CHAPTER 107

Design of beach nourishment scheme

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1 Introduction

An artificial beach nourishment used to replenish an eroding part of a coast may seem expensive and the need for repetition may discourage coastal managers. However, careful considerations of capital and maintenance cost frequently prove that it may be, in fact, the optimum solution. An added advantage is that the recreational function of the beach is preserved.

In spite of a great number of research-reports and publications on coastal processes and beach nourishment, the practical applicability of this knowledge is still in an initial stage, i.e. formulating the general concepts and trying to test their validity and practical applicability.

On the other hand, the solution of many practical coastal engineering problems cannot wait until complete understanding of these processes and the existing knowledge on this subject (though limited) should be made available for designers and managers involved in coastal engineering. This was the main reason for the Rijkswaterstaat (Dutch Public Works Department) to prepare a manual on artificial beach nourishment.

In 1983, this Department established the task-group 'Profile Formation of Beaches', with the aim to study the relevant aspects of beach nourishment. These aspects concern among other things the influence of a beach fill on the coastal morphology and the environment, and the design and execution of a beach nourishment scheme.

The members of the task-group originate from various governmental departments, research institutes (Delft Hydraulics) and private organisations (Volker Stevin Dredging, Zanen Verstoep Dredging Contractors). In addition to the members of the working-group some other persons and organizations (also outside the Netherlands) have contributed to the final report.

The results of the studies have been described in a Manual on Beach Nourishment (Manual, 1986). This manual contains both theoretical and practical information, and is intended for persons and organisations who are involved in the prevention of beach erosion. Nearly all available and relevant literature to this subject has been incorporated.

The actual paper reviews part of the contents of the Manual and summarizes aspects related to the aim, the different types and the design process of beach nourishment schemes.

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2 Contents of the Manual

The Manual presents a comprehensive overview of matters related to shoreline protection by artificial beach nourishment and has been written for any authority, organization or person responsible for assessment of measures to protect, maintain or extend coastal areas. Government bodies, planners, designers and contractors will find the basic information they need. The various aspects to develop a strategy of artificial beach nourishment will pass in review: background information on coastal processes and shoreline evolution, design requirements and parameters, design methods, execution methods, and environmental aspects are the major elements presented in this manual. Furthermore, a number of implemented schemes are evaluated to indicate the applicability and accuracy of present design methods and the gaps in knowledge of this moment. In addition inventories have been made of artificial nourishment projects both in and outside The Netherlands.

The final document consists of two separate reports. The Manual (1986) comprises basically the findings of the working group, whereas the Background Report (1986) is a compilation of relevant information gathered in the scope of this project. Thus the Manual can be used separately without the need to consult the Background Report.

"Manual on Artificial Beach Nourishment" deals with the basic information for planning and design of a scheme of artificial beach nourishment. Coastal processes, computational methods, design parameters and execution methods are discussed here. General conclusions and recommendations for the future are presented in the report.

"Background Information on Artificial Beach Nourishment" comprises the information and detailed data collected, and computations carried out during the study. Literature abstracts, questionnaires on past artificial nourishment projects, model descriptions, hindcast computations and the specific Dutch situation with respect to artificial beach nourishment are comprised by the report.

3 Type in view of the aim of beach nourishment

Artificial beach nourishment schemes are generally executed with the aim to protect the coastline against beach erosion and/or to enlarge the beach for recreational purposes.
The following examples of causes of beach erosion can be mentioned:
- interruption of longshore transport by coastal structures;
- reduction of sediment supply by rivers;
- dune and beach erosion by storm surges;
- shifting of tidal channels;
- alongshore migration of large sand waves;
- relative sea level rise;
- beach mining.

The different types of beach nourishment can be characterized by the location where the sand is placed in the coastal zone, viz.:

(a) position in cross-shore direction (at the back, on top or at the face of dunes, on the beach or on the offshore zone);
(b) position in alongshore direction (placed along the beach, a stock pile of sand, or a continuous supply of sand).

Which specific type to select, depends on the aim of the beach nourishment and/or the cause of beach erosion.

4 Design process of beach nourishment scheme

The design process for an artificial beach nourishment scheme is schematically given in Figure 1. For a proper definition of the type and scale of the beach erosion problem, an assessment should be made concerning the causes of beach erosion and the interests of the actual beach with respect to safety, recreation, environment and economy.

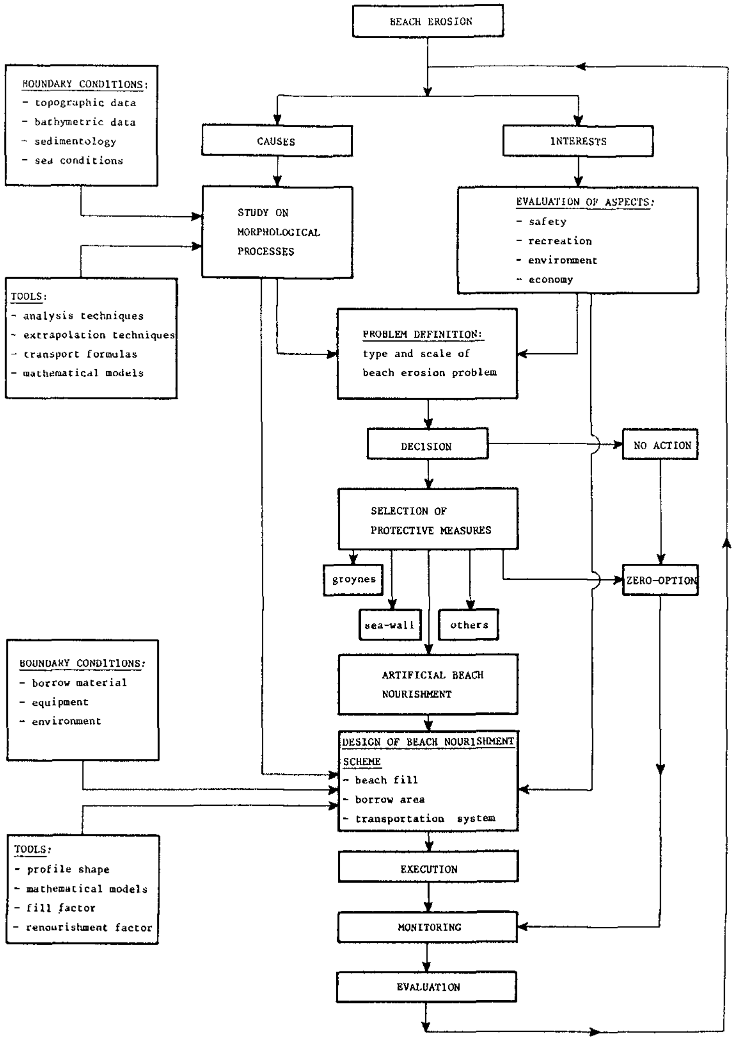

Figure 1 Process of design, execution and evaluation

The causes of beach erosion are determined in a study on morphologic processes, including the analysis of hydro-sedimentological data and the hind- and forecast of the coastal development by means of extrapolation techniques and mathematical models.

Once the problems have been defined, like short-term or long-term erosion (Figure 2), a decision can be made whether or not protective measures should be taken, and if so, which type of measures should be applied (beach nourishment, groynes, detached breakwaters, seawalls, revetments, etc.).

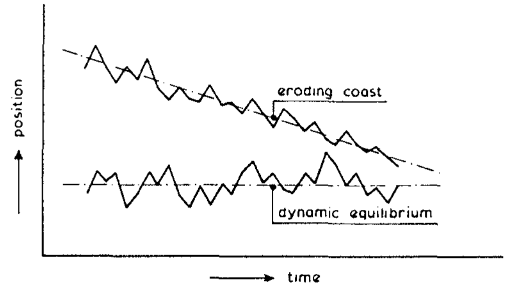

Figure 2 Short-term and long-term coastline variations

Aspects such as effectiveness, flexibility, spreading of cost, execution, harmony with nature, environment, etc., should be considered before selecting the protective measure (Figure 3).

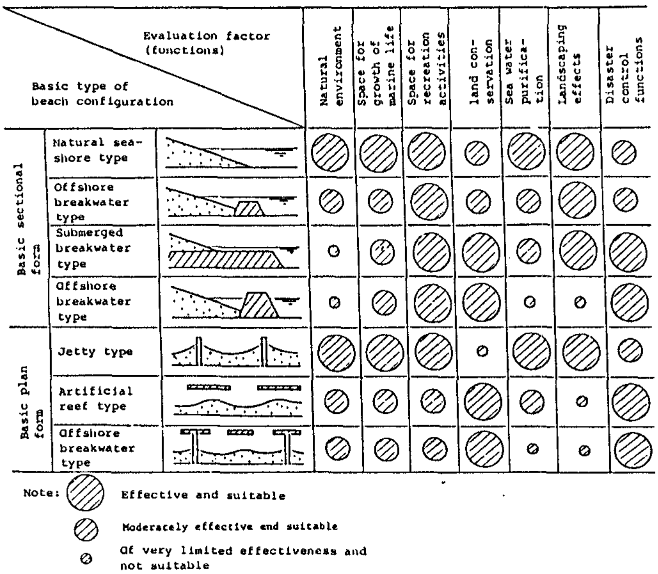

Figure 3 Selection of beach protection measure for project at Yokohama. (Kobayashi et al., 1985)

In this paper only attention is paid to the design of artificial beach nourishment schemes, for which three design elements can be distinguished, viz. the beach fill, the borrow area and the transportation system.
The dimensions of the fill should be such that the effectiveness as a coastal protection is guaranteed during a pre-defined period of time. Different tools are available to determine the deformation of the fill as a function of the hydraulic boundary conditions and the applied borrow material (mathematical coastal morphology models, adjusted SPM fill factor and renourishment factor, see Manual (1986) and Shore Protection Manual (1984)).
The selection of the borrow area and the transportation system depends among other things on the available fill material, the influence of the borrow area on the coastline, the local conditions and regulations, the available equipment and the execution method.
It is recommended, that after execution of the beach nourishment, regular surveys are executed to monitor the behaviour of the beach fill and borrow area.

5 Design of beach fill

5.1 Introduction

A major question concerning the design of a beach nourishment is the determination of the required volume of sand, such that the beach fill satisfies the specified requirements during a specified time. As a result of the sand transport in the coastal zone, the beach fill will be reshaped, and possibly sand is leaving the area to be protected. In particular a sand fill placed on an eroding beach, which is the usual case, has a restricted lifetime.
For the design of a beach fill it seems convenient to make a distinction between cross-shore transport and longshore transport. The cross-shore transport is responsible for the shaping of the coastal profile till more or less an equilibrium form is attained. Due to this profile development a retreat of the shoreline may occur. Usually the longshore transport is the main agent in the reshaping of the planform of the beach fill. As a result of this reshaping of the planform sand may leave the coastal area to be protected, while on the other hand sand may also enter the protected coastal area.

5.2 Coastal profile of beach fill

The required volume of sand for a beach fill is to a large extent determined by the development of the coastal profile. In this connection different aspects can be considered, viz. the shape of the active profile as a result of the prevailing hydraulic forces, and the depth to which this profile will develop. Below this depth usually a transition zone has to be defined which meets the original profile.

Shape of active profile:

Many researches have studied the development of coastal profiles under wave attack in order to derive relations between profile shape, wave motion and sediment characteristics. Most of the derived relations are based on the results of small-scale tests in wave-channels. However, the inevitable scale effects and the strong schematization of the conditions in the model do not permit an exact extrapolation of the data to nature. The schematization applies to both the sedimentologic and the hydraulic conditions. In models mostly one type of sand is used as bed material, whereas in nature the sediment characteristics vary often strongly along the profile. In addition the results of model testing have usually been obtained by applying fixed wave conditions, while in nature the wave conditions are quite variable. As a matter of fact the whole wave climate is responsible for the shape of the coastal profile, while also other factors play a role, like tides, surf beats, coastal currents, etc. Obviously the complexity of the factors has also caused that the analyses of measurements in nature have not led to applicable relations for predicting the shape of coastal profiles.

In case a former situation of the beach should be restored it is obvious to start from the coastal profile at that time, if available. The difference between this former coastal profile and the present profile then equals the volume of sand to be supplied per unit length of beach, provided that the borrow sand is similar to the native sand. If the former profile is not known it can be assumed that the coastal profile will develop according to the present profile up to a certain depth.

The native profile and its dynamics are important to estimate the eventual shape of the beach fill. From curve-fitting on numerous profiles Dean (1983) and Moore (1982) developed an usable relation representing the effect of the particle diameter on the beach shape (see Figure 4):

$$h(y) = Ay^{m} \approx By^{2/3}\ D^{1/3} \tag{1}$$

where h is water depth, A is a constant roughly proportional to $D^{1/3}$ and should be determined for each particular case, D is particle diameter, y is distance from water line, m is exponent (usually assumed equal to about 2/3), B is an unknown factor which has to be determined for each specific case.

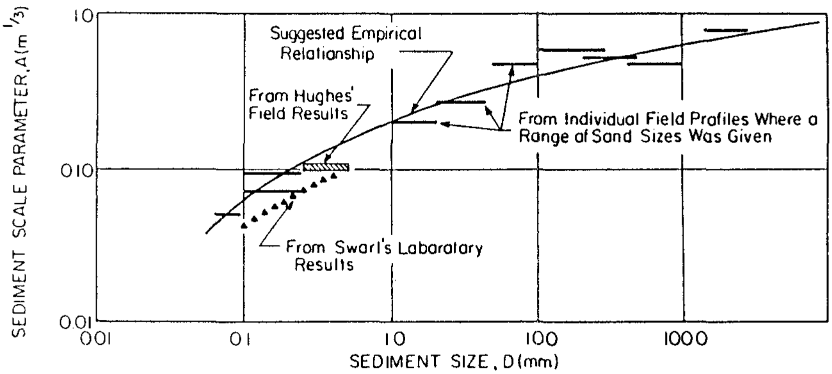

Figure 4 Value of A in h = Ay^{m} versus sediment size (Dean, 1973, modified from Moore, 1982)

Generally the profile adapts itself rather quickly to the actual wave impact. Erosive profiles occur under severe wave conditions and lead to so-called bar profiles. Accretive profiles are characterized by moderate wave impact and are referred to as step-profiles. Graphs of Dalrymple and Thompson (1976) give a rather illustrative picture of the influence of the wave-grain size parameters on the slope of the profile, both for model and prototype conditions (see Figure 5).

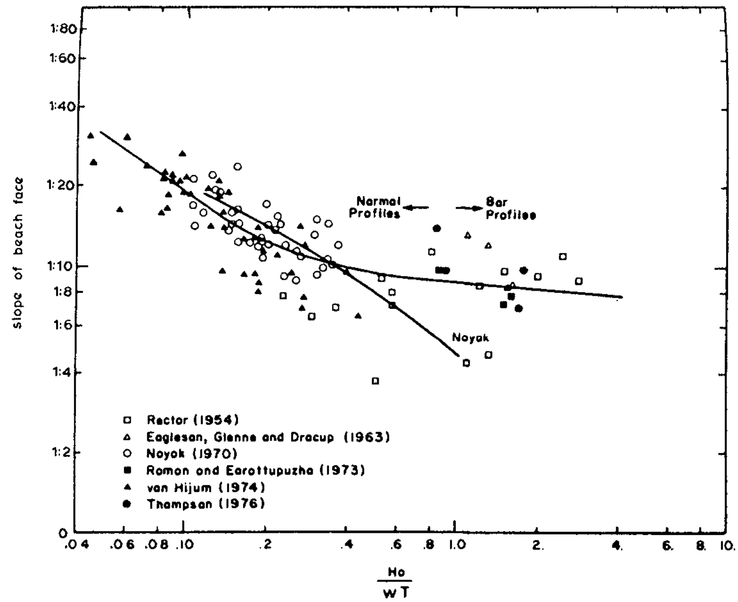

Figure 5 Beach slope versus fall velocity parameter (Dalrymple and Thompson, 1976)

Quite often the borrow sand will not be similar to the native sand, and then it is to be expected that the ultimate profile will differ from the present one. For an estimate of the new profile use can made of the scale relationship for the profile steepness as derived from extensive tests of dune erosion at different scales (Figure 6, see Vellinga (1982)). This relation is as follows:

$$\frac{n_l}{n_d} = \left(\frac{n_d}{n_w^2}\right)^{0.28} \qquad (2)$$

in which n_l is the horizontal scale, n_d is the vertical scale, n_w is the scale of the fall velocity of the sand, which is related to the median grain diameter D_{50}.

Now the coastal profile of the replenished beach can be considered as a model of the present profile. The vertical scale n_d is directly related to the scale of the wave height thus $n_d = n_H$. Since the beach fill is subject to the same wave conditions as the present beach, it is clear that $n_d = 1$. Consequently:

$$n_l = n_w^{-0.56} \qquad (3)$$

This relation should be read as follows. Suppose that the fall velocity of the native sand is w_1 and that of the borrow sand is w_2. If in the present profile the depth contour d is situated at a distance l_1 from

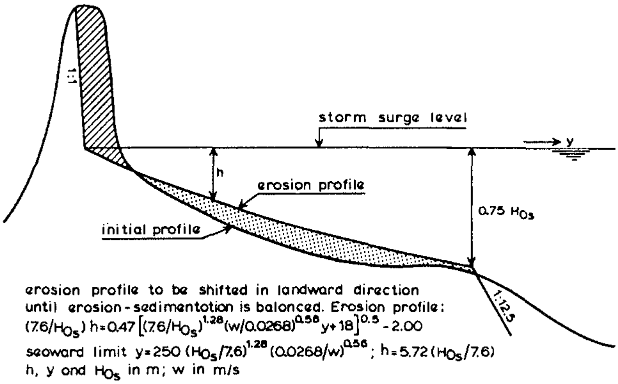

Figure 6 Erosion profile after storm surge (Vellinga, 1984)

the shoreline, then the distance of the same depth contour to the new shoreline of the replenished beach is determined by the relation:

$$\frac{l_1}{l_2} = \left(\frac{w_1}{w_2}\right)^{-0.56} \qquad \text{or} \qquad l_2 = \left(\frac{w_1}{w_2}\right)^{0.56} l_1 \tag{4}$$

The effect of this relation is illustrated in Figure 7. If the borrow sand is coarser than the native sand, thus $w_2 > w_1$, then the profile of the replenished beach is steeper than the original profile, and conversely. It is clearly shown that the use of coarse sand is profitable in view of the required volume of sand to obtain a certain widening of the beach.

It is observed that the method described above provides a fair estimate of the profile shape of the replenished beach. A condition, however, is that representative values for the fall velocity of the native sand and of the borrow sand are applied. This means that, because of the sorting effect of the waves, a large number of samples of the native sand has to be collected and analysed, and this may also apply for the borrow sand. Moreover, because of the handling of the borrow sand, finer parts may be washed out so that the median grain size increases. Because of these reasons an exact prediction of the equilibrium profile of the replenished beach is not possible.

Depth of active profile:

From Figure 7 it can be concluded that it is important to know to which depth the coastal profile will develop. This holds, in particular if the borrow sand is similar or finer than the native sand. In case the profile should develop unlimitedly in seaward direction enormous amounts of sand are needed to obtain a widening of the beach.

It should be stated beforehand that the seaward limit of the profile that is shaped by the action of the waves cannot be ascertained. In first instance the profile will extend rapidly by which sand is removed from the upper part of the profile to deeper water. If the lower limit

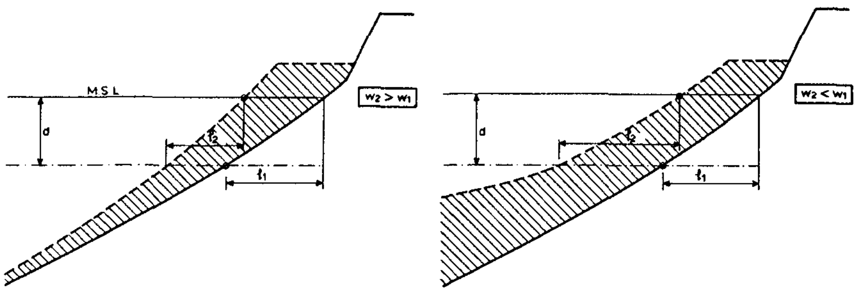

Figure 7 Effect of grain-size on profile steepness

of the developing profile has reached deep water only the infrequent higher waves are able to create offshore transport at that depth. So the development of the profile in seaward direction is slowing down with time, but it is not possible to determine when this process will stop. Nevertheless for the assessment of the quantity of sand needed for a specified widening of the beach, an idea should be achieved of the depth up to which the profile will develop. In case the fill sand is coarser than the native sand, the uncertainty in this depth does not play a prominent role in the determination of the required volume of sand, but it does if the borrow sand is finer.

For an estimation of the lower limit of the active coastal profile use can be made of the relations derived by Hallermeier (1978). He divides the coastal profile into three zones (see Figure 8):

- littoral zone up to depth d_l with significant alongshore transport and intensive on/offshore transport throughout a typical year;
- shoal zone with significant on/offshore transport up to depth d_i, at which depth expected surface waves are likely to cause little sand transport;
- offshore zone where the surface wave effects on the bed are usually negligible.

In view of the definition mentioned above it is recommended to assume that the active coastal profile will develop up to a depth d_l by wave action, although below this depth still significant cross-shore transport will occur.

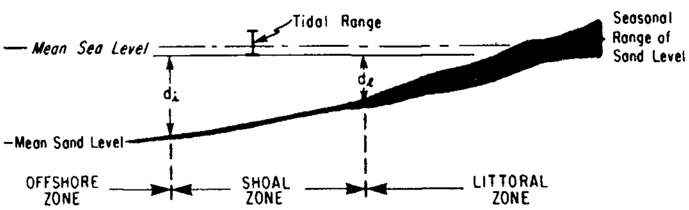

Figure 8 Zonation of seasonal beach profile (Hallermeier, 1978)

On basis of an analysis of available data Hallermeier arrives at the following relation for the lower limit of the littoral zone:

$$d_l = 2.28\ H_s - 68.5\ (H_s^2/gT_s^2) \tag{5a}$$

where d_l is water depth below low water level, H_s is the local significant wave height with a frequency of occurrence of 0.137% (12 hours per year) and T_s is the associated significant wave period.

Birkemeier (1985) has evaluated Hallermeier's method and on the basis of field measurements at the CERC's Field Research Facility in North Carolina. He suggests the relation:

$$d_l = 1.75\ H_s - 57.9\ (H_s^2/gT_s^2) \tag{5b}$$

For a Jonswap spectrum the relation $(H_s/gT_s^2)^{0.5} = 7.1 \times 10^{-2}$ holds good by approximation and for a Pierson-Moskovitz spectrum the relation $(H_s/gT_s^2)^{0.5} = 6.4 \times 10^{-2}$ can be assumed. By substituting these relations into Eq. (5a) it is found that d_l = 1.93 or 2.00 H_s and into Eq. (5b) d_l = 1.46 or 1.51 H_s.
Unless the wave spectrum deviates significantly from the above mentioned spectra, it can be assumed for practical purposes that:

$$d_l = 1.75\ H_{s\ 0.137} \tag{6}$$

It is stressed that H_s pertains to the nearshore wave condition. In case wave condition are only known far offshore, computations are to be done for transferring these data to the nearshore zone.

Transition zone:

If the borrow sand is coarser than the native sand, then the profile of the beach fill may intersect the original profile at a level that is above the profile depth as defined above. In that case the coastal profile is completely fixed. However, in many cases the required intersection between the new and original coastal profile takes place at a lower level. In order to obtain this intersection a transition zone should be defined.
In first instance it seems reasonable to assume that the lower limit of this transition zone is located at the depth d_i so that the boundaries of the transition zone coincide with the boundaries of the shoal zone as defined by Hallermeier (see Figure 8). Hallermeier arrives at the following critical condition for the lower limit of the shoal zone:

$$\phi_c = (U_o^2/\Delta gD) = 8 \tag{7}$$

where U_o is maximum orbital velocity at the bed, Δ is specific density of sand in seawater (= 1.6), g is gravitational acceleration and D is median sand particle diameter.

In Equation (7) the value of U_o is computed according to the linear wave theory:

$$U_o = \pi H/T \sinh\ (2\pi d_i/L) \tag{8}$$

in which H is annual median significant wave height, T is average wave period associated with the median wave height and L is wave length.

From Equations (7) and (8) it follows that:

$$\frac{2\pi d_i}{L} = \text{arc sinh}\left(\frac{\pi H}{T\sqrt{8\Delta g D}}\right) \tag{9}$$

For known values of H, T and D the value of $2\pi d_i/L$ can be computed.

Measurements seaward of the mouth of the Haringvliet in the Netherlands at a depth of MSL-6 m yield an annual median significant wave height H = 0.55 m with a period T = 3.5 s. Thus for D_{50} = 200 μm the value of d_i = 5.8 m and for D_{50} = 100 μm the value is d_i = 7.1 m. However, the same measurements show that $H_{s\ 0.137}$ = 3.0 m, which means that d_l = 6.0 m. So d_i and d_l have virtually the same value in this case, which does not seem realistic. Obviously the relation between d_i, which is the lower limit of the shoal zone in deep water, and the annual median significant wave height does not hold for the observed wave climate in the mouth of the Haringvliet. The relations of Hallermeier are based mainly on wave observations along the U.S. coasts with low wave steepnesses.

Because the relation for the lower limit of the shoal zone, as derived by Hallermeier, cannot be generally applied for defining the lower limit of the transition zone, it is suggested that this lower limit is defined as:

$$d_i = (1.5 \text{ to } 2)\ d_l \approx 3\ H_{s\ 0.137} \tag{10}$$

The thickness of the beach fill between the depths d_l and d_i can be assumed to decrease linearly with distance (see Figure 9).

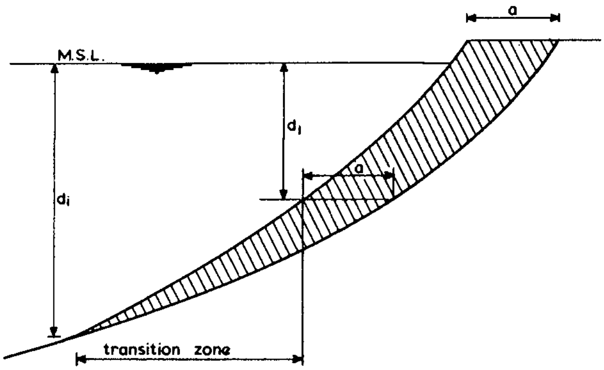

Figure 9 Profile of beach fill, borrow sand equal to native sand

5.3 Adjusted SPM fill factor and renourishment factor

In the Shore Protection Manual (1984) two models are recommended as design tools for beach fills. These models have been developed for the condition that the textural properties of the borrow sand differ from those of the native sand. The aims of the two models can be defined as follows:

a. The adjusted SPM fill factor (R_A) is used to determine how much overage of borrow sand may be required.
b. The renourishment factor (R_J) is used to determine the relative frequency of renourishment.

Both beach fill models use the mean and sorting values of the composite grain size distributions of the native and the borrow sediments as basic input. This means that careful attention should be paid to the design of sediment sampling plans, since the quality of any beach fill calculation is, at best, only as good as the native beach and borrow composites have been determined. The number of samples to be analyzed for determining the composite grain size distribution depends on the variation of the materials and their individual properties.

Further it is observed that the models only take into account the effect of a possible difference between the properties of the native sand and the borrow sand. Consequently for the application of the models first other aspects of the design of a beach nourishment scheme should be determined, in particular the required volume of sand and the frequency of renourishment in case the properties of the borrow sand and the native sand are similar. For more information regarding the use of the factors reference is made to the Shore Protection Manual (1984).

5.4 Planform of beach fill and mathematical coastal morphology models

During and some time after the placement of a beach fill the reshaping of the coastal profile by onshore/offshore transport is usually the most noticeable phenomenon. However, at the same time the longshore transport will start to reshape the planform of the beach fill, which process may continue for a long period. The effect of the longshore transport on the planform of the beach fill is in particular perceptible at the transition between the replenished beach and the adjacent non-replenished beach. In Figure 11 the morphologic process at the end of a beach fill has been reflected schematically. Because of the replenishment the coastline has moved seaward and a transition zone develops where the direction of the coastline differs from the original direction. In case of a longshore transport from left to right, as drawn in the figure, this longshore transport will be larger in the transition zone due to this difference in coastline direction. The result is that erosion occurs along the left part of the transition zone and accretion along the right part. Because of these processes the transition zone will expand in both directions. If the longshore transport is from right to left, then the coastal development is the same as drawn in Figure 10.

An important question is to predict the dimensions of the initial beach fill, which are required to protect a coastal area during a desired guarantee period. Different methods are available, ranging from simple analytical to sophisticated mathematical, for the prediction of the morphological behaviour of the fill. In the simplest analytical theory, the coast is schematized by one line (Bakker, 1970).

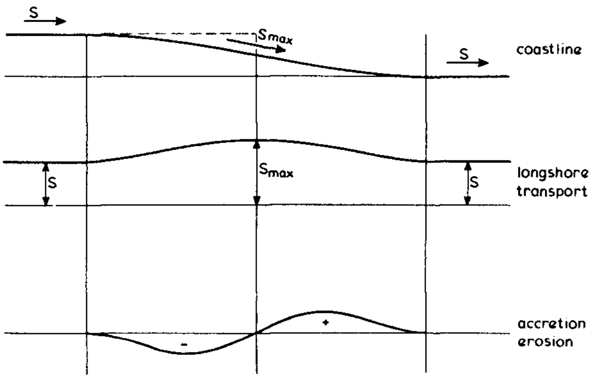

Figure 10 Schematic view of coastal processes at end of beach fill

An example of the one-line theory has been illustrated in Figure 11 for a beach fill with initially a rectangular shape (LxB). This figure shows the parameters B/b (ratio between the initial width B and the minimum required width b), A/a (ratio between the initial area A and the minimum area a) and x_0/L_0 as a function of the dimensionless length ℓ/L_0, where ℓ is the length of beach to be preserved and $L_0 = \sqrt{4(s/h)t}$, (s is the variation of the longshore transport per radian of coastline rotation, h is the schematized thickness of the active profile and t is time). It will be clear that the coastal stretch where the sand is supplied has to be larger than the area to be protected, in order to account for losses along the sides.
For instance, if the beach area (ℓxb) to be protected during 5 years is 5000 x 50 m^2, while the coastal constant s is 300,000 m^3/rad/yr and the height of the profile is 6 m, then the dimensionless length ℓ/L_0 is 5000/1000 = 5. From Figure 12 it can be seen that the initial width of the area should be 1.1 x 50 = 55 m and the extra length at both sides of the fill (x_0) should be 1.2 x 1000 = 1200 m. Consequently the fill should have an area which is about 50% larger than the area to be protected (A/a ≈ 1.5).
This one-line method is rather a strong schematization of reality and the results should therefore be interpreted with care. More sophisticated models give the opportunity for more "taylor made" solutions, as presented in the Manual (1986).

6 Conclusions and recommendations

Generally, artificial nourishment turns out to be a feasible and attractive method to restore, protect, extend and maintain beaches. The essence of the reported advantages are flexibility and harmony with nature. This is concluded after review of literature on about 60 artificial nourishment projects (Manual, 1986).

Inevitably artificial beach nourishment will be applied in the future more and more as standard method for coastal protection and extension of recreational facilities. Whenever technically possible and economically feasible, it is recommended to accomplish the remedy on artificial supply rather than by fixed structures.

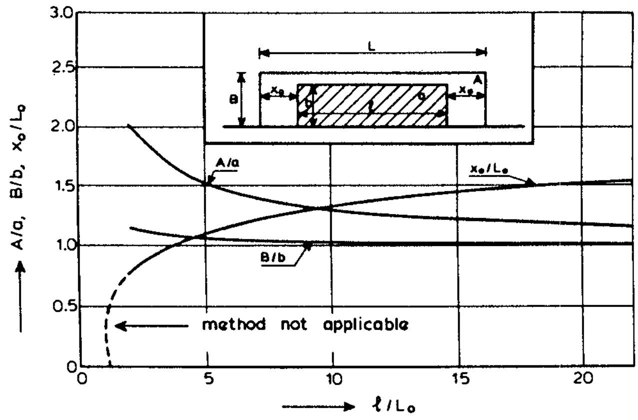

Figure 11 Optimal dimensions of sand supply according to one-line theory

An integral design method for artificial beach nourishment, including all relevant parameters, is not yet available. However, for separate aspects of the design of the beach nourishment various design tools are available, such as models for the prediction of the morphological behaviour of the fill and methods for the determination of the effect of different grain size characteristics.

The performance and deformation of artificial beach fills, which significantly affect the coastal geometry, can be predicted with different tools, ranging from simple to complicated, depending on the boundary conditions of the actual situation. It is foreseen that in future use will be made of two-dimensional horizontal and (quasi) three-dimensional coastal morphological computer models to evaluate the effect of artificial beach fills and to select via comparative computations the optimum location and shape. At the same time it must be stressed that the presently available techniques (long-term coastal monitoring, fill- and renourishment models, profile shape formulations and one- and multi-line models) certainly suffice in the proper cases.

Conclusions about the performance of a fill are often based upon observed changes of only a restricted section of the profile above a certain elevation. Although profile development may extend to greater depths than surveyed, in many cases a reasonable idea is obtained of the performance of the fill. However, it is stressed that surveying of only the subaerial section certainly is insufficient.
Both gradients in longshore transport and severe wave impact generally cause the reported losses. The quantity of sand loss depends on the surveyed profile lengths; therefore care should be taken with the definition of beach loss, since material which is transported further offshore is not necessarily lost for the beach development. Gradients in longshore transport are mostly responsible for "real" losses. It should be stressed that no strict guide-lines can be presented regarding the measurements to be carried out for the evaluation of a beach replenishment project.

Official procedures to attune different projects are still tiresome. In future it will become more necessary to try to use the sand, which comes available from other planned or ongoing dredging projects, for artificial beach nourishment. Material from maintenance dredging should be used after a close examination of its characteristics. Maintenance dredging is normally the removal of siltation which is most of the time odorous and contains a large percentage of fines, which makes it unsuitable for beach nourishment schemes. However, granular material from capital dredging work should well be suitable and could reduce the total coast of a planned nourishment scheme. Therefore it makes sense to enhance the cooperation between the various governmental agencies, who are in charge of such civil engineering projects.

The results of this study underline once again the statement that "still, the more is learned about coastal processes, the more it is realized how little is known yet". Because of the complexity of the problem and its world wide importance, close international co-operation in this field is strongly recommended.

7 Acknowledgements

Apart from the contributions to the Manual (1986) by the members of the working group, many other sources were used in the form of oral or written information, publications or other written documents. The substäntiated input of any public or private organization and any person or author who readily made information available for use in the preparation of the report is highly acknowledged.

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