, can be calculated.

Recreational beach

In behalf of the exploitation of the beach sometimes artificial berms are created to widen the beach above high water level. However the foreshore becomes steeper and nature will try to restore the initial slope. To give beach exploiters insight in the risks for their interests, the Vellinga-concept is used for a model that calculates the probability of berm erosion from the combined local water-level and wave climate. A second aim of the model is to give the coastal authorities a tool for planning preservation works at the dunefront.

Compensation of sand losses

Since 1965 along the Dutch coast yearly a strip of at least 1000 m is measured. Figure 7 gives examples of sand budget calculations for two sections of the Holland coast. For the design of replenishments to compensate sand losses extrapolation of the trend of the losses can be applied. Short-term linear extrapolation will satisfy. To estimate the sand losses for a longer period one must take into account long-periodical fluctuations of the coastline, the so-called sand waves. This phenomena appears from long time series of positions of the lines of low water, high water and dunefoot. These positions are measured since the middle of the 19th century. Figure 8 shows the movements of the low water line at the Schouwen coast. There a sand wave migrated along the coast with a velocity of 70 m/year. Apart from a mean withdrawal of about 3 m/year the coastline fluctuated about 100 meter.

Figure 7. Volume of sand versus time.
Figure 8. Migration of sand wave along the coast of Schouwen.

For calculations of coastline development in longshore direction analytical one-line and two-line models are available. With the help of these models the planform of a sandfill can be designed, based on the expected deformation of the fill due to wave-induced longshore transport. These strongly schematized models have the possibility to make time-dependent calculations. More detailed numerical models only calculate the initial transports. Some models have the possibility to calculate the combined effects of waves and tidal currents.

The Dutch Design Method
In the design practice in the Netherlands up to now the use of analytical and numerical models for coastline development in longshore direction has not become routine. Because of the complicated morphologic processes in the Dutch situation with tidal inlets and various types of groynes, it is not easy to find out the dominant processes and to interpret model results. In most cases the sandfills are very long to their width, so longshore deformation is seldom the most important process. Therefore generally a simple, but extremely practical approach is followed. We have good experience with this method, and therefore we think the method is very trustworthy, if applicable.
step 1: Perform coastal measurements (for at least 10 years, preferable for more than a century).
step 2: Calculate the "loss of sand" in m³/year per coastal section for the total height of the coastal profile.
step 3: Add 25 - 50 % for losses and futural dispersion.
step 4: Multiply this quantity with a nice lifetime (for example five years).
step 5: Put this quantity somewhere on the beach between the dune foot and the line of low-water-minus-1-meter.

This method is simple and straightforward. It does not require mathematical models, but good quality profile measurements are absolutely necessary.

Problems with the Dutch Design Method
Of course there are also problems with the Dutch Design Method. There is one very important assumption:

The beach nourishment has no influence on the long-term natural coastal processes. Or, in other words, the erosion rate before replenishment equals the erosion rate after replenishment.

This general assumption is true in the Netherlands when the beach replenishment is relatively long and the shifting of the water-line because of the replenishment is not too much. In the Netherlands the ratio between length of a sandfill and seaward movement of the water-line (width of the sandfill, w) L/w is in the order of 20 - 40. Of course, one should realise that the Dutch coast has a tidal difference of 2 - 4 meter, a tidal current along the coastline and an almost perpendicular wave attack. We have the impression that also for other locations in the world, provided the L/w ratio is in the order of 20 or more, this assumption is valid.

Directly after the replenishment, the shape of the beach profile is not optimal. Nature will adapt the profile of the sandfill. Also, because of the sandfill protrudes into the sea, the current-attack on the beach will be more. So, dispersion in cross-shore and longshore direction has to be expected. It is difficult to predict the extra loss of sand from the replenished area. Our experience shows that in cases with less influence of tidal currents an extra surcharge of 25 % on the designed quantity covers all losses. In coastal sections with a deep tidal channel near to the shore a higher surcharge is needed. Only occasionally more than 50 % will be advisable.

The beach profile
It is very difficult to design the new beach profile. A good assumption is that the profile after the replenishment eventually will be the same as before the replenishment, provided the same type of sediment has been used. Nature will form that profile. Therefore it does not matter very much where the sand is placed in the profile. After one or two smaller storms the complete profile is reworked by nature and the natural (stable) profile is formed. From this one may conclude that one should dump the sand on that place, where dumping is the cheapest.

In the Netherlands, the cheapest way is placing the sand on the beach, preferably on the higher section. All discharge pipes can be placed out of the reach of waves, and after the replenishment a beautiful, wide beach is formed. However, the slope of the foreshore and just under the low-water line has become too steep, and the first storm causes sand transport from the beach towards the under-water-shore. From a morphological point of view, this is no problem at all. From an economical point of view, this is the optimal solution. So, a number of replenishments in the Netherlands have been designed in this way.

However, from a political point of view this is not a good replenishment. The public has a beautiful beach in the summer, directly after the replenishment. All parties involved are happy. But in autumn, after a minor storm, the
public observes a largely disappeared beach. They do not observe that the sand is deposited just below the low-water line. The public concludes that the replenishment was not successful at all. The wide beach has disappeared. In case of a relatively steep shoreface dumping of sand below the low-water line can be the cheapest way of combating erosion. By wave action also sediment will be transported towards the beach. Some extension of the foreshore can be the result. Soon this will be dominated by the long-term beach erosion. In public opinion this type of nourishment also is not a success. The beach was not widened and the placed amount of sand was not even visible. The temporary extension of the foreshore will not be distinguished from the normal natural fluctuations.

Because beach nourishment is generally paid by a public authority, public opinion is important in getting sufficient funds. Therefore it is wise to design a beach replenishment in such a way that the public can observe that the beach after the replenishment is somewhat wider, but there is no major adaption in the beach profile after the first storms in autumn. If the purpose of the nourishment is to make a wide recreational beach, this is very important. If the purpose is to protect interests in and behind the dunes, the best place is as high as possible on the beach. If the purpose is to combat chronic erosion, the best place is in the breakerzone.

The mean grain size of the Dutch beaches generally lies between 0.2 and 0.3 mm. This material is available in the North sea and the Delta area. In general sand is used which textural properties are rather similar to those of the native sand. Therefore the use of a fill factor or a renourishment factor based on grain size was exceptional.

6. BEACH REPLENISHMENT IN THE NETHERLANDS

In the Netherlands up till 1990 nearly 50 beach nourishment projects have been carried out, with a total amount of 60 million m³ (Roelse, 1990). The main objectives were as follows:

<table>
<thead>
<tr>
<th>Main objective</th>
<th>Volume</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>safeguarding the land</td>
<td>24.6 million m³</td>
<td>(40%)</td>
</tr>
<tr>
<td>nature conservation</td>
<td>12.3 &quot;</td>
<td>(20%)</td>
</tr>
<tr>
<td>recreational interests</td>
<td>5.1 &quot;</td>
<td>(9%)</td>
</tr>
<tr>
<td>dumping dredged material</td>
<td>19.1 &quot;</td>
<td>(31%)</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>61.1 million m³</strong></td>
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During the last 20 years, the experience with the different aspects of beach and dune nourishment has grown considerably and led in 1987 to the publication of the "Manual on Artificial Beach Nourishment" (Rijkswaterstaat and Delft Hydraulics, 1987).
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