BEACH NOURISHMENT

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1 Introduction

An attractive, high-quality beach has a long, wide and slightly curved bay-type appearance and consists of clean, yellow, well-sorted, fine to medium grained sand (0.2 to 0.4 mm); the beach slope is gentle up to a depth of about 2 m promoting spilling, breaking waves rather than plunging waves, which should not be much larger than about 1 m in the summer period. Rocky outcrops may be present on both ends protecting the beach against too strong wave attack from oblique directions. However, touristic beaches along erosion-dominated coasts often are relatively narrow strips of sand, protected by various types of structures (groins, breakwaters, etc.) resulting in small pocket-type beaches crowded by people in the summer period, see **Figure 1.1**.

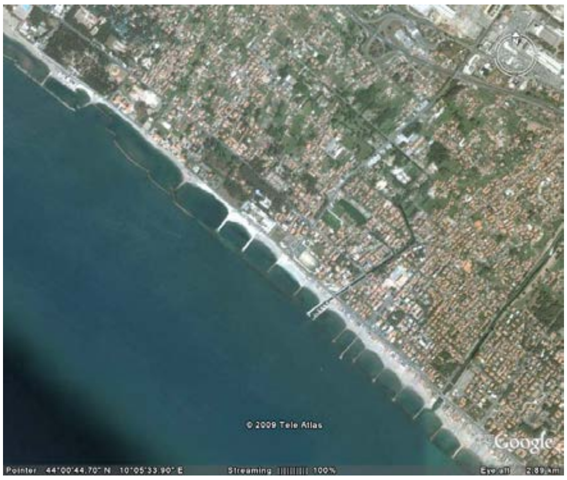

Figure 1.1
Left: Mediterranean coast near Carrara (Italy) Right: Golfo de Morrosquillo near Covenas, Colombia

Narrow beaches suffering from coastal erosion generally are mitigated by beach nourishments, artificial structures or both. In some coastal countries (USA, Denmark and The Netherlands) with sufficient sources of sand coastal erosion is primarily mitigated by intensive schemes of beach nourishment in line with the concept of 'building with nature' resulting in long, wide, attractive beaches.

At other locations with insufficient economic availability of sand, the presence of coastal structures often is a necessary solution to prevent or reduce long-term beach nourishment. However, these stuctures generally are seen as unattractive, visual elements blocking the view of the tourists. Furthermore, rip currents may be generated close to the tip of structures during windy conditions due to variations in wave set-up resulting in dangerous swimming conditions. The inefficiency of many traditional groin field systems in protecting the coastline, along with a much higher social importance nowadays given to environmental, recreational and aesthetic values, have caused a shift in beach developments. Modern landscaping ideas are focussed on the design of long and wide beaches with a minimum number of structures enhancing the natural appearance of the beach. Structures should be designed and planned as multifunctional facilities.

Some countries (Spain, Italy) around the Mediterranean have launched initiatives to adopt a new coastal policy of replacing the traditional small-scale groin fields by large-scale, more open recreational beaches, see **Figure 1.2** (Gómez-Pina, 2004) and **Figure 1.3**. This policy basically consists of the removal of ineffective and non-aesthetical coastal groins in combination with new beach fill operations, while keeping the terminal groins combined with a submerged or low-crested breakwater in the middle of the beach to give sufficient protection against wave attack. Such a design might offer a much better aesthetic solution at many places. This may also improve bathing safety as the larger waves will break on the low-crested, detached breakwater in the middle of the beach. Wave diffraction around the terminal groins will promote shoreline curvature towards both ends of the beach, creating a visually, attractive crescent bay-type beach. Beach restoration requires close collaboration between coastal engineers and landscape architects to arrive at an attractive, sustainable coastal beach in harmony with its surrounding. Essential for a successful beach restoration project is a clear understanding of the local natural processes and environments, local societal demands and economical issues as a basis for the design of an attractive, high-quality beach.

Figure 1.2 *Example of the removal of a coastal groin system in Compostela beach (Spain) before (left) and after beach restoration (right); fill nourishment is included.*

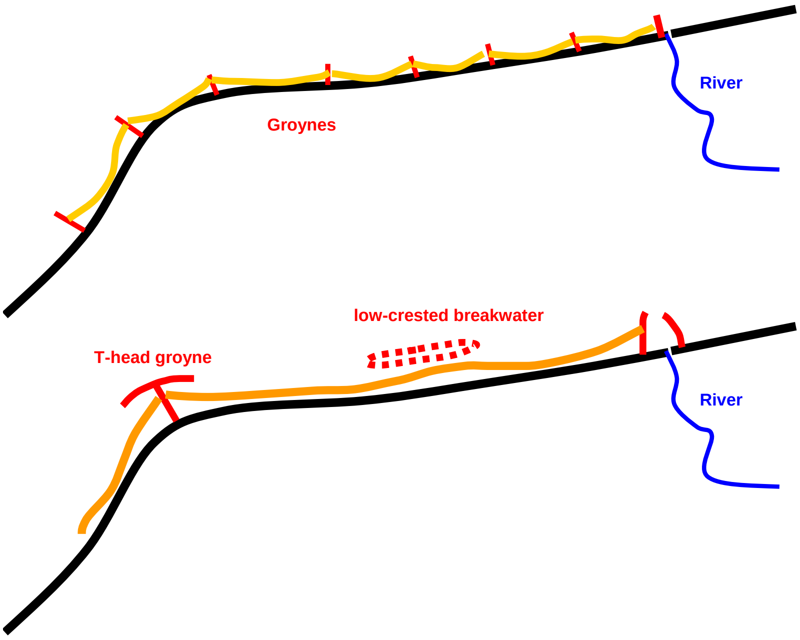

Figure 1.3. *Long, wide beach replacing small cell-type beaches*

The beach should be stable in planform to ensure minimum maintenance. This means that the beach orientation should be as much as possible perpendicular to the prevailing wave direction. The terminal groins should be designed to reduce wave attack on the beach and to reduce variation of the beach planform. Curved terminal groins promoting wave diffraction around the tip are more efficient than

straight, perpendicular groins as they can protect a larger part of the beach while they are also more attractive from a visual point of view.
Detached or shore-parallel breakwaters can be used to protect the coastal cell on the seaward side, see **Figure** 1.**4**. These types of structures are built as offshore barriers parallel (occasionally obliquely positioned) to the shore protecting a section of the shoreline by forming a shield to the waves (blocking of incident wave energy). Emerged breakwaters cannot stop storm-induced erosion completely, as large storm waves will pass over the structure in conditions with high surge levels above the crest level.

The armour cover layer of artificial structures should consist of well-placed rocky elements rather than of dumped rip-rap materials for reasons of aesthetics, see **Figure 1.4**. Boulevards should be bordered by decorated ornaments of natural materials, see **Figure 1.4**.

Figure 1.4 *Groins consisting of rip-rap dumped rocks and well-placed rocks*

The selected beach fill material should be similar to that of the original beach; the percentage of fine and coarse fractions should not be larger than 1% to 3%. Well-sorted sand is prefered above graded sand because it has a much higher permeability promoting beach draining close to the water line. The water circulation and its influence on the water quality shuld have considerable attention during the design. Water circulation and wave penetration should be sufficient to prevent the gradual seasonal growth of seagrasses and/or slimey algae layers due to the deposition of fine sediments and organic materials. This may easily lead to a seabed covered with a layer of soft sediment, which feels muddy when walking on it and which is unattractive for recreational purposes.

2 Beach nourishment/fill

2.1 Objectives and types

Beach nourishment or beach fill is the mechanical placement of sand on the beach to advance the shoreline or to maintain the volume of sand in the littoral system. It is a soft protective and remedial measure that leaves a beach in a natural state and preserves its recreational value. The method is relatively cheap if the borrow area is not too far away (<10 km). Beach nourishment requires a basic understanding of beach and shoreline variability. Nourished beaches need regular maintenance (replenishment) of sand, otherwise the beach nourishment will gradually disappear due to erosion.

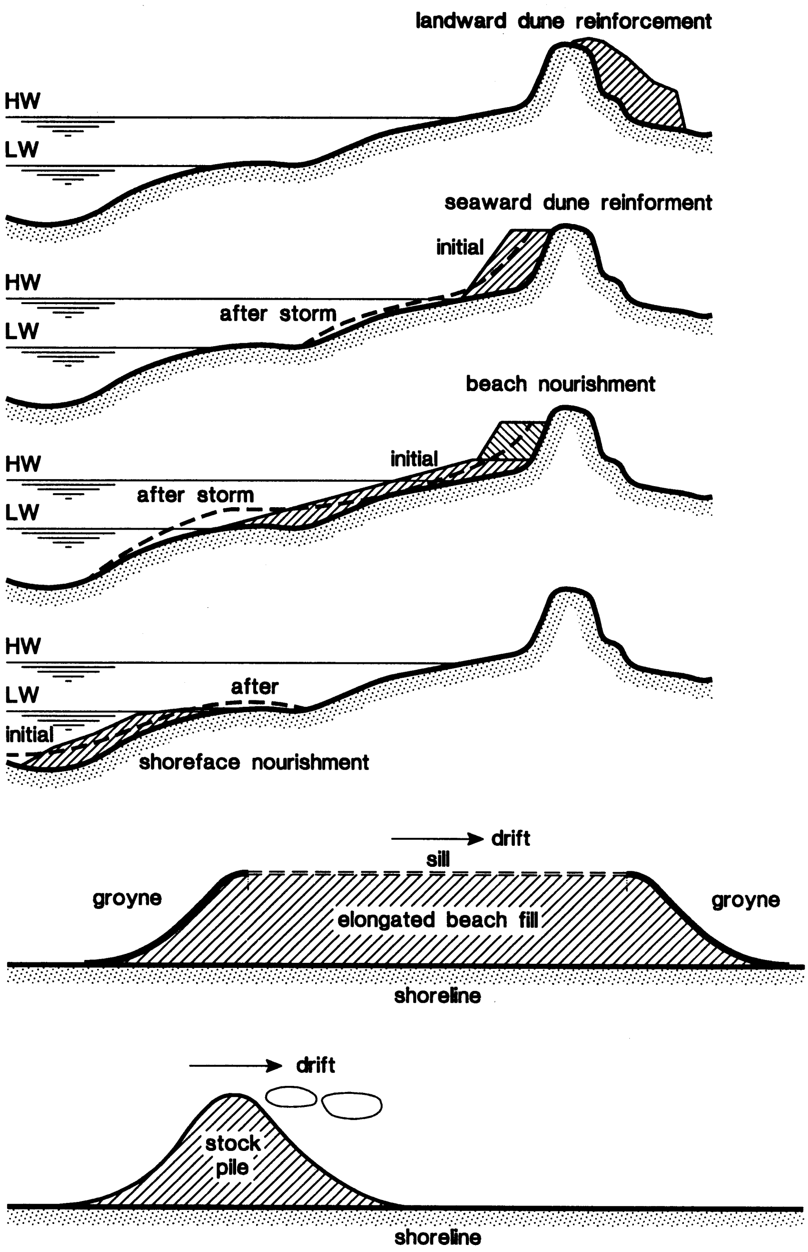

Figure 2.1 *Dune, beach and shoreface nourishments*
Top: Cross-shore profiles
Bottom: Planforms

The objectives of nourishments can be (see **Figure 2.1**):

- formation/restoration of recreational beach;
- land reclamation;
- maintenance of shoreline (chronic erosion or lee-side erosion);
- reinforcement of dunes against breaching (landward or seaward);
- protection of coastal structures (seawalls, groynes,etc.);
- reduction of wave energy arriving at beach/dune (submerged artificial bars along non-barred profile); protection and feeding of beach/dune system;
- filling/closure of scour channels or tidal channels close to shoreline;
- stockpiling in nearshore zone; creation of massive localized buffer of sand generally placed updrift of the zone to be nourished; the buffer may have the form of a cuspate foreland; especially suitable for maintenance of shoreline; it may also be used to stop erosion due to nearshore rip/swash channels by making a stockpile (large dump) updrift of the channel.

A beach fill functions as an eroding buffer zone. The initial fill should be as large as possible (overfill). It is a temporary measure as the natural littoral processes (causing erosion) remain unaltered. Regular maintenance is required. Maintenance can be reduced by using relatively coarse sand as fill material.

Sand nourishment can be carried out at various locations in the profile and along the shoreline (**Figure 2.1**), as follows:

- ***beach and surf zone*:** sand is dumped as high as possible on the beach to obtain a recreational beach in combination with revetments, groynes, detached breakwaters and submerged sills; dumping of sand can be done as:
  - an elongated buffer layer of sand on the beach (direct placement for recreational beach or for protection of a structure or in an environment with dominant offshore transport), or
  - a continuous source at one or more specific locations (dump site of bypassing plant or stock pile); landward of high tide line at updrift side of eroded section for maintenance of shoreline;
- ***shoreface zone*:** nearshore berms or mounds are constructed from dredged material;
  - feeder berms: placement of sediment material in shallow water to create an artificial longshore bar and to promote the feed of sediment to the beach by onshore transport processes; if bars are present the berm generally is placed on the seaward flank of the most offshore bar (draft of dredger is mostly larger than water depth above bar crest);
  - reef berms: placement of sediment material seaward of closure depth to act as a reef-type wave filter for storm waves;
- ***dune zone*** (landward and seaward above dune toe level): dune is reinforced/protected against breaching during storms.

2.2 Design aspects

Fill dimensions

An elongated (trapezoidal) fill should be placed as much as possible landward of the high tide line in a layer of 2 to 3 m thick (volumes of 50 to 200 m^3/m) with a berm of about 20 to 30 m wide (if required) at the dune foot level (**Figure 2.1**).
The length of the fill should be about 2 to 3 km to minimize the sand losses at both alongshore ends due to dispersion effects under shore-normal wave attack. Any nourishment placed on an open beach suffers from dispersion alongshore; the longer the length of placement, the lesser the relative effect of end losses. Recreational beach fills can be enclosed by a sill at the seaward side and by two terminal groynes at both longshore ends to create a pocket beach;

Volume of sand

The fill volume should not be too large (overnourished profile) to prevent excessive initial erosion due to steep beach profiles. A large fill volume has a smaller unit dredging price and a longer life time; it may be cheaper despite bigger initial losses.

Practical volume ranges are:

- 10 to 50 m^3/m/yr for low-energy coasts;
- 50 to 150 m^3/m/yr for moderate-energy coasts;
- 150 to 300 m^3/m/yr for high-energy coasts.

Sand composition

Ideally, the fill material should be slightly coarser than the native beach material in the beach/swash zone. Sand coarser than the native material can be placed at a steeper slope; the slope will remain somewhat steeper than the original slope until most of the fill material is removed by wave action.

Fine sand fill material will not be effective in the beach/swash zone; fines between 0.06 and 0.125 mm will be washed out easily during dredging/dumping operations and carried to the offshore zone where slopes are lower; the finer fractions dumped on the beach will be winnowed rapidly by wave action until the fill material has the same composition as the native material. Finer fill material will require a relatively large overfill volume to compensate the losses.

The sand size and composition largely depend on economically available sand in the borrow area (if possible, selective dredging should be applied). Sand from maintenance dredging of navigation channel deposits generally is relatively fine. The finer sand fractions (<0.125 mm) can be eliminated partly by using proper dredging methods (hopper dredging with overflow, dumping in rehandle pit, etc.); about 10% to 30% of the base material may be lost during dredging operations and hence the grain size may increase by 10% to 30%; nourishment cost will increase (larger volumes required).

Sand finer than native beach material should be placed high up the beach. The effectiveness of beach sand fills increases considerably for sand larger than 0.3 mm.

Initial profile shape

The initial slopes are 1 to 30/50 for the upper beach above -1 m depth line; 1 to 20/30 for the lower beach between -1 and -3 m depth lines. The dump slopes of the lower beach will be smoothed out by wave action. The precise slope of the lower beach immediately after nourishment is not so important as long as it is not too steep (not steeper than 1 to 20 for sand beaches); the profile will be reworked by the first autumn storms to a more natural profile (the slope should be economic; easy to make by the contractor);

The initial losses of beach nourishments are largely determined by the initial beach slope and profile shape.

Experience at the exposed Sylt beach (Germany; Raudkivi and Dette, 2002) shows a beach loss of about 120 m^3/m in about 4.5 months (winter period) or about 1 m^3/m/day for a beach nourishment with an intial toe slope of 1 to 5 (lower beach). The beach width above the MHW line at about +1 m remained relatively stable (about 50 m).

Experience at the exposed Egmond beach (Netherlands) also shows relatively short beachfill lifetimes of about 1 to 2 years. The beach nourishments generally have a volume between 100 and 200 m^3/m and are placed as a layer of about 1 m on the beach. The natural beach profile at Egmond has a beach slope of about 1 to 30 with a low tide terrace (at about -0.5 m below NAP). The new profile (immediately after nourishment) also has a slope of about 1 to 30 at the lower beach. This reduces excessive erosion of sand at the lower end of the beach.

Herein, it is concluded that the lower beach of a beach nourishments should have a relatively gentle initial slope (1 to 20/30). Preferably, an underwater berm at about -1 m should be included to minimize the initial sand losses.

Beachfill design method
The design procedure for beach nourishment in The Netherlands (sand sizes between 0.2 and 0.4 mm) is, as follows (Verhagen, 1992; Rijkswaterstaat, 1996):

- determine the erosion volume (m^3/yr) of sand in the active zone (say between dune top and -6 m) along the considered coastal section over a period of about 10 years using regression analysis, see **Figure 2.2** ; if volume values are absent, the annual shoreline recession rate can be multiplied with the profile height (say 15 to 20 m, between -6 m and dune top) to obtain an estimate of the sand volume loss per year;

- multiply the annual erosion volume by an overfill factor to account for losses due to washout of fines and due to the presence of steeper initial profiles after nourishment (overfill factor= 1.3 to 1.5, depending on sand size and coastal configuration such as nearby channels, etc.; usually 1.4 is taken);

- multiply annual volume by required lifetime (say, 5 years) to obtain the total fill volume; the total fill volume generally is of the order of 3 to 5 times the net annual longshore transport rate (order of 0.1 million m^3/year) in the nearshore zone (above -1 m line) at the nourishment location, yielding values of 0.3 to 0.5 million m^3 beach fill above the -1 m line; shoreface nourishment volumes seaward of the outer breaker bar are considerably larger (factor 5), yielding values of 1.5 to 2.5 million m^3;

- beach fill sand is dumped on the beach between dune toe level and -1 m line (ratio of fill length alongshore and fill width above MSL is between 20 and 40); shoreface fill sand generally is dumped on the most seaward flank of the outer bar (as far shorewards as the draft of the dredger allows).

The design method applied in The Netherlands is rather efficient for shoreline maintenance in terms of sand volumes in the zone between +3 and -3 m.

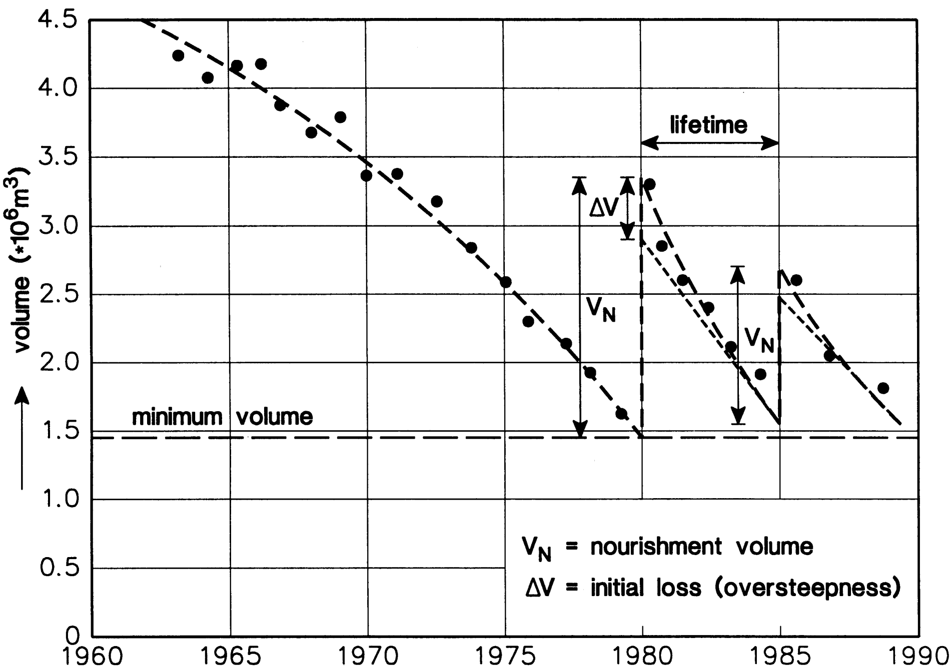

Figure 2.2 *Sand volume in beach zone (between 3/-3 m lines) as function of time*

3 Evaluation of beach fill projects

Based on practical nourishment experience in the Netherlands, it can be concluded that **shoreface nourishments** have an efficiency, defined as the ratio of volume increase of the nearshore zone and the initial nourishment volume, of 20% to 30% after about 3 to 5 years; the nearshore zone is defined as the zone between -1 and -4.5 m NAP (landward of the nourishment area). The remaining part (70% to 80%) is lost from the nourishment site.
The feeding of sand from the shoreface nourishment zone to the beach zone between -1 m and +3 m is extremely low (about 2% to 5% after 3 to 5 years). Given a typical shoreface nourishment volume of 400 m^3/m, the potential increase of the beach volume after 3 to 5 years is not more than about 10 to 15 m^3/m or a layer of sand with thickness of about 0.1 m to 0.15 m over a beach width of 100 m.

Rijkswaterstaat (1996) has evaluated nine beach nourishment projects (volumes between 50 and 100 $m^3/m/yr$; sand sizes between 0.15 and 0.3 mm) carried out along various coastal sites (tidal range of about 2 m) of The Netherlands in the period 1975-1994. Several characteristics were determined:
$K_3= V_N/V_E$= ratio of design nourishment volume and required volume to compensate erosion,
$K_4= V_{E,before}/V_{E,after}$= ratio of annual erosion volume in active zone before nourishment and after nourishment.
Ideally, the K_3-factor should be 1 or slightly larger. The K_3-factor was found to vary in the range of 0.7 to 2.5 and was >1 in about 50% of the projects.
The K_4-factor was found to vary in the range of 0.3 to 2 and was <1 in about 80% of the projects. In most cases the erosion volume increased considerably after nourishment, which was most probably related to the increase of beach slopes after nourishment (increased erosion of the beach). To compensate this effect, an overfill of about 20% to 50% is required. The grain size of the fill material (0.15-0.3 mm) was not found to have much influence for this size range. An opposite effect was observed at one location, where 0.3 mm sand was supplied on a beach consisting of 0.2 mm native material; the effectiveness of the fill was relatively low.
Five projects have been described in great detail; some results are given in **Table 3.1**. The barrier islands Ameland and Texel belonging to the West Frisian islands along the North Sea coast, are exposed to high energy waves plus tidal currents. The other locations are situated in less exposed conditions. At most locations the nourishment volumes were 20% to 50% (depending on conditions; overfill factor is largest near deep tidal channels) larger than the estimated erosion volumes before nourishment, anticipating for initial losses due to increased beach slopes (extra erosion immediately after nourishment). The nourishment volumes were sufficient to maintain the shoreline position for about 3 to 5 years at most locations. The nourishment volumes at the location N-Holland could even be reduced in the course of time, probably as a result of favourable effects of nourishments carried out in updrift sections.
Based on the results of **Table 3.1**, it can be concluded that beach nourishments have relatively low life times of 2 to 4 years along the Holland coast.

LOCATION	LENGTH (km)	ENVIRONMENT	V_E ($m^3/m/yr$)	V_N ($m^3/m/yr$)	LIFETIME (yr)
Ameland (NL) 1980-1994	10	central zone of barrier island, meso-tidal, 0.16-0.18 mm, moderate energy coast	25	30	4-5
Texel (NL) 1979-1994	13	northern part of barrier island, meso-tidal, 0.2 mm, moderate energy coast	50	70	2-4
N-Holland (NL) 1976-1994	15	northern part of straight coast, meso-tidal, 0.2-0.3 mm, moderate energy coast	30	20	2-3
Schouwen (NL) 1987-1994	6	head of island near inlet, meso-tidal, 0.22 mm, moderate energy coast	60	95	3-4
Walcheren (NL) 1984-1994	4	head of island near inlet, meso-tidal, 0.2-0.3 mm, moderate energy coast	30	40	2-3

V_E= erosion volume over 10-yr period before nourishment; V_N= nourishment volume

Table 3.1 *Beach nourishment characteristics in meso-tidal conditions, The Netherlands*

Leonard et al. (1990) evaluated a large number (155 projects) of beach replenishment projects in the U.S.A. In all, about 300 million m^3 of sand was placed along 700 km of shoreline (470 km along Atlantic coasts, 180 km along Gulf coasts and 50 km along Pacific coasts). Beach lifetime is defined as the amount of time between fill emplacement and the loss of at least 50% of the original fill volume. About 30% of the beach fills along the Pacific coasts had a lifetime greater than 5 years; this value was about 10% for the other coasts. The effects of the most important design parameters (length of fill, fill volume, grain size, presence of groynes, storm activity) were evaluated.

The results are:

- *fill length*: longer beach fills are assumed to experience greater lifetimes than shorter beach fills; the shorter fills along the Pacific coasts performed rather well; longer fills along the Atlantic coasts behaved better than the shorter fills; length was not important along the Gulf coasts;
- *fill volume per unit shoreline*: no effect of the fill volume was found along the Pacific and Gulf coasts; larger fills had longer lifetimes along the Atlantic coasts;
- *grain size*; no effect was found along all three coasts, which was most probably related to the relatively small range of grain sizes that has been used;
- *groynes*: the presence of groynes appears to increase the lifetime of nourished beaches along the Atlantic and Pacific coasts; the latter coasts benefit from natural groynes provided by rocky headlands;
- *storm activity*: the lifetime of the fills along the Atlantic and Pacific coasts is closely linked to the number of storms in the first year after the fill, as well as the time between the fill and the first storm event.

The apparent success of some beach fills can also be contributed to sociopolitical factors. Along the Pacific coasts a maintenance type of approach is applied; beaches are nourished on a pre-determined schedule, whether it is necessary or not. This approach has proven to be successful. Along the Atlantic and Gulf coasts a crisis-type of approach is followed. Beaches along the Pacific coasts and Gulf coasts benefit from bypassing projects (pumping of sand to adjacent beaches) across inlets and harbour entrances.

4 Beach fill losses

4.1 Beach fill losses due to longshore transport gradients

4.1.1 Erosion of trapezoidal beach fill

In reality a beach fill is placed as triangular layer on top of the original beach. The fill volume per unit length of beach is of the order of 100 to 300 m^3/m for exposed beaches. Usually, the beach fill layer has a thickness of the order of 0.5 m near the dune front increasing to about 3 m at the -1 m depth line and then decreasing to about 0 m at the -3 m depth line, as shown in **Figure 4.1**. Nourished beaches need regular maintenance (replenishment) of sand, otherwise the beach nourishment will gradually disappear (in about 3 to 10 years, depending on wave intensity) due to longshore and cross-shore transport gradients.
Using a 1D coastline model (LONGMOR-model), the erosion of the beach nourishment/fill due to longshore transport gradients can be computed. The beach fill is schematized into a rectangular (box-type) cross-section with the same area as the beach fill layer, see Figure 4.1. This results in a schematized box with width of 30 to 50 m and a heigth of about 6 m seaward of the original coastline. In plan view a beach fill has a trapezoidal shape (see Figures 4.2 and 4.4).

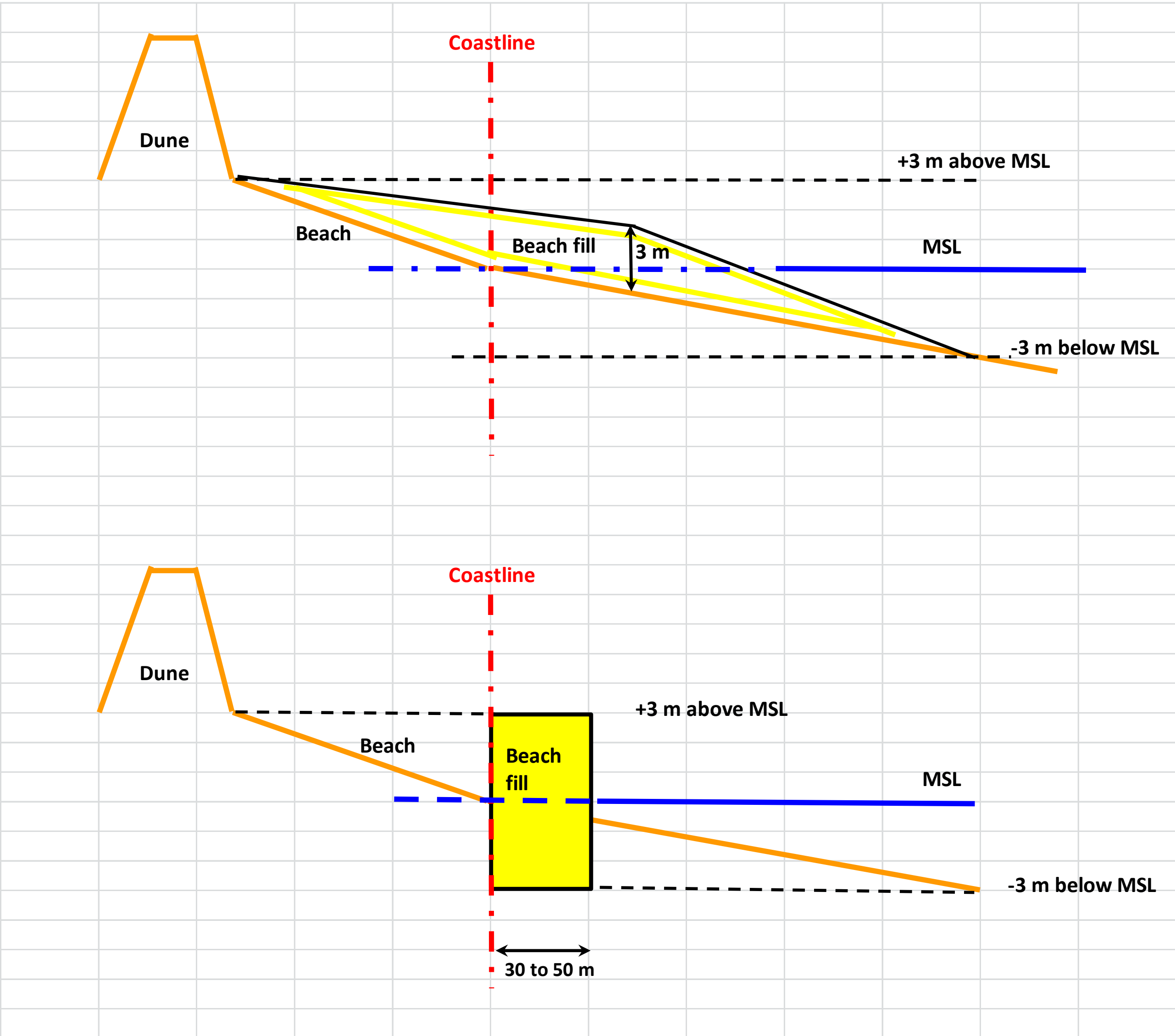

Figure 4.1 *Schematization of triangular beach fill layer (upper) into a rectangular beach fill (lower) for 1D coastline modelling*

The 1D **LONGMOR model** (Van Rijn, 2006, 2012) has been used to compute the shoreline changes for a trapezoidal beach fill (0.2 mm sand) with a longshore length of 2500 m and a cross-shore length of 50 m. The longshore transition sections on both ends have a length of 350 m. The total beach fill volume is 850,000 m^3. The active layer thickness of the fill and coastal profile is assumed to be 6 m. The beach sediment is sand with d_{50}= 0.2 mm and d_{90}= 0.3 mm. The local beach slope is assumed to be $\tan\beta$=0.01 (slope from waterline to 8 m depth contour). The tidal longshore velocities in the surf zone are assumed to be 0.3 m/s during flood and -0.1 m/s during ebb. The local wave breaking coefficient is assumed to be γ_{br}=0.6. The longshore grid size is 50 m and the time step is 0.05 days. The shoreline changes over a period of 6 winter months have been determined using a symmetric wave climate. **Table 4.1** shows the (symmetric) wave climate over one month. The wave climate of each winter month is assumed to be the same. The offshore wave angle has been varied: WC1=angle of 30^o and -30^o degrees, WC2=angle of 0^o degrees=waves normal to shore). The longshore transport rates have been computed by using the methods of CERC, KAMPHUIS and VAN RIJN (Van Rijn 2006, 2012). As the wave climate (WC1) is symmetric with respect to the shore normal, the net longshore transport is approximately zero.

Time **(days)**	**Significant wave height** $H_{s,o}$ **(m)**	**Peak wave period** T_p **(s)**	**WC1** **Offshore wave angle to shore normal of original beach** θ_o **(degrees)**	**WC2** **Offshore wave angle to shore normal of original beach** θ_o **(degrees)**
0	1	5	30	0
12	1	5	30	0
13	2	6	30	0
14	2	6	30	0
14.5	3	7	30	0
15	4	8	30	0
15	4	8	-30	0
15.5	3	7	-30	0
16	2	6	-30	0
17	2	6	-30	0
18	1	5	-30	0
30	1	5	-30	0

Table 4.1 *Wave climates of winter month (waves and longshore currents coming from left of shore normal are assumed to be positive for observer at beach facing the sea)*

Figure 4.2 shows the computed shoreline changes after 6 winter months (WC1; wave angle of 30^o and -30^o). The shoreline recession based on the CERC method varies from about 5 m in the middle of the fill to about 20 m at the corner points. Overall about 20% of the initial fill volume (based on CERC-method) is lost to adjacent beach sections (sedimentation over a length of about 2000 m on each side). The loss of beach fill after one winter season is much smaller (approximately 5% to 10%) for the methods of KAMPHUIS and VAN RIJN or a life times of 20 years based on KAMPHUIS and 10 years based on VAN RIJN.

Figure 4.3 shows the effect of different offshore wave angles (WC1 and WC2 , see **Table 4.1**) based on the CERC method. Waves normal to the shore (WC2) result in larger gradients of the longshore transport rate at both ends of the fill and hence in larger erosion of the beach fill.
The effect of the sediment size was studied by using the method of KAMPHUIS with sand of d_{50}=0.1 mm resulting in a 15%-increase of the longshore transport rates. The effect on the shoreline changes is relatively small (not shown).

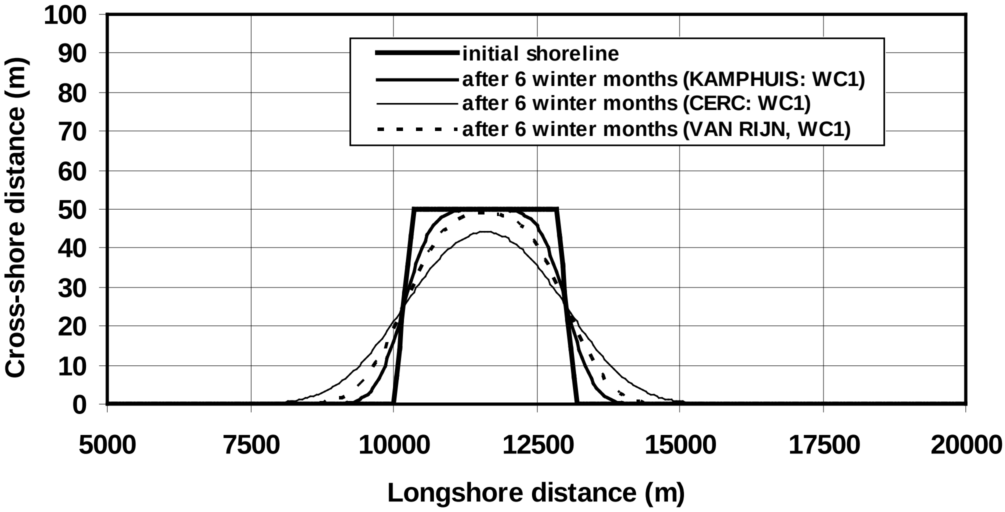

Figure 4.2 *Computed shoreline changes of beach fill (wave climate WC1)*

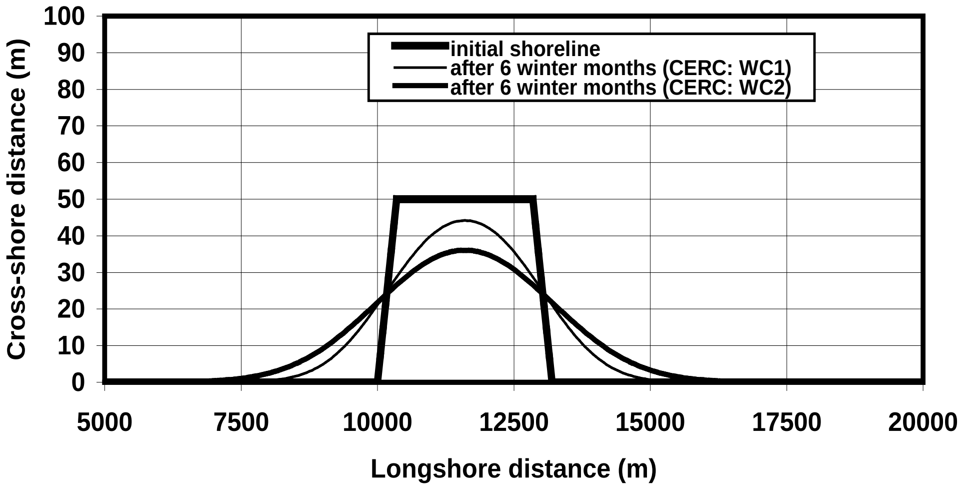

Figure 4.3 *Computed shoreline changes of beach fill (wave climate WC1 and WC2)*

4.1.2 Initial erosion loss of various trapezoidal beach fill designs

The erosion of four beach fill designs (Case A, B, C and D) have been studied using the LONGMOR-model (file: beachs1.inp; Δx=25 m and Δt=0.005 day). The dimensions of the trapezoidal beach fills are given in **Table 4.2**. The plan views are shown in **Figure 4.4**. The transition sections on both ends of the beach fill have a length equal to 5 times the cross-shore width of the beach fill. The annual wave climate in the undisturbed situation without beach fill was varied to obtain a net annual longshore transport of approximately 100,000 m^3/year (typical for sheltered coasts); 200,000 m^3/year and 400,000 m^3/year (typical for very exposed coasts). Hence, the erosion of each beach fill was computed for three conditions (three values of the net annual longshore transport rate in the undisturbed situation). The net longshore sediment drift is from left to right (west to east).

Figure 4.5 shows the net annual longshore transport along the beach fill of CASE C during the first year (initial situation) The net annual longshore transport in the undisturbed situation far away (x=0 to 3000 m and x= 9000 to 12000 m) from the beach fill is approximately 200,000 m^3/year.

Parameter	CASE A	CASE B	CASE C	CASE D
Cross-shore extension of coastline (waterline)	15 m	30 m	50 m	100 m
Alongshore length of the central section	2000 m	2000 m	2000 m	2000 m
Alongshore length of both transition sections	2x75 m	2x150 m	2x250 m	2x500 m
Total alongshore length at beach	2150 m	2300 m	2500 m	3000 m
Layer thickness	6 m	6 m	6 m	6 m
Beach fill volume (V_s)	2075x15x6= 187,000 m^3	2150x30x6= 390,000 m^3	2250x50x6= 675,000 m^3	2500x100x6= 1,500,000 m^3
Beach fill volume per unit length (v_s)	187000/2075= 90 m^3/m	390000/2150= 180 m^3/m	675000/2250= 300 m^3/m	1500000/2500= 600 m^3/m

Table 4.2 *Dimensions of beach fills*

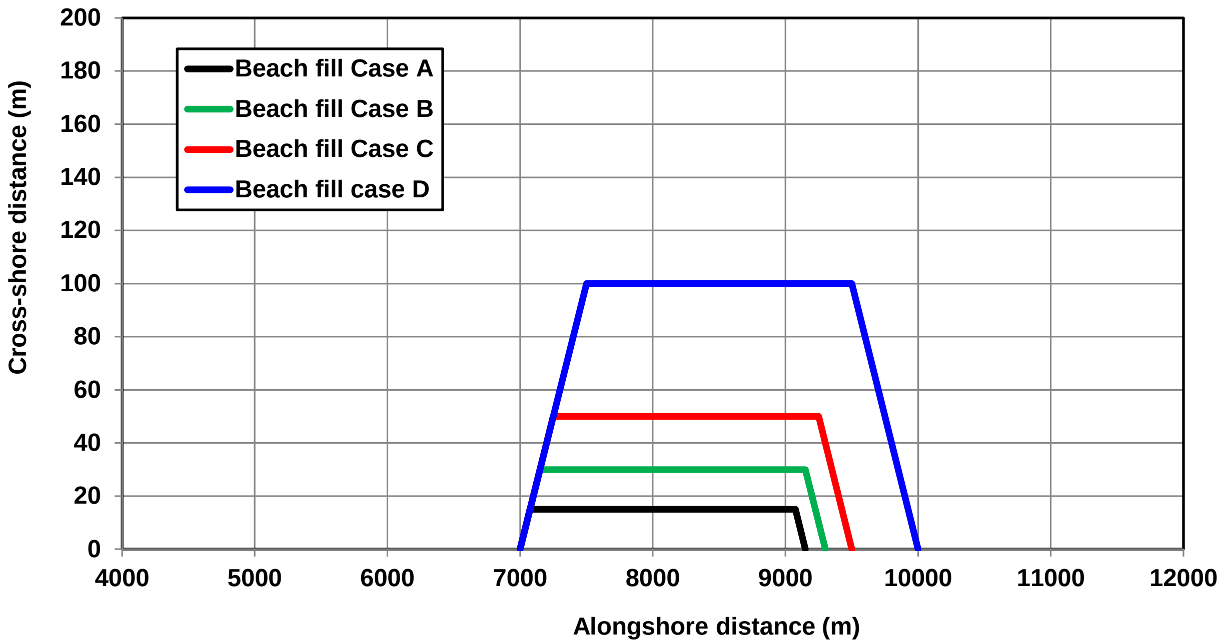

Figure 4.4 *Plan view of beach fills*

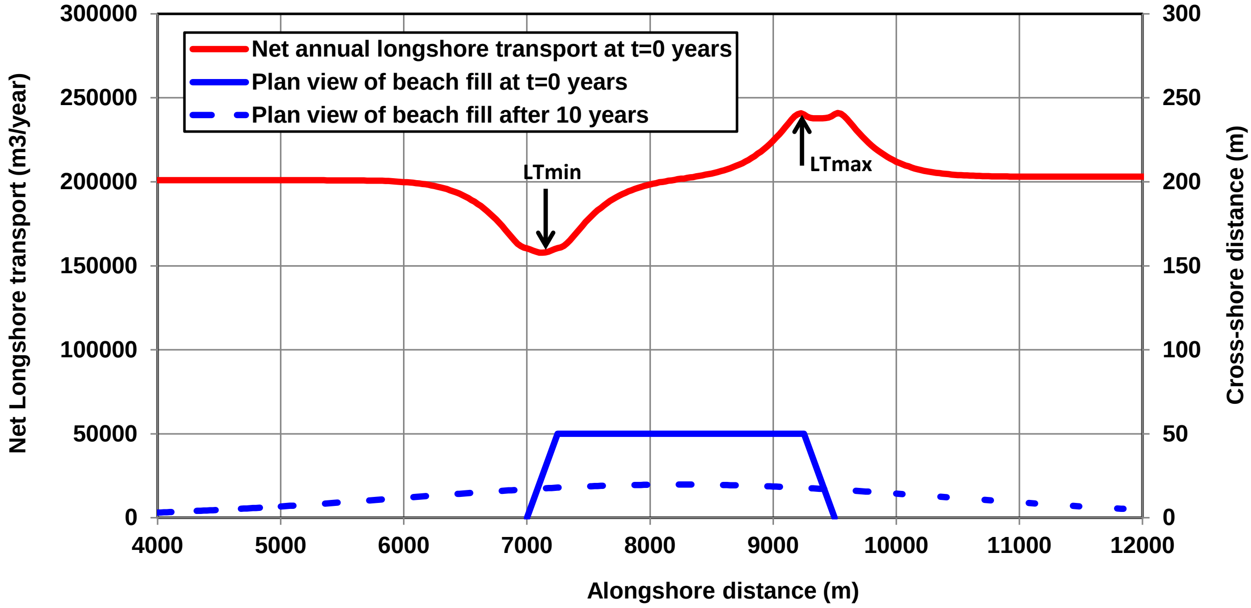

Figure 4.5 *Beach fill (CASE C) with net longshore transport of 200,000 m^3/year in undisturbed situation*

The erosion volume is largest during the initial situation (first year) and can be computed as (see **Figure 4.5**): V_e= $LT_{maximum}$-$LT_{minimum}$ = 240,000-160,000= 80,000 m^3/year.
The ratio of the initial erosion volume and beach fill volume is: r_e= V_e/V_s = 80000/675000 = 0.12. Hence, about 12% of the beach fill volume is eroded in the first year.
Figure 4.5 also shows the beach fill after 10 years (based on an effective layer thickness of 6 m). About 65% of the initial fill volume has been eroded after 10 years; about 12% during the first year.
Figures 4.6 and **4.7** show the V_e and r_e-values for all computations. **Figure 4.6** can be used to get an estimate of the initial erosion losses of a beach fill due to longshore transport gradients for three values of the net longshore transport rate. The data of Figure 4.7 show a decreasing trend for increasing cross-shore extension (between 15 and 100 m), which means a longer lifetime for a larger cross-shore extension.
Based on **Figure 4.6**, the annual erosion per unit length for a beach fill of 2000 m long and 50 m wide is in the range of 50,000/2000=25 m^3/m/year to 150,000/2000=75 m^3/m/year.

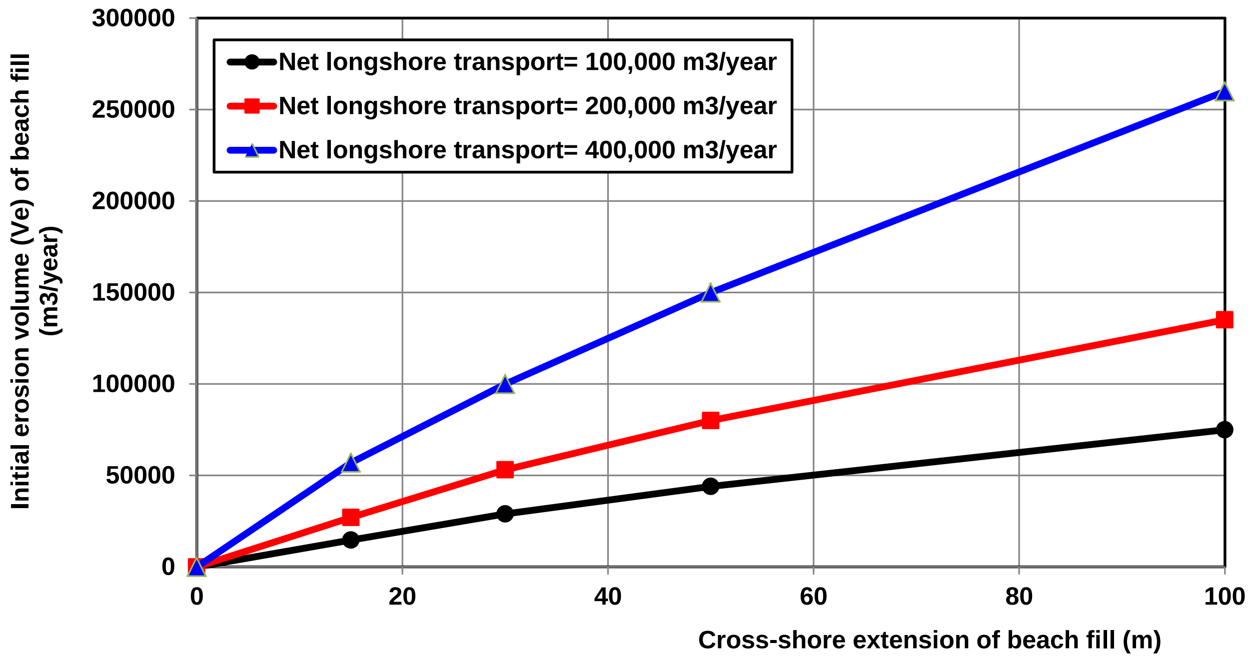

Figure 4.6 *Initial erosion volume due to longshore transport gradients as function of cross-shore coastal extension of the beach fill*

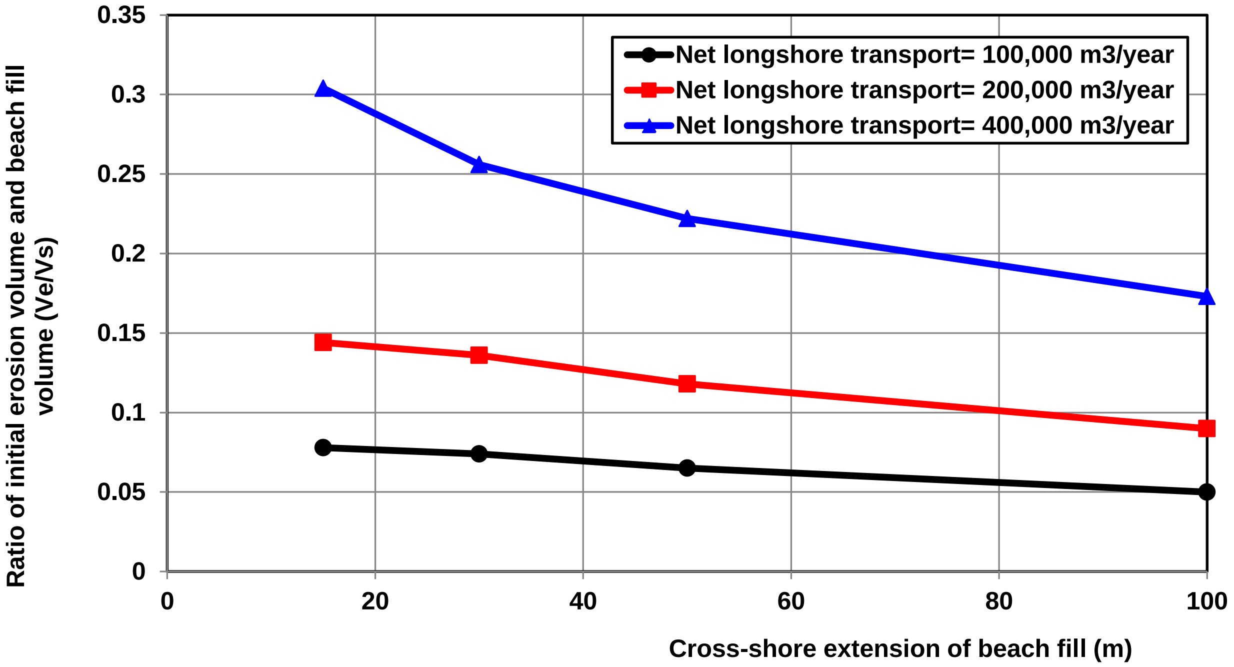

Figure 4.7 *Ratio of initial erosion volume (due to longshore transport gradients) and beach fill volume as function of cross-shore coastal extension of the beach fill*

4.1.3 Lifetime of trapezoidal beach fill designs

To determine the lifetime of trapezoidal beach fill designs, the coastline changes over a period of 20 years have been computed for each beach fill design (Case A, B, C and D) using the 1D LONGMOR-model.

Figure 4.8 shows the beach fill evolution over time for a beach fill of 30 wide in cross-shore direction (Case B); the net longshore transport rate is 400,000 m^3/year (from left to right or west tot east). Approximately 80% of the beach fill is eroded after 20 years. As the net longshore transport is directed to the right, the deposition of sand on the right side is larger than on the left side. Hence, the adjacent coastal sections also benefit from the beach fill.

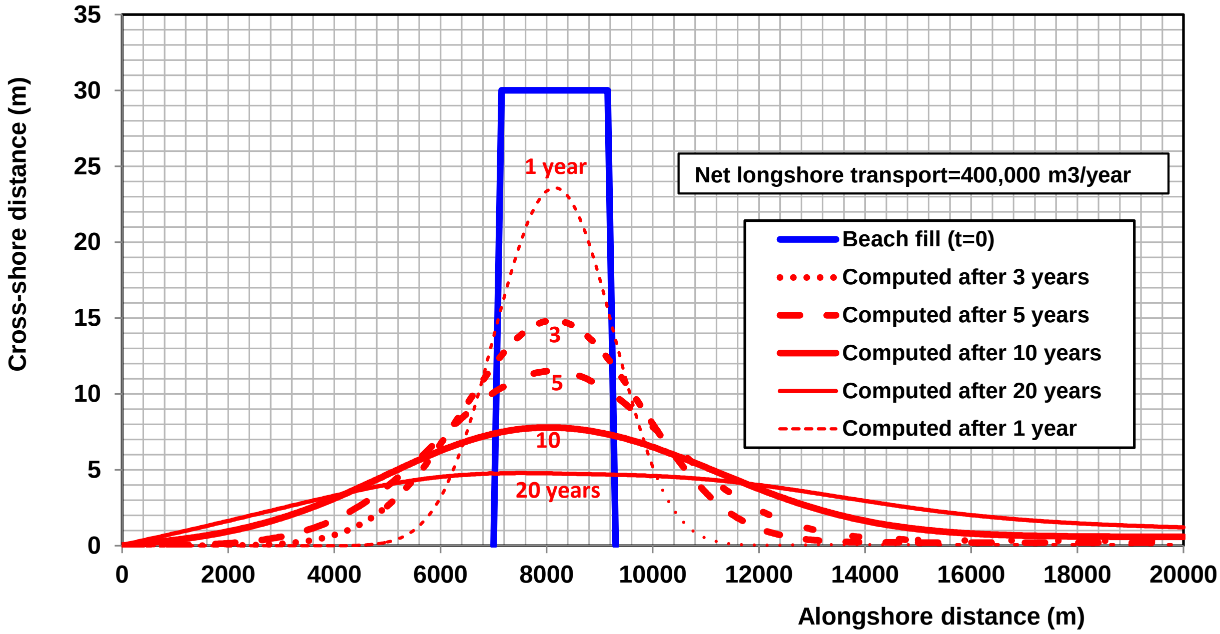

Figure 4.8 *Beach fill evolution as function of time; Case B and net longshore transport of 400,000 m^3/year*

Figure 4.9 shows the ratio of the erosion volume and initial beach fill volume as function of time for all cases with net longshore transport rates in the range of 100,000 to 400,000 m^3/year. Most of the erosion occurs in the first 5 to 10 years resulting in a smooth coastline after thad period, see also Figure 4.8. The erosion along a smooth coastline during later years proceeds relatively slow.

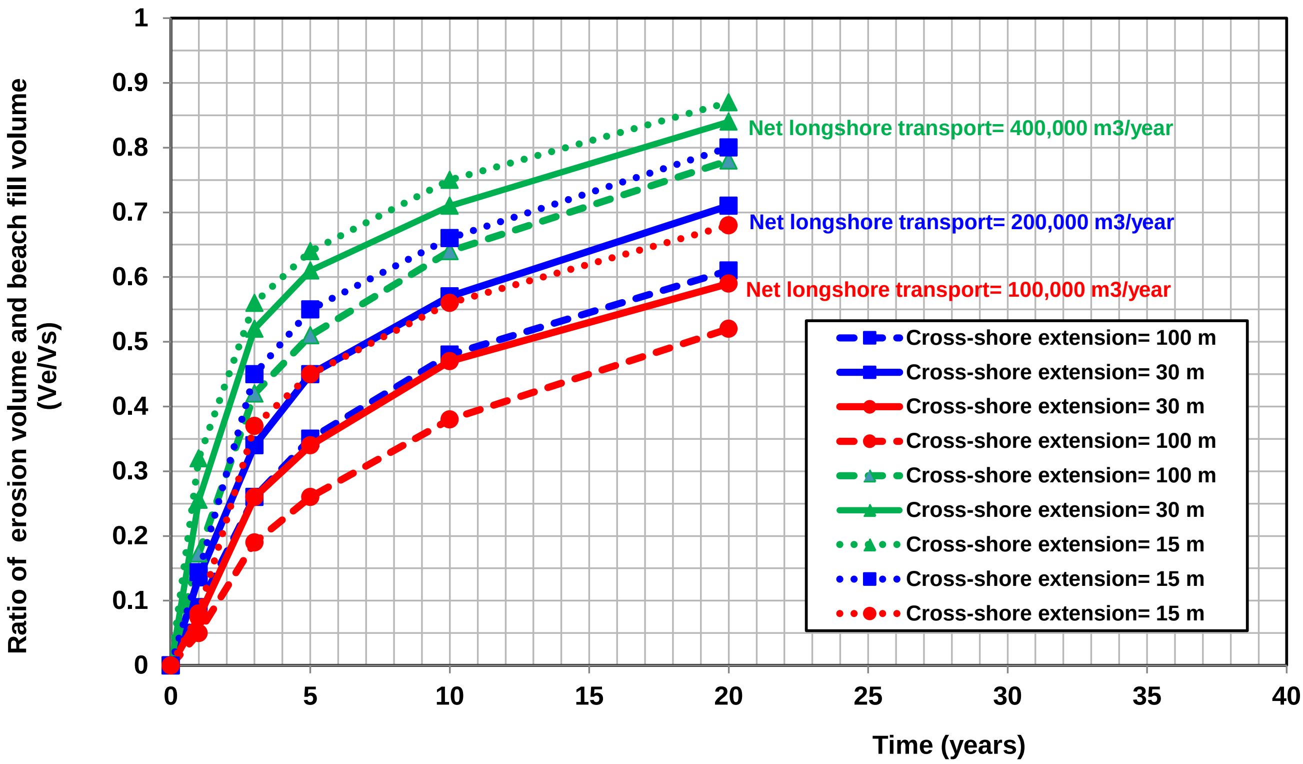

Figure 4.9 *Ratio of erosion volume and initial beach fill volume as function of time for all cases*

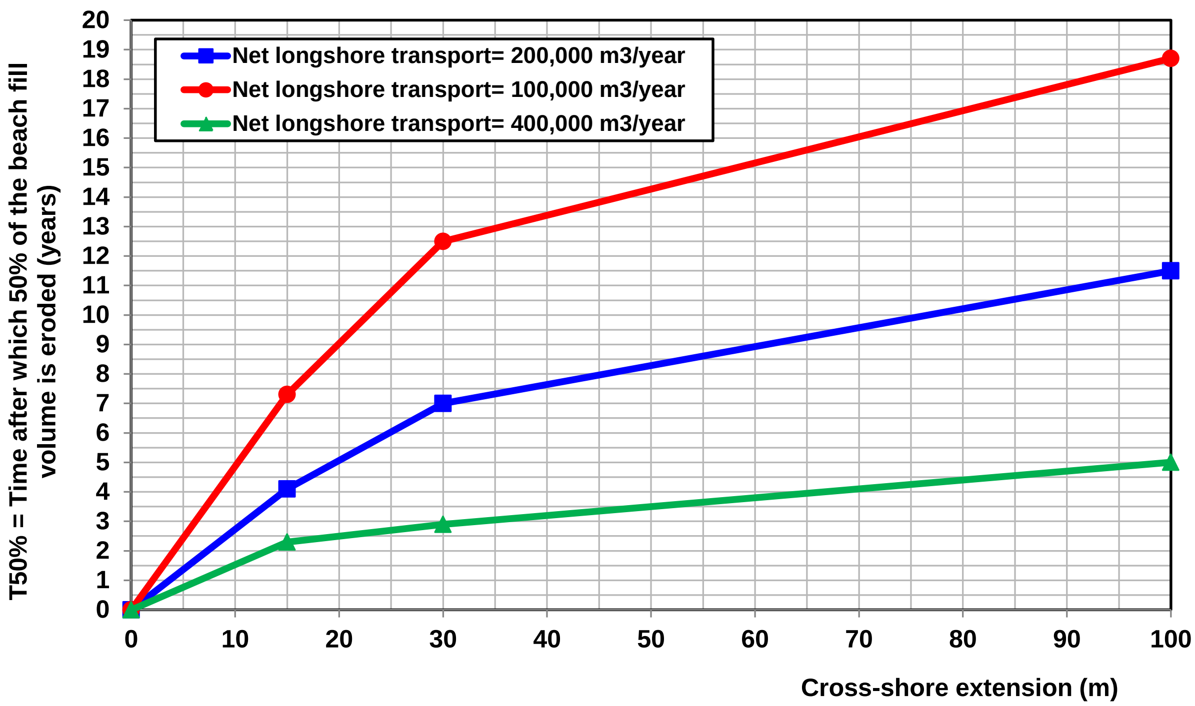

Figure 4.10 *Lifetime ($T_{50\%}$) as function of beach fill extension and net longshore transport rate*

Figure 4.10 shows the time period ($T_{50\%}$) after which 50% of the original beach fill volume is eroded as function of the cross-shore extension of the beach fill and the net longshore transport rate. The $T_{50\%}$-values vary between 2 years for a very small beach fill of 15 m wide and a large net transport rate of 400,000 m^3/year and 20 years for a large beach fill of 100 m wide and a net longshore transporty rate of 100,000 m^3/year.
The $T_{75\%}$ -values is about 2 to 3 times larger than the T50%-values, based on Figure 4.9.
Most beach fills along exposed coasts with net longshore transport rates in the range of 100,000 to 200,000 m^3/year have a cross-shore extension of the order of 30 to 50 m (Cases B or C), resulting in a lifetime ($T_{50\%}$) in the range of 3 to 8 years. In practice, the lifetime of these types of beach fills along the Dutch coast is in the range 2 to 4 years. So, the practical lifetime is much smaller than the computed lifetime, which is most likely caused by the presence of cross-shore transport processes in nature.
It is emphasized that the life time of **Figure 4.10** is based on the assumption that erosion is only caused by longshore transport gradients as represented in the 1D LONGMOR-model. In this latter modelling approach, the beach fill is assumed to have a rectangular cross-section with a height of 6 m (see **Table 4.2** and **Figure 4.1**) in front of the original coastline. Erosion due to cross-shore transport gradients is neglected.
In reality, a beach fill is placed as triangular layer on top of the original beach, **see Figure 4.1**. The cross-shore shape of the beach fill does not represent equilibrium conditions and hence the profile shape near the waterline will be modified (smoothed) by cross-shore transport processes. These latter effects cannot be taken into acount by the LONGMOR-model. To assess the cross-shore effects, the CROSMOR-model has been used (see Section 4.2).

4.1.4 Terminal groins to reduce erosion due to longshore transport gradients

It may be attractive to protect a large beach fill by terminal groins on both ends of the fill location.
Figure 4.11 shows a beach fill of 50 m wide and 2000 m long protected by terminal groins; at t=0 and after 5 years. The net longshore transport is set to 100,000 m^3/year from west to east (left to right). It is assumed that about 50% of the longshore transport can pass around the seaward end of both groins. Using terminal groins, the beach fill will act as a large-scale groin by partly blocking the longshore transport. Accretion occurs on the west side of groin A and erosion occurs on the other side of groin A. A similar pattern occurs on both sides of groin B. The beach between the groins will get an orientation normal to the main wave direction. The beach fill between the groins should be regularly replenished (every 5 to 10 years). Beach fill may also be required on the downdrift side of groin B to compensate local beach recession.

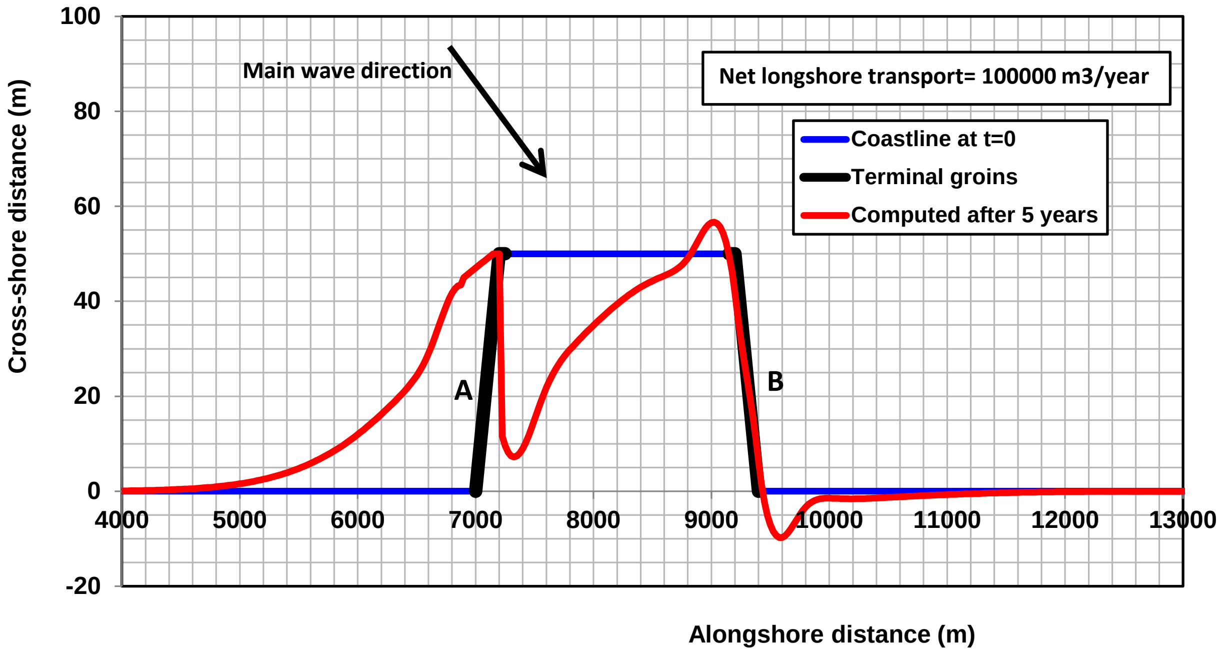

Figure 4.11 *Beach fill protected by terminal groins*

4.2 Beach fill losses due to cross-shore transport gradients

4.2.1 Laboratory experimental results

A beach fill generally is placed as a layer of sand on top of the existing beach between +3 m and -3 m (with respect to Mean Sea Level (MSL)) resulting in a plane sloping beach, see **Figure 4.1**. The (lower) beach below the high tide line will be transformed into a more natural profile with nearshore bars due to cross-shore transport processes, particularly during stormy conditions.

The erosional behaviour of plane sloping beaches due to cross-shore transport gradients has been studied extensively by performing small-scale and large-scale tests in wave tanks/flumes (Deltares, Delft, 2008).

Figure 4.12 shows beach profiles for an initial slope of 1 to 10, 1 to 20 of the Delft tests and an earlier Delft test with 1 to 40. The results refer to small-scale tests with $H_{s,o}$ = 0.18 m and sand of 0.13 mm (Deltares, 2008 and Bosboom et al., 1999). The small-scale test results have been upscaled to prototype conditions with sediment of 0.27 mm and waves of about 1 m at the toe of the beach (length scale= depth scale= 5.5; sediment scale = morphological time scale = 2).

Figure 4.13 shows the beach erosion volumes as a function of time. The upscaled results represent prototype erosion by fair weather waves of about 1 m at the toe of the beach.
The steepest initial slope of 1 to 10 yields an erosion volume after 1 day of about 12 m^3/m.
The beach erosion is of the order of 6 to 9 m^3/m/day for milder slopes between 1 to 20 and 1 to 40.
These results suggest that the erosion of beachfills can be substantially reduced by using relatively gentle slopes at the the lower beach (not steeper than 1 to 20).
Beach erosion of about 5 m^3/m per day by fair weather waves would mean that a beach fill of about 200 m^3/m can be removed in a few winter months.

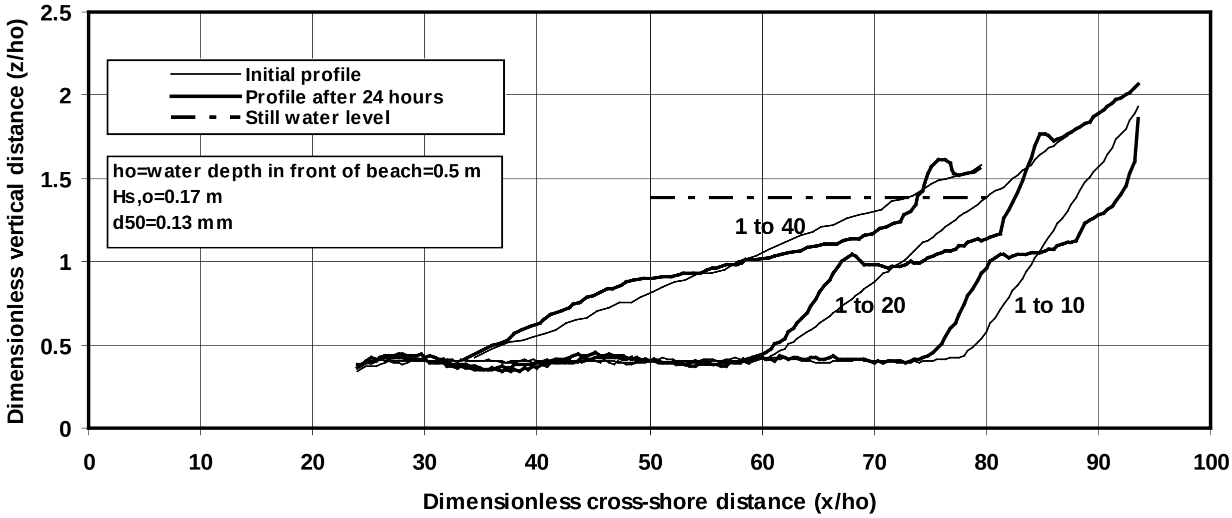

Figure 4.12 *Beach profile development due to cross-shore processes for intial slopes of 1 to 10, 1 to 20 and 1 to 40 (laboratory tests).*

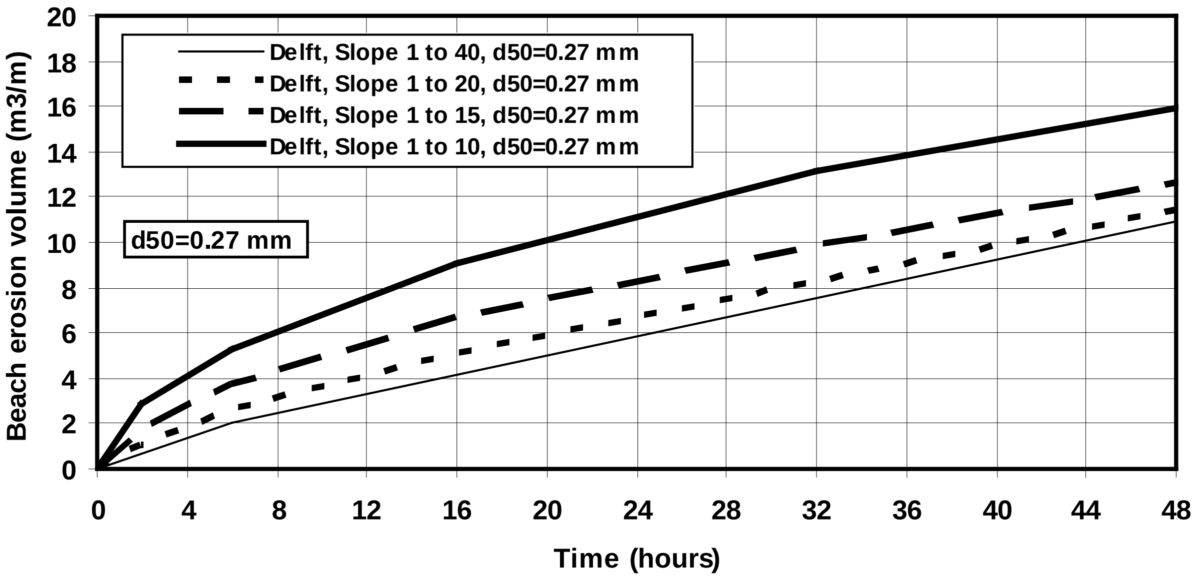

Figure 4.13 *Beach erosion volumes due to cross-shore processes for plane sloping beaches in nature with daily waves of about 1 m at toe of beach; slopes between 1 to 10 and 1 to 40, d_{50} = 0.27 mm*

Dette et al. 2002 studied beach erosion and profile shape due to cross-shore processes by performing large-scale tests in wave tanks/flumes). The experimental results show the following basic phenomena:

- an initial lower beach slope (between -1 m and +1 m) of 1 to 10/20 and consisting of 0.2 to 0.3 mm sand results in excessive erosion of the lower beach zone; generally, an underwater terrace is generated with a slope of 1 to 30/40 in the underwater zone at the lower end of the beach; the total erosion of the lower beach and the underwater zone may be as large as 25 m^3/m/day for an initial lower beach slope of 1 to 10/20 and an offshore wave height of 1.6 m;
- an initial lower beach slope of 1 to 40 (between -1 m and +1 m) shows relatively small erosion values of about 1 m^3/m/day for an offshore wave height of about 1 m and even beach deposition for an offshore wave height of 1.4 m;
- swell over a steep beach of coarse sand of 0.4 mm produces a berm type profile with substantial deposition on the beach and severe erosion at the lower end of the underwater bed slope; irregular waves in combination with a tidal water surface variation produce berms at the low and high water marks.

These results show that a beach profile of fine sand (0.2 to 0.3 mm) with an initial slope (between 1 to 10 and 1 to 40) landward of the -1 m depth contour is not stable and will be transformed into a profile with an underwater terrace at the lower beach end. Sand will be eroded at the upper beach and deposited in the underwater zone around the -1 m depth contour.
Beach erosion rates during fair weather conditions are of the order of 1 m^3/m/day for relatively smooth profiles with underwater slopes (lower beach zone) of 1 to 40.
Beach erosion rates during fair weather conditions increase to the order of 10 m^3/m/day for steep underwater slopes (lower beach zone) of 1 to 10.

Given these findings, it may be attractive to design a beach fill profile with an underwater terrace at the low tide mark. This terrace will better protect the upper beachface against wave-induced erosion. The crest level of the terrace or berm should be maintained as much as possible at a level of -1 m (to MSL). **Figure 4.14** shows an example of a major beach fill (about 250 m^3/m) with relatively gentle slopes and a flat underwater terrace at the -1 m. The beach slope of the lower beach between -1 m and +1 m is 1 to 40.

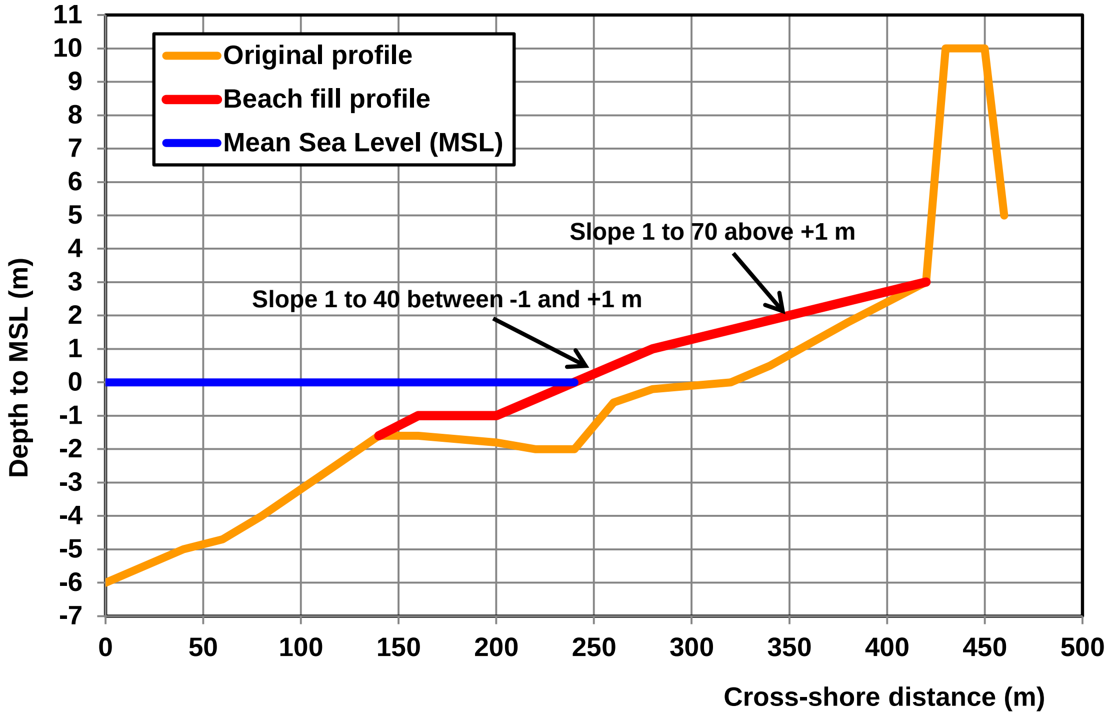

Figure 4.14 *Example of major beach fill (250 m3/m) with gentle lower beach slope*

4.2.2 Numerical CROSMOR-model results

To determine the erosion losses of beach fills due to cross-shore transport processes, the 2DV CROSMOR-profile model has been used for a schematized case (see **Figure 4.15**) along the Dutch coast (North Sea wave climate). The depth is given with respect to the mean sea level (MSL). The initial beach fill volume is about 230 m^3/m.

The slope of the upper beach is set to 1 to 150; the initial slope of the lower beach is 1 to 20.

The mean waterline shows a shift of about 75 m in seaward direction.

The North Sea wave climate along the Dutch coast during the winter season is given in **Table 4.3** (wave incidence angles are set to 0).

The tidal range is set to 1 m. The tidal cycle (ebb plus flood) has been represented by six blocks of 2 hours; each with a constant water level and velocity based on the tidal curve (input data). So, the tide is just causing a change of the sea level over time. An additional storm set-up of 0.5 m has been used during offshore waves of $H_{s,o}$ = 3 m.

Three types of beach material have been used: d_{50}= 0.2, 0.3 and 0.4 mm. The offshore boundary conditions are applied at a depth of 15 m to MSL.

Figure 4.16 shows computed results for the wave height of H_s= 3 m over 10 days and three types of beach materials (0.2, 0.3 and 0.4 mm). Erosion mainly occurs in the beach fill section above the water line (0 to +1.5 m). The eroded sand is deposited at the toe of the beach fill between the 0 and -1.5 m depth contours. The deposition layer in front of the beach nourishment slows down the erosion in time by reducing the wave height.

Time (days)	Significant wave height $H_{s,o}$ (m)	Peak wave period T_p (s)	Offshore wave angle to shore normal θ_o (degrees)
40	0	0	0
100	0.6	5	0
30	1.5	7	0
10	3	8	0

Table 4.3 *Wave climate of winter season North Sea (180 days; October to March)*

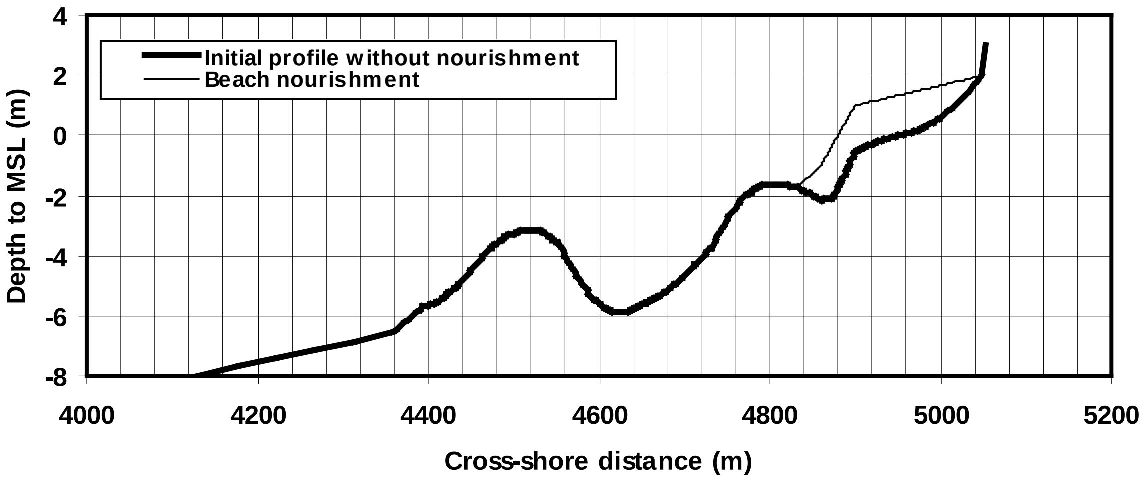

Figure 4.15 *Schematized beach nourishment profile along Dutch coast (Egmond profile)*

The cumulative erosion volumes (in m^3/m/day) for the three wave classes (0.6, 1.5 and 3 m) are shown in **Figures 4.17, 4.18** and **4.19**. Runs without tide show similar values (5% to 10% smaller). The tidal range of 1 m has almost no effect on the overall cumulative erosion volumes, but the cross-shore profile is slightly different in the upper beach zone. The tide merely causes a redistribution of the upper cross-shore profile. The initial erosion volumes in the upper beach zone (after 1 day) for waves < 1.5 m are about 6 m^3/m for sand of 0.4 mm to 10 m^3/m for sand of 0.2 mm. These values are in line with the initial erosion volumes of the upscaled laboratory data (**Figure** 4.13) yielding values of about 6 to 8 m^3/m after 1 day for sand of 0.27 mm (slopes between 1 to 15 and 1 to 20).

Monthly-average erosion volumes (cumulative erosion divided by total duration) are in the range of 1 m^3/m/day for sand of 0.4 mm to 2.5 m^3/m/day for sand of 0.2 mm and waves with H_s<1.5 m (based on **Figure 4.18**).

For waves of H_s= 3 m these values increase to 4 m^3/m/day to 10 m^3/m/day (**Figure 4.19**).

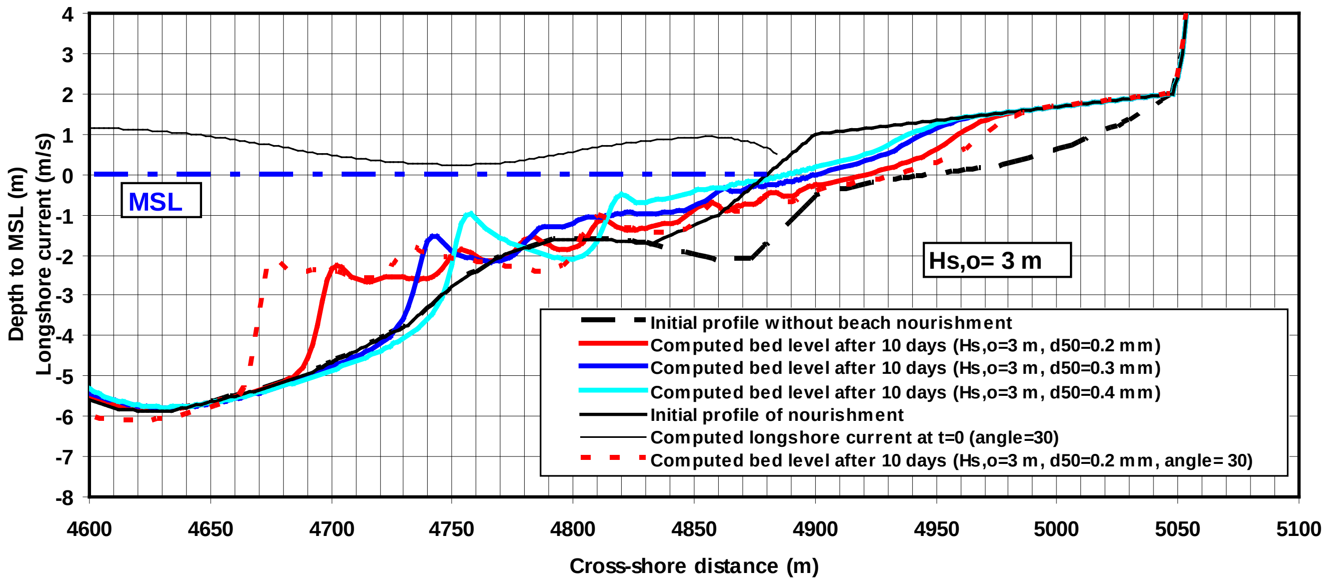

Figure 4.16 *Computed erosion of beach nourishment; $H_{s,o}$= 3 m; sediment d_{50}= 0.2, 0.3 and 0.4 mm*

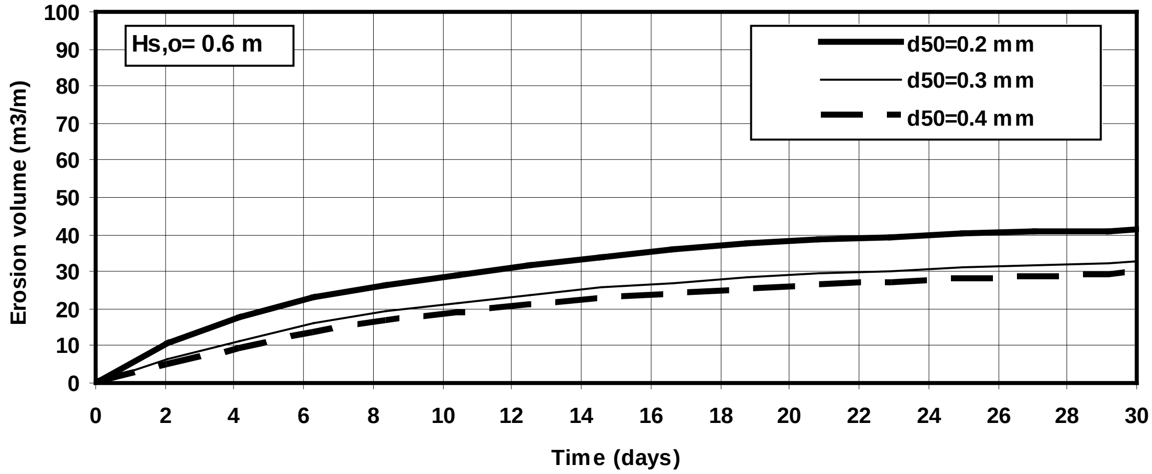

Figure 4.17 *Cumulative computed erosion of beach nourishments due to cross-shore transport gradients; $H_{s,o}$= 0.6 m; d_{50}= 0.2, 0.3 and 0.4 mm*

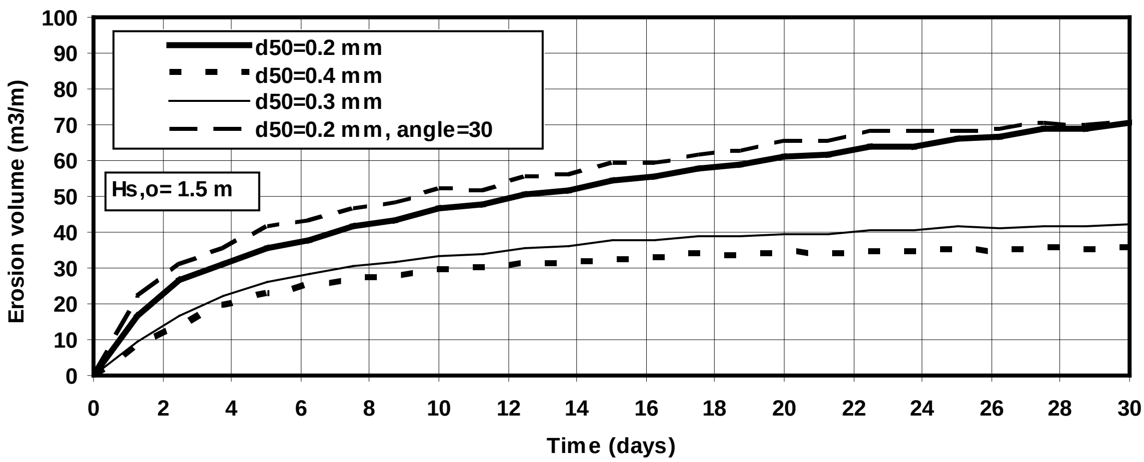

Figure 4.18 *Cumulative computed erosion of beach nourishments due to cross-shore transport gradients; $H_{s,o}$= 1.5 m; d_{50}= 0.2, 0.3 and 0.4 mm*

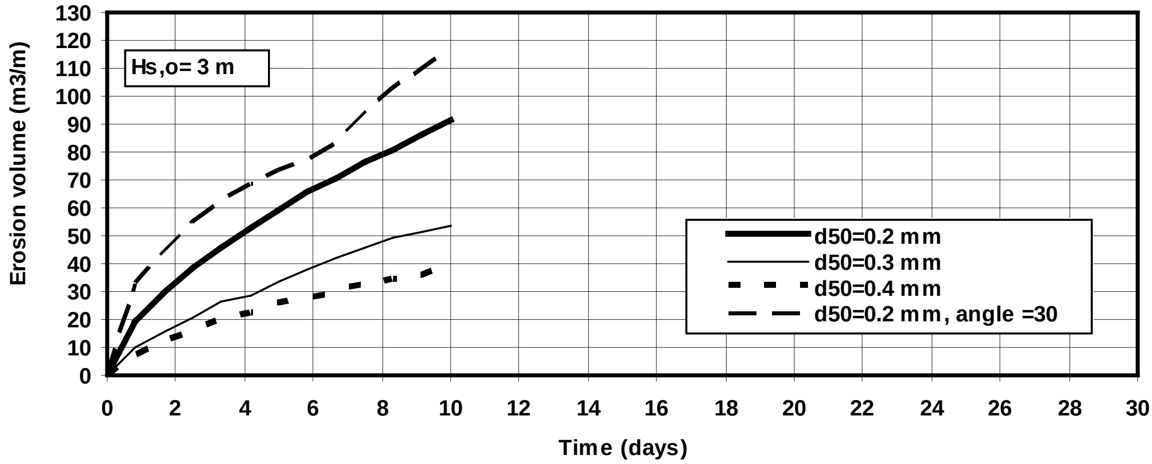

Figure 4.19 *Cumulative computed erosion of beach nourishments due to cross-shore transport gradients; $H_{s,o}$= 3 m; d_{50}= 0.2, 0.3 and 0.4 mm*

The computed bed profile of a run with $H_{s,o}$= 3 m and an offshore wave angle of 30^o has also been plotted in **Figure 4.16**, showing an increase of the total erosion volume by about 20%. The cumulative erosion is plotted in **Figure 4.19**. The wave-induced longshore current at initial time is also shown in **Figure 4.16**. The maximum longshore current is of the order of 1 m/s just in front of the beach nourishment, which enhances the transport capacity and hence the erosion power of the system. The eroded sediments are deposited at the seaward edge of the inner breaker bar. This wave angle effect is a typical storm feature, as it is hardly noticeable for an offshore wave height of 1.5 m (see **Figure 4.18**).

Figure 4.20 shows the computed bed level after 1 winter period with a sequence of waves, as follows: 100 days with $H_{s,o}$ = 1 m, 30 days with $H_{s,o}$= 1.5 m and 10 days with $H_{s,o}$= 3 m for three sediment diameters (d_{50} = 0.2, 0.3 and 0.4 mm).

As can be seen, the beach erosion after 140 days with waves is approximately 150 m^3/m for d_{50} = 0.2 mm; 100 m^3/m for d_{50} = 0.3 mm and 90 m^3/m for d_{50}= 0.4 mm.

The beach nourishment volume of 0.2 mm sand is almost completely removed after 1 winter season. At the landward end of the beach a typical scarp-type erosion front is present, which is often observed in nature. The eroded beach sediment is deposited as a new breaker bar beyond the -4 m depth line.

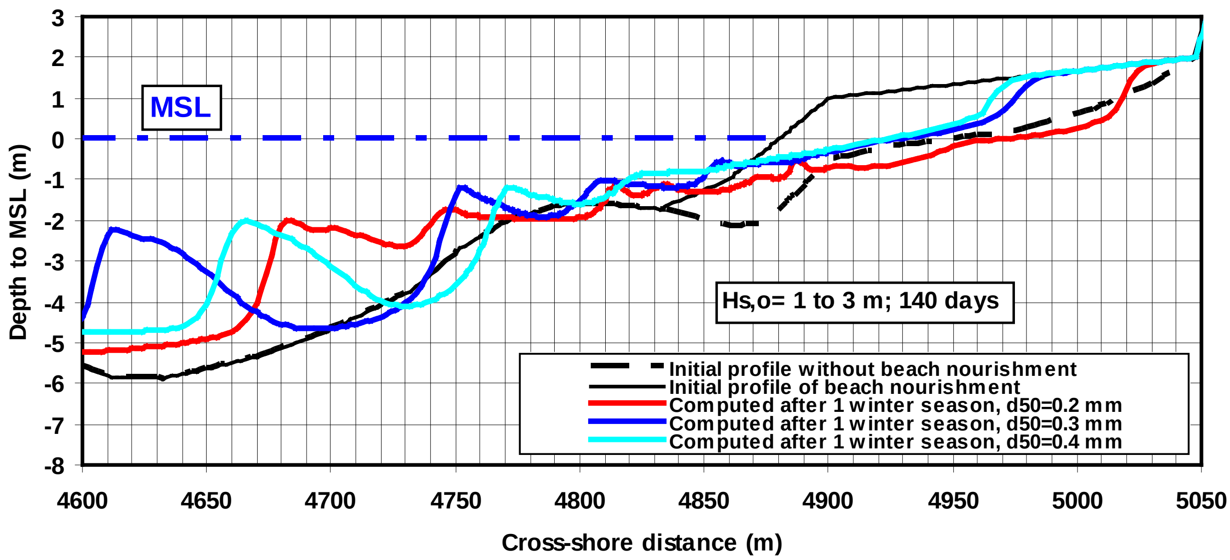

Figure 4.20 *Computed erosion of beach nourishment after 1 winter season with waves between 1 and 3 m; d_{50}= 0.2, 0.3 and 0.4 mm*

Using the data of **Figures 4.17, 4.18** and **4.19** and adding the results of each wave class (H_s = 0.6, 1.5 and 3 m) linearly, yields beach erosion volumes of 210, 130 and 120 m^3/m/year for d_{50} = 0.2, 0.3 and 0.4 mm. This approach leads to an over-estimation of about 30% compared with the earlier results based on **Figure 4.20**, as the time history effect of the beach profile development is not taken into account. This approach can be used to get a first rough estimate of the beachfill erosion during a winter season.

Figure 4.21 shows the initial bottom (green line) and the computed bed levels after 1, 2 and 5 years for a another beach with a relatively large nourishment volume along the Holland coast (d_{50} = 0.25 mm). The applied North Sea wave climate is a yearly-averaged wave climate based on observations in the period 1980-1988 and has 8 wave height classes ($H_{significant}$) between 1.5 and 3.2 m. A storm with a deep-water wave height of $H_{s,o}$= 6 m and a duration of 12 hours is added. This is an extreme wave height with a recurrence period of 100 years, which is applied 5 times over the computation period of 5 years. Two storm surge levels (including tide levels) of +3 and +4 m NAP have been used (NAP is about equal to MSL). The wave asymmetry of the near-bed velocities is computed by the method of Isobe-Horikawa. The net streaming near the bed is computed by the method of Longuet-Higgins. The vertical tide lies between +1 and -0.8 m NAP. Two median particle sizes have been used: d_{50}= 0.21 and 0.25 mm. The green line of **Figure 4.21** represents the base beach level without nourishment. The purple line represents the beach level with nourishment. The slope of the upper beach is about 1 to 50. The nourishment layer has a length of about 200 m and a thickness of about 2 m. The unit nourishment volume is about 200x2=400 m^3/m. Most of the erosion takes place at the lower beach.

Table 4.4 shows the erosion results for two computations (0.25 and 0.21 mm sand). The average erosion volume is of the order of 60 to 85 m^3/m per year, which means that the lifetime of this beach nourishment is of the order of 5 years.

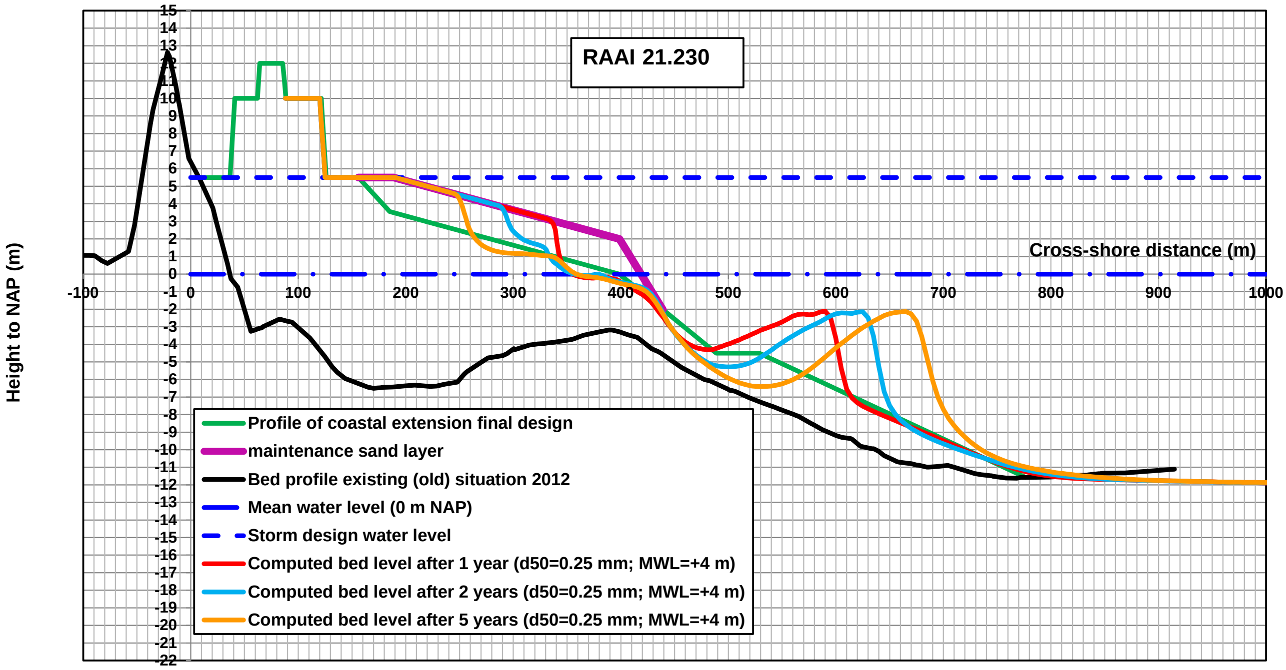

Figure 4.21 *Computed bed level of cross-shore profile with beach nourishment along the Dutch coast; d_{50}= 0.25 mm; maximum water level=+4 m.*

COASTAL EROSION AND RECESSION	BEACH EROSION VOLUME (beach slope 1 to 50 and d_{50}=0.25 mm)	BEACH EROSION VOLUME (beach slope 1 to 50 and d_{50}=0.21 mm)
Erosion volume after 1 year Coastal recession after 1 year	140 m^3/m 70 m	180 m^3/m 80 m
Erosion volume after 2 year Coastal recession after 2 year	200 m^3/m 70 m	240 m^3/m 70 m
Erosion volume after 5 year Coastal recession after 5 year	310 m^3/m 90 m	430 m^3/m 120 m
Average erosion volume (5 years)	60 m^3/m	85 m^3/m

Table 4.4 *Erosion volumes (above 0 m level) and recession due to cross-shore transport*

These computational results with yearly-average erosion values of the order of 50 to 100 m^3/m/year depending on sediment size and wave climate show that a beach nourishment volume of the order of 100 to 200 m^3/m may be easily eroded away in one or two winter seasons in line with observations at the Dutch coast where beach fills have, on average, to be repeated at two year intervals. The trough seaward of the inner breaker bar acts as a sink to the erosion of beach sediments.
Relatively coarse beach material of 0.3 or 0.4 mm has a lifetime which is significantly larger (50%) than that of 0.2 mm.
The beach nourishment is most effective when it is made landward of the inner bar crest, which can act as a terrrace (or reef) reducing the wave height. The presence of a trough in front of the beach nourishment should be avoided (trough between inner bar and beach should always be filled with sand)

4.3 Beach fill losses due to both longshore and cross-shore transport processes

To estimate the 3D effects of beachfill erosion, the DELFT3D model system (in full 3D-mode) has been used. The beach profile and the wave conditions are exactly the same as those used for the CROSMOR runs, but only one bed material diameter (0.2 mm) has been used. Two wave directions have been used: all waves perpendicular to the coast and all waves oblique to the coast (30 degrees with coast normal at deep water). **Figure 4.22 left** shows sedimentation/erosion plots after 140 days for waves perpendicular to the coast; these plots are obtained by subtracting the initial bed levels from the computed bed levels after 140 days. The outer breaker bar shows a meandering pattern due to the generation of second order circulating flows as a result of small variations in set-up values. Rip channel erosion spots can be observed in the nearshore zone (close to the mean water line; initial water line indicated by black line in **Figure 4.22**). These oscillating patterns are absent for oblique waves, which generate relatively large longshore currents (**Figure 4.22 right**). In both cases the total beachfill volume is completely eroded away after 140 days. Most of the erosion takes place during conditions with the higher waves of 1.5 and 3 m.

Figure 4.23 shows the computed profiles in the central section of the beachfill for waves perpendicular to the coast. A new breaker bar is generated at a more offshore location.
Figure 4.24 shows similar results for the case with oblique waves, but now two new and more peaky breaker bars are generated. The erosion of the beach zone is also much larger than that for the case with perpendicular waves.
Figure 4.25 left shows the time development of the total beach fill volume, while **Figure 4.25 right** shows the beachfill volume development of the central (middle) section. The total initial volume is about 300,000 m^3 and the initial volume per m length of coast is about 230 m^3/m. Both plots clearly show that the first period of 100 days with low waves of 1 m does not yield any significant erosion. The erosion starts after 100 days when waves of 1.5 m are generated during a period of 30 days. Most of the beachfill has disappeared after this period. The erosion proceeds much faster when the waves are oblique to the coast due to the generation of strong longshore currents (of the order of 1 m/s close to the shore) which enhance the sediment transport capacity considerably. The erosion volume in the central section computed by DELFT3D

for the case with waves perpendicular to the coast is slightly larger than that computed by the CROSMOR-model (compare **Figures 4.20** and **4.23** for d_{50}= 0.2 mm).
Both models have the same sand transport formulations, but the DELFT3D-model includes an advection-diffusion scheme to represent the spatial lag effects. As the results of both models are very similar, it can be concluded that spatial lag effects of the suspended transport rates are not very important for the erosion in the high-energy upper beach zone.
Based on the DELFT3D results, the beachfill erosion is found to be considerably larger (about 20% to 30%) for oblique wave conditions. This also is in line with the CROSMOR-results including a wave angle of 30 degrees, see **Figures 4.16, 4.18, 4.19** and **4.20**. The data of **Figures 4.17** to **4.19** should roughly be increased by about 20% to 30% for conditions with oblique wave attack.

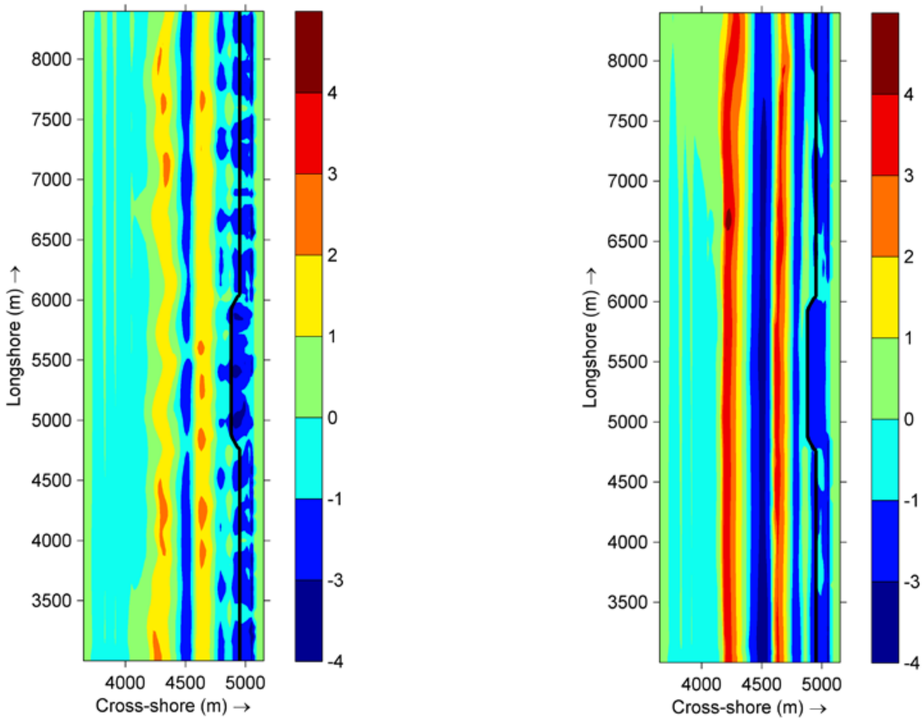

Figure 4.22 *Sedimentation/erosion plots over 140 days (scale in m: red=sedimentation; blue=erosion)*
Left: waves perpendicular to coast *Right: waves oblique to coast (30 degrees)*

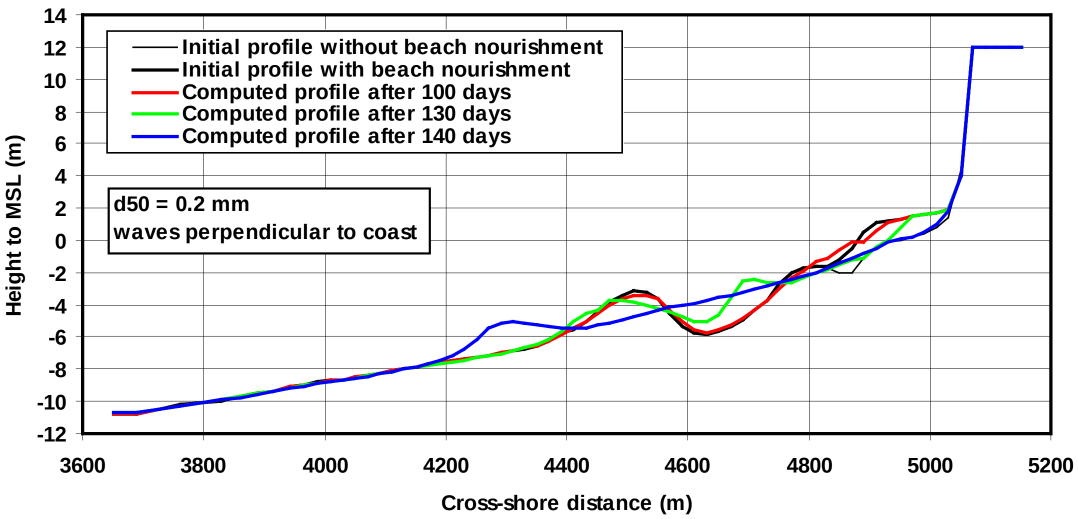

Figure 4.23 *Cross-shore profiles in central section computed by DELFT3D-model (waves perpendicular to coast)*

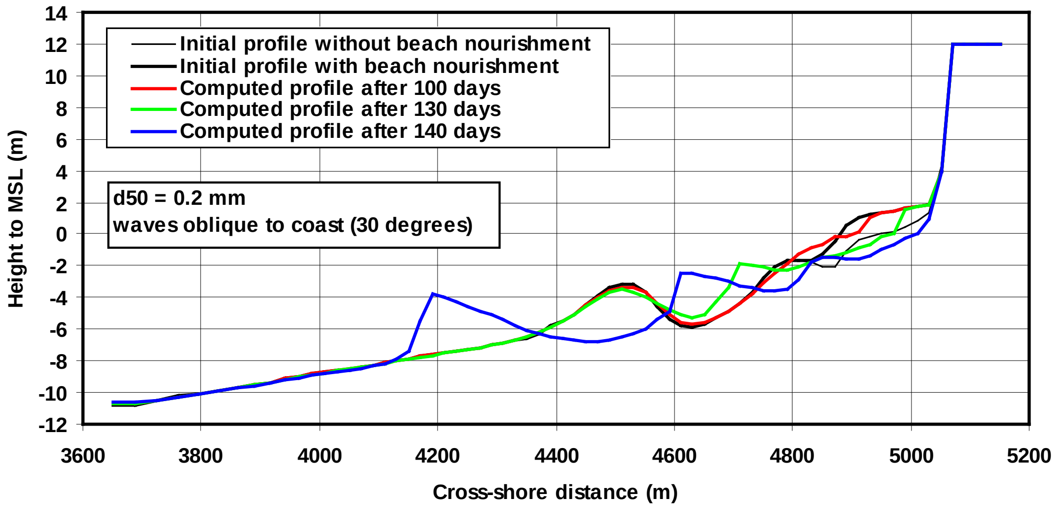

Figure 4.24 *Cross-shore profiles in central section computed by DELFT3D-model (waves oblique to coast)*

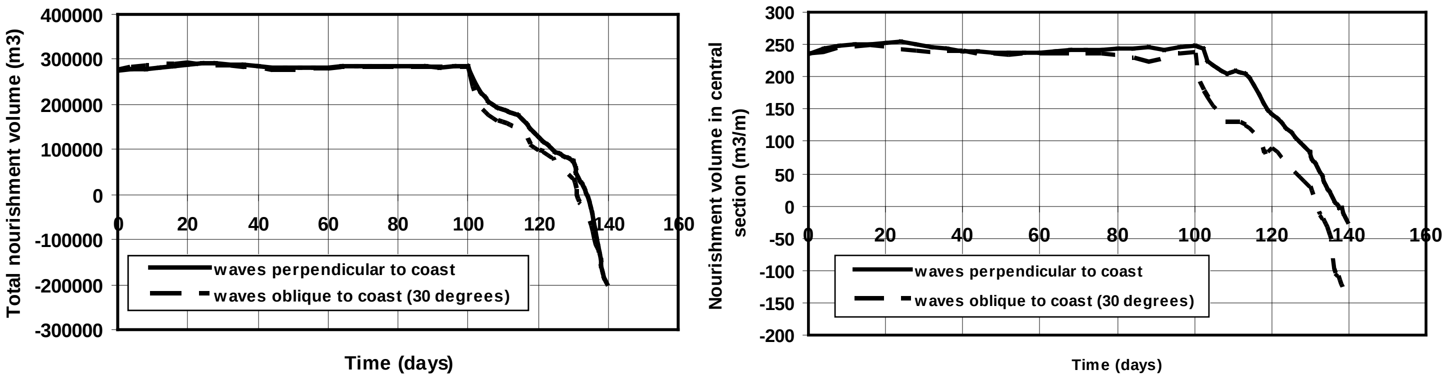

Figure 4.25 *Time development of beach nourishment volume computed by DELFT3D-model*
Left: Total volume (in m^3) *Right: Volume in central section (in m^3/m)*

4.3 Discussion of results

Most beach fills have a length in the range of 1 to 2 km and a cross-shore width in the range of 30 to 100 m and are placed as a layer of sand on top of the original beach. Beach fills will be gradually eroded by longshore and cross-shore transport processes.

Based on the results of Section 4.1 (erosion due to longshore transport gradients) and 4.2 (erosion due to cross-shore transport gradients), it is concluded that the erosion due to longshore transport processes is of the same order of magnitude as the erosion due to cross-shore transport processes.

The yearly-average erosion volume per unit length of a beach fill (0.20 to 0.25 mm sand) due to ***longshore*** transport gradients is estimated to be in the range of 10 to 100 m^3/m/year for a beach fill with a cross-shore extension of the order of 50 m and a length of the order of 2 km (**Section 4.1**). The values are largest for very exposed sites (open coasts) and considerably smaller for sheltered sites, see **Table 4.5**.

The yearly-average erosion volume per unit length of a beach fill (0.20 to 0.25 mm sand) due to ***cross-shore*** transport gradients also is estimated to be in the range of 10 to 100 m^3/m/year (see **Table 4.5**).

Both processes (erosion due to cross-shore and longshore transport gradients) have been computed separately, but will occur simultaneously in practice. Herein, it is assumed that the erosion loss due the combined effect can be estimated by quadratic summation.
Assuming a major beach fill in the range of 200 tot 300 m^3/m along a very exposed coast, the yearly-average erosion will be of the order of $(70^2+70^2)^{0.5} \cong 100$ m^3/m/year. This means that this type of beach fill will be removed in 2 to 3 years.
Practical experience at the exposed Dutch coast shows a maximum lifetime of these types of beach fills of the order of 2 to 4 years.

Type of coast	Initial erosion loss due to longshore transport gradients (m^3/m/year)	Initial erosion loss due to cross-shore transport gradients (m^3/m/year)
Sheltered	15±5	15±5
Medium exposed	30±10	30±10
Very exposed	70±30	70±30

Table 4.5 *Initial erosion losses due to longshore and cross-shore transport processes*

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