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ARTICLE

Design of Artificial Beaches at Sheltered and Exposed Sites

Leo van Rijn [1*], *Arjan Mol* [2], *Merel Kroeders* [2]

[1] *LVRS-Consultancy, Domineeswal 6, 8356DS Blokzijl, The Netherlands*

[2] *DEME-GROUP, Haven 1025, Scheldedijk 30, 2070 Zwijndrecht, Belgium*

ABSTRACT

The paper is focused on the design of artificial sand beaches at sheltered and exposed sites. The methodology applied includes the study of the most essential design parameters and the application of numerical models to compute the beach erosion and maintenance. The computed erosion volume decreases for coarser sand (0.5 mm sand instead of 0.3 mm). Beach erosion increases for more graded sand, but the effect is small (10%–15%). The slope of the artificial beach at sheltered sites is commonly between 1 to 15 and 1 to 30 in conditions with a micro tidal range and mild waves. Slopes between 1 to 30 and 1 to 50 are used for more open exposed sites. The effect of the upper and lower beach slope (1 to 15 or 1 to 20) on beach erosion is marginal for sand in the range of 0.3 to 0.5 mm. A break in slope is quickly adjusted by transport processes. The volume of beach sand required may be reduced by constructing a submerged sill at the toe of the beach. Analysis of costs shows that the construction costs including maintenance over a period of 50 years of a submerged sill are about the same as that of beach fill including maintenance. Hence, the beach fill volume can be twice as large for a solution without a sill. Beach erosion due to alongshore transport processes is minimum if the beach line of the planform is perpendicular to the main wave direction (equilibrium beach).

Keywords: Design Artificial Beaches; Submerged sills/breakwaters; Beach Extensions and Land Reclamations

*CORRESPONDING AUTHOR:
Leo van Rijn, LVRS-Consultancy, Domineeswal 6, 8356DS Blokzijl, The Netherlands; Email: info@leovanrijn-sediment.com

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1. Introduction

Coastal zones are very popular for living and recreation. Currently, about 25% of the world population lives in coastal zones (about 15% in low-lying areas vulnerable to flooding). Many of the coastal areas suffer from erosion and degradation, requiring rehabilitation and extension. A feasible solution to this is the construction of small-scale artificial beaches (perched beaches) and large-scale land reclamations using highly sustainable sand as building material, preferably at sheltered locations to minimize coastal erosion. Small-scale beach fills at sheltered sites are often protected by a submerged sill at the toe of the (perched) beach. The focus point (purpose) of this paper is the design of artificial beaches with or without a toe structure at sheltered sites, but additionally examples for exposed sites are presented. Coasts along seas, estuaries, bays, lagoons and lakes in conditions with mild waves (wave heights $H_{s,o}$ < 1.5 m) and micro-tides (tidal range <1 m) are known as low-energy coasts or sheltered coasts.

Only few studies have focused on beach behavior at low-energy coasts. Jackson et al.[1] and Nordstrom and Jackson[2] have given reviews of the differences between sheltered and exposed beaches. Their attention was focused on beaches in basins where fetch distances are <50 km. Tide-and wind-induced currents are more important for these beaches than wave-induced currents. Vila Consejo et al.[3, 4] have made a detailed descriptive inventory (conceptual model) of sandy beaches in estuaries and bays, which are classified as BEBs. Sandy beaches in these conditions are distinct from exposed open-coast beaches, because they are partially or fully sheltered from ocean waves and undergo relatively little variation. Long (infra-gravity) waves propagating into the sheltered system may be more important, as well as tide-and wind-induced currents contributing to beach erosion and deposition. It is concluded that sandy beaches in estuaries and bays should be recognized as a distinct class of beach in contrast with wave-dominated open-ocean beaches.

A typical feature of sheltered beaches is the existence of a low gradient sub-tidal terrace or platform with depths between 0.5 and 1.5 m below mean sea level and a narrow and often steep foreshore[3–5] . Overall, the beach profiles differ in form and scale from the breaker bars in more exposed conditions. Generally, the bar forms are much smaller and show less movement, except during storm events.

Sheltered artificial beaches may also be part of a large-scale land reclamation, which is the construction of new land for industrial, housing and recreational activities. The development of land reclamations with artificial (perched) beaches along sheltered coasts raises various questions, such as: 1) what is the optimum initial beach slope and what is the long-term beach slope?, 2) what type of sand is required and available (sand size and grading)?, 3) what is the benefit of a submerged sill or breakwater at the toe of the upper beach to reduce the volume of sand and to minimize beach erosion?, 4) what is the required maintenance volume? and 5) what is the environmental impact on the adjacent coastal zones (Environmental Impact Assessment. EIA)?

In the past only few studies have been done to better understand the behavior of artificial beaches (perched beaches)[6–11] . Most of these studies are related to experimental work in laboratory flume and basins. Recently, efforts have been done to make two dimensional-horizontal (2DH) numerical simulations for a protected beach fill (perched beach) in storm conditions, but long-term simulations on a fine grid (<2 m) remain a problem (lack op computer power)[12]. In this paper, the focus point is on numerical simulations using practical engineering models, which can be used for both short and long-term morphology. The methodology (including models) applied herein to answer the above questions are presented in Section 2. Basic design requirements are given in Section 3. Beach erosion and maintenance along artificial beaches due to cross-shore and longshore sand transport processes are discussed in Sections 4 and 5. Conclusions are given in Section 6.

2. Methodology and Models

2.1. General

The general purpose of the present paper is to study the design of artificial beaches for recreation with minimum beach erosion and maintenance based on available field data and available practical engineering tools (models).

The methodology applied to answer the questions related to the design of artificial beaches consists of three steps. First, the design requirements (parameters) of artificial beaches are studied in detail and five alternative beach designs are formulated (Section 3). The next step is the quantitative evaluation (minimum beach erosion) of these five alternative beach designs based on numerical modelling using the CROSMOR-model for cross-shore processes (Section 4) and the LONGMOR-model for longshore processes (Section 5). The description and validation of the numerical models including model settings given in Sections 2.2 and 2.3. Finally, general guidelines for the most optimum beach design with minimum maintenance are presented (Section 6).

2.2. LONGMOR-Model

The LONGMOR-model[13] is a 1D coastline model based on the sand balance equation for the littoral zone (surf zone with breaking waves) with layer thickness (h). The model computes coastline changes based on the alongshore variation of the longshore transport rates. Basically, the sand balance equation states that a coastal section erodes if more sand is carried away than supplied; vice versa coastal accretion occurs in a coastal section if there is a net supply. Coastline changes are linearly related to the depth (h) of the active littoral zone.

Three longshore sand transport (LST) equations are available: CERC[14], Kamphuis[15, 16] and Van Rijn[17]. The LST-equations are semi-empirical equations which can be used to compute the bulk longshore sand transport in the surf zone as function of the wave height and wave incidence angle at the breaker line and the sediment properties. Long term computations require the schematization of the annual wave climate into a series of representative wave conditions. The offshore wave climate has to be converted to a nearshore wave climate at the breaker line, which can be done by simple wave refraction/shoaling theory or by using a numerical wave model. The LONGMOR-model has been extensively validated earlier[13].

2.3. CROSMOR-Model

The CROSMOR-model is a sophisticated numerical (Fortran) model comprising sub-models for wave propagation, tidal currents, cross-shore and longshore sediment transport and cross-shore bed level changes on time scales up to 5 years[18, 19]. The propagation and transformation of individual waves (wave by wave approach) along the cross-shore profile is described by a (probabilistic) model solving the wave energy equation for each individual wave. The individual waves shoal until an empirical criterion for breaking is satisfied. The default wave breaking coefficient is represented as a function of local wave steepness and bottom slope. Wave height decay after breaking is modelled by using an energy dissipation method. Wave-induced set-up and set-down and breaking-associated longshore currents are also modelled. The cross-shore wave velocity asymmetry under shoaling and breaking waves is described by the semi-empirical method of Isobe and Horikawa[20, 21]. Near-bed streaming effects are modelled by semi-empirical expressions. The velocity due to low-frequency waves in the swash zone is also taken into account by an empirical method. The depth-averaged return current under the wave trough of each individual wave is derived from linear mass transport and the water depth under the trough. The wave model has been extensively tested for high-energy field conditions[11]. Herein, the wave model is tested for cases with a submerged sill/breakwater at the toe of the beach. **Figure 1** shows the computed wave transmission coefficients for a structure with height of 3 m and slopes of 1 to 2. The water depth above the crest of the structure (R_c) is varied in the range of 0.5 to 3 m (negative for submerged case). The significant wave height far seaward of the structure was $H_{s,o}$ = 2 m with peak period of T_p = 7 s. The wave transmission coefficient is defined as $K_T = H_{s,toe}/H_{s,lee}$ with $H_{s,toe}$ = significant wave height at the seaward toe of the structure and $H_{s,lee}$ = significant wave height in the lee of the breakwater. The experimental range of many laboratory data[22] are also shown. The model results are within the experimental range for $R_c/H_{s,toe} < 0.7$, but are too low for higher crest levels. Most likely, the wave overtopping effects and the extra water mass piling up in the lee of the submerged breakwater (not included in the model) lead to higher wave heights in the lee of the structure. The model cannot be applied for emerged breakwaters.

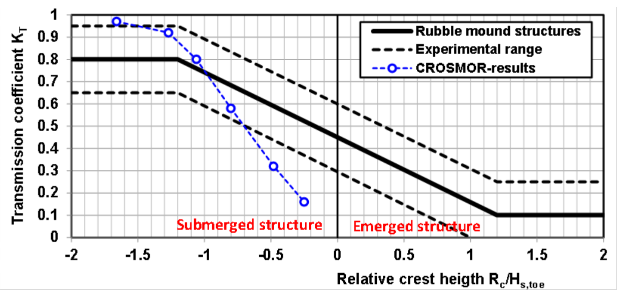

Figure 1. Wave transmission coefficient for a submerged breakwater (R_c = water depth above crest).

The sand transport of the CROSMOR-model is based on the transport formulations of Van Rijn [23, 24]. CROSMOR-model can be used to simulate the morpho-dynamic changes around a submerged sill or breakwater at the toe of the beach, excluding the effects of additional turbulence generated by violent wave breaking on the local bed changes. To show that the CROSMOR-model produces realistic beach erosion values for sheltered sites, three validation cases for mild wave conditions are described hereafter: nearshore mound in Florida (USA) and two beaches in lakes, The Netherlands. The general model settings are given in **Table 1**.

Table 1. General model settings of CROSMOR-model.

PARAMETERS	Values
Boundary depth near beach	0.3 m
Grid size; total length	Variable (1 to 2 m)
Number of wave classes per wave height	1
Wave asymmetry	Isobe-Horikawa 1982
Coefficient wave breaking roller (f_{rol})	0.5
Coefficient Longuet-Higgins streaming (cfh)	0.5
Coefficient sand entrainment beach zone (sef)	1
Coefficient undertow (f_{rip})	1
Coefficients bed smoothing (facsmooth)	10
Coefficients sand transport (f_{bed}; f_{sus}; f_{susw})	1 to 1.5; 1 to 1.5; 0

2.3.1. Validation Case Nearshore Mound, Florida, USA

The morphological behaviour of a nearshore berm or mound (made of sand with d_{50} = 0.3 mm) under micro-tidal conditions at Perdido Key, northwest Florida, USA [25–27]. The berm (length = 4000 m, width = 300 m, relief = 1.5 to 2 m) was placed at a depth of about 6 m in 1991; the crest level was at −4 to −4.5 m, see **Figure 2**. Two-years of post-placement survey data indicated that the berm did not migrate during this period, although it was smoothed slightly by wave action. The measured erosion volume along the profile of **Figure 2** is 60 m^3/m after 2 years. The measured deposition volume is only 35 m^3/m, which means the presence of 3D-effects. The largest significant wave height measured in the nearshore area was about 2.9 m (period of 13 s). As the water depth above the crest is about 4 to 4.5 m, wave breaking on the berm will only occur during storm periods. Most likely, major morphological changes only occur during storm periods. The computed bed levels of the CROSMOR-model (file: perdi1.inp) are shown in **Figure 2.** The wave climate over 2 years is assumed to consist of 4 storm events, each of 60 hours. Each storm event consists of 24 hours with $H_{s,o}$ = 1.4 m, T_p = 8 s, 12 hours with $H_{s,o}$ = 2.1 m, T_p = 12 s and 24 hours with $H_{s,o}$ = 1 m. The storm set-up is assumed to be 0.5 m. The water level variations of the micro-tidal conditions have been neglected. The wind-included velocity is set to 0.2 m/s. The bed material is sand with d_{50} = 0.3 mm and d_{90} = 0.6 mm (uniformity coefficient $c_u = d_{60}/d_{10}3$). The bed roughness is assumed to be 0.03 m. The calibration coefficients of the sand transport is set to 1.5 (default 1). The agreement between measured and computed bed levels is quite good, particularly in the erosion area. The computed deposition is about 60 m^3/m (same as the erosion volume; closed balance in model) which is much larger than the measured deposition of 35 m^3/m. The Brier Skill Score (BSS) of the predicted profiles in comparison to measured profiles is about 0.7 which means a good prediction (BSS in range of 0.6–0.8 [18].

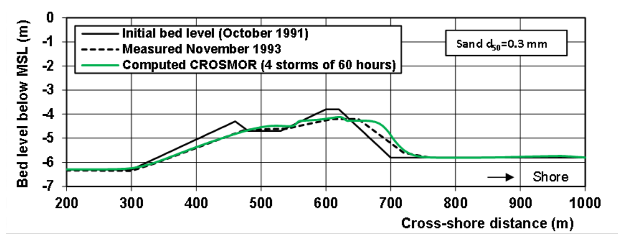

Figure 2. Measured and computed bed level changes along nearshore mound, Perdido Key, Florida, USA.

2.3.2. Validation Case Pilot Beach Houtribdijk, Marker Lake, The Netherlands

This validation case refers to a short sand beach (d_{50} = 0.25 mm) at the north side of the large Marker Lake in The Netherlands [28], see **Figure 3**. Measured wave heights at a depth of 2.5 m are up to H_s = 1.2 m, mostly from west to south-west. The lake level varies between −0.2 m and

−0.4 m NAP. Waterlevel setup due to wind forces is up to 0.4 m. Wind-induced circulation currents to the east may be as large as 0.4 m/s during stormy periods. The measured wave climate is schematized to 6 wave classes for model input with direction of 30° to shore normal (file:HDIJK1J). The calibration factor of the suspended load transport was set to 1.5 (default 1).

Figure 3 shows the measured and computed bed profiles after 2 years in the middle section along the beach for d_{50} = 0.25 and 0.3 mm (250 and 300 m). The measured bed profile shows the typical low gradient terrace with length of about 40 m between −1 m to −0.5 m. The measured erosion above −1 m NAP is about 20 m^3/m after two years. The computed erosion of about 10 m^3/m after two years is less than the measured value, but it is a fairly good result given the fact that some of the measured erosion is caused by longshore transport processes which are not taken into account by the model. The computed bed profile also shows a low gradient terrace but shorter and less deep. The Brier Skill Score (BSS) of the predicted profiles in comparison to the measured profiles is about 0.8 which means a good prediction (BSS in the range of 0.6–0.8 [18].

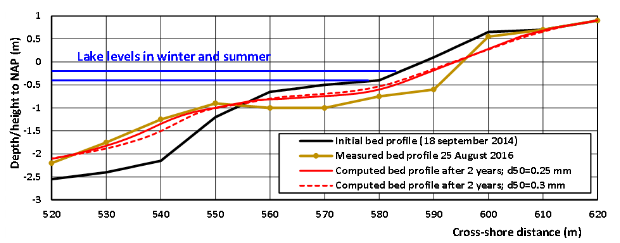

Figure 3. Computed beach profiles for daily waves; Pilot beach Houtribdijk, The Netherlands.

2.3.3. Validation Case South-West Beach, Marker Wadden, Marker Lake, The Netherlands

This validation case refers to a sand beach (d_{50} = 0.35 mm) at the south-west side of an artificial island (Marker Wadden) at the north-east side of the large Marker Lake in The Netherlands [29], see **Figure 4**. Measured wave heights at a depth of 4.3 m are up to H_s = 1.4 m, mostly from west to south-west (directions of +45° and –45° to shore normal). The lake level varies between −0.2 m and −0.4 m NAP. Water level setup due to wind forces is up to 0.4 m. Wind-induced circulation currents to the east may be as large as 0.2 m/s during stormy periods. The measured wave climate was schematized to 11 wave classes for model input (file: MW-ZS1.inp). The calibration factor of the suspended load transport was set to 1.2 (default 1).

Figure 4 shows the measured and computed beach profiles in the middle of the south-west beach after 1.15 years. The agreement between measured and computed bed profiles is quite good. The measured bed profile shows the typical low gradient terrace with length of about 35 m between −1 m to −0.75 m. The computed erosion above −1 m is about 27 m^3/m, which is somewhat lower than the measured value of about 30 m^3/m after 1.15 years. This discrepancy can be explained by additional erosion due to longshore transport processes and gradients which are not taken into account by the CROSMOR-model. The erosion at the dune crest is caused by aeolian sand transport, not included in the model. The Brier Skill Score (BSS) of the predicted profiles in comparison to the measured profiles is about 0.74 which means a good prediction (BSS in the range of 0.6–0.8 [18].

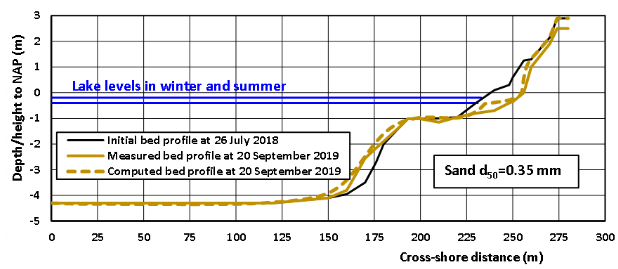

Figure 4. Computed beach profiles for daily waves; South beach Markerwadden, The Netherlands.

3. Design Requirements for Artificial Beaches

3.1. General Requirements

The focus point (purpose) is the design of artificial beaches for recreational beaches using sand as highly sustainable building material. Alternative building materials (dolomite or crushed concrete) are not considered.

The basic requirements for a well-designed artificial beach of sand are, as follows:

- stable sandy material with high erosion resistance; coarse sand (0.4–0.6 mm) is more stable than fine sand (0.2–0.4 mm), but very coarse sand (0.6–1 mm) is less attractive for beach recreation; beaches of coarse materials are steeper requiring a smaller volume of new sand, but steeper beaches are more reflective and promote plunging breaking waves, which may be unpleasant for unexperienced swimmers and may require more maintenance; beaches of fine sands have flatter slopes requiring a larger volume of new sand to be dredged from offshore borrow sites;

- good permeability for drainage of the beach sand; the permeability strongly depends on the porosity of the sand and the porosity in turn depends on the grading of the sand; uniform clean sand has porosity in the range of 0.35 to 0.4, but decreases rapidly for more graded sand with fine particles in the voids of larger particles; graded sand with some content of fines has a very low porosity value (<0.3) and low permeability; the beach will drain slowly or may even remain wet at depressions promoting algae etc.;
- safety against wave overtopping and flooding; the beach should be backed by a sand dune with a sufficiently high crest level and dune volume to prevent wave overtopping, crest erosion and flooding of the hinterland during extreme storm events; the dune volume should be higher than the potential dune erosion volume due to an extreme storm (with return period > 100 years);
- beach line orientation should be close to the equilibrium value to minimize erosion; the beach orientation should be as much as possible perpendicular to the main wave direction; supporting terminal groins may be necessary at both ends of the planform to prevent the alongshore movement of beach sands;
- esthetic appearance should be in accordance with that of local beaches (white sands with low content of gravels and silts); a beach of very find sand with traces of silt is less permeable for runup water, which may lead to local water puddles with algae growth and muddy sediments.

These basic parameters are studied in more detail in Sections 3.2 to 3.6, see also Mangor 2004[30].

3.2. Beach Sand Size and Grading and Effect on Sand Transport

3.2.1. Size and Grading

Natural sand mixtures are inherently non-uniform, which means that the sand mixture consists of multiple sand fractions with slightly different particle sizes, as expressed by the particle size distribution (psd-curve). Basic parameters of the psd-curve are: 1) median particle diameter (d_{50}), 2) uniformity coefficient ($c_u = d_{60}/d_{10}$) and 3) grading coefficient $c_c = (d_{30})^2/(d_{60}d_{10})$. The uniformity of natural sands strongly depends on the median particle size (d_{50}-value). Practice shows that finer sands are more uniform than coarser sands (**Table 2**). Thus, the c_u-value increases for increasing median particle sizes. Very fine sands with $d_{50} < 0.2$ mm generally have c_u-values < 2.5 and coarser sands with $d_{50}$of about 0.5 mm generally have c_u-values 3. According to Mangor[30], high quality beach sand should have a c_u-value 2, which is a rather strict requirement for natural sands, particularly for more stable coarser sand with d_{50} in the range of 0.4 to 0.5 mm. Very uniform coarse sand with d_{50} of about 0.5 mm and $c_u < 2$ is very difficult to find in nature. It can be made artificially by removing (sieving) the very fine and the very coarse fractions, but this is an intensive and time-consuming operation. Practical c_u-values are given in **Table 2**.

Table 2. Practical sand parameters.

Sand	d_{10} (mm)	d_{30} (mm)	d_{50} (mm)	d_{60} (mm)	d_{90} (mm)	c_u (-)	c_c (-)
fine	0.1	0.15	0.2 (0.1–0.25)	0.25	0.5	2.5	0.45
medium fine	0.15	0.2	0.3 (0.25–0.5)	0.4	0.8	2.7	0.7
coarse	0.25	0.45	0.6 (0.5–1)	0.75	1.5	3.0	1.1
very coarse	0.35	0.7	1.0 (1–1.5)	1.2	2.0	3.4	1.2

The permeability of beach sand strongly depends on the porosity of the sand and the porosity in turn depends on the grading uniformity coefficient (c_u) of the sand material. The data of Van Lopik et al.[31] show that the porosity is in the range of 0.3–0.35 for sand with $c_u < 3$. The porosity decreases rapidly for more graded sand with fine particles in the voids of larger particles, particularly for $c_u > 4$.

3.2.2. Effect of Grading on Sand Transport

Natural graded sands are non-uniform with different size fractions and basically the sand transport should be computed by using a multi-fraction method (MF-method), which is rather problematic as simple and generally accepted MF-methods are not available. The MF-approach was explored by Van Rijn [32–34] in comparison with the single fraction (SF) method based on the median particle size d_{50}. It was found that the results of MF-methods are fairly similar (somewhat higher) to that of the SF-method for sands with $d_{50} < 0.5$ mm. It is noted that most methods for computation of sand transport and beach erosion are based on the assumption of almost uniform sand represented by the median particle size d_{50}, neglecting the effect of the c_u-value. Three types of sand beds are herein distinguished, see **Table 3**.

The computation of sand transport using the SF-method (with or without correction factor) is quite straight forward. At present stage of research, no generally accepted MF-method is available [34]. Given the complexity of this method and the associated book-keeping process of fractions in the bed, it is not much applied in most numerical morpho-dynamic coastal models.

As quasi-uniform sand is present at most beach sites, the SF-method has to be applied with a correction factor to include the effect of the finer fraction resulting in slightly higher sand transport rates [32, 33]. The correction factor for river flow conditions was determined by Van Rijn 1984 [32, 33] using the multi-fraction method (MF) for a medium fine sand bed with d_{50} = 0.25 mm. Using the SF-method for the same case, it was tried to find the same transport rates by varying the representative size (input parameter d_s) of the suspended sediments. The d_s-values for river flow conditions can be described by Equation (1): [32, 33]

$$d_s/d_{50} = 1 + 0.011(\sigma_s - 1)(T - 25) \tag{1}$$

with: d_s = representative size of suspended sediments; T = $(\tau_b - \tau_{cr})/\tau_{cr}$, τ_b = bed-shear stress, $\tau_{b,cr}$ = critical bed-shear for initiation of motion based on Shields' curve, σ_s = gradation parameter = $0.5(d_{84}/d_{50}+d_{16}/d_{50}$; $\sigma_s \cong 0.6c_u)$.

Depending on the gradation parameter and the flow strength (bed-shear stress parameter), the suspended size d_s varies approximately in the range of $d_s \cong 0.6d_{50}$ to $d_s \cong d_{50}$. At low flow strength (T < 5) and a wide grading, only the very fine sand particles are winnowed from the bed resulting $d_s \cong 0.6d_{50}$. At very high flow strength (T ≅ 25), all sand particles from the bed go into suspension resulting in $d_s \cong d_{50}$.

In the CROSMOR-model for coastal conditions, a similar Equation (2) is used, as follows:

$$d_s/d_{50} = 1 + 0.0006(c_u - 1)^{0.5}(M - 550) \tag{2}$$

with: $c_u = d_{60}/d_{10}$ = uniformity coefficient, M = $[(U_R{}^2+V_L{}^2)^{0.5}]^2/[(s-1)gd_{50}]$ = mobility parameter, U_R = cross-shore return current; V_L = longshore current, s = ρ_s/ρ_w = relatively density, g = acceleration of gravity, d_{50} = median particle diameter.

Table 3. Sand transport along a bed of uniform, quasi-uniform and non-uniform sand particles.

Uniform Sand **c_u = 2 to 2.5**	**Quasi-Uniform Sand** **c_u = 2.5 to 4**	**Non-uniform Sand** **c_u > 4**
Single fraction method (SF)based on median diameter d_{50} and fall velocity w_s of bed material $q_s = f(d_{50}, w_s, ...)$	Single fraction method (SF) Bed load depends on median diameter d_{50} and fall velocity w_s of bed material. Suspended load depends on d_{50} of bed material and on suspended sediment size d_s and corresponding fall velocity w_{ss} $q_s = f(d_{50}, d_s, w_{ss}, ...)$	Multi-fraction method (MF) $q_s = \sum_{i=1}^{N}(d_{i,mean}, w_{si,mean},...)$ summation over N-fractions

Equation (2) is shown in **Figure 5** for various values of the c_u-coefficient. The ratio d_s/d_{50} is relatively small for low mobility parameters and increases to 1 for very high mobility parameters. The ratio d_s/d_{50} decreases for increasing c_u-values (more graded sand), because more fine sediments of the bed material are available for erosion and entrainment into suspension (winnowing of fines). In coastal conditions with wave attack on a sloping beach, the mobility parameter M generally is fairly high in the range of 250 to 500 for medium fine sediments with c_u of 2 to 3, particularly in storm conditions. Most likely, the representative particle $d_s$is then close to the value of the d_{50} (d_s = 0.8 to 1 d_{50}) resulting in slightly higher sand transport values for coastal conditions. Equation (2) is implemented in the CROSMOR-model (Section 2.3) with c_u as input parameter.

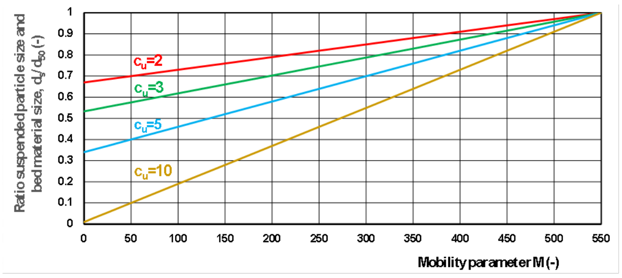

Figure 5. Dimensionless suspended particle size as function of uniformity coefficient and mobility parameter (Equation 1b).

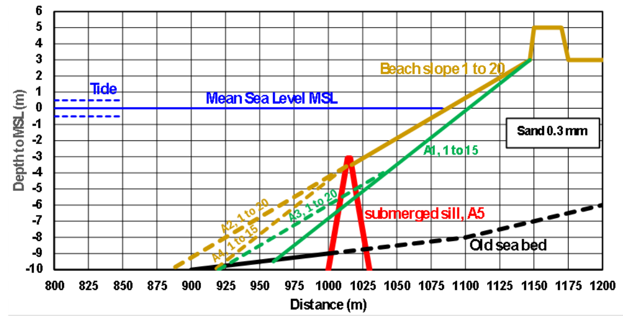

Figure 6. Alternative solution for an artificial beach in sheltered (mild wave).

3.3. Beach Slope and Toe Structures

The slope of artificial beaches in sheltered conditions is commonly in the range of 1 to 15 and 1 to 30, see **Figure 6**. The beach width increases for a milder beach slope which is attractive for densily populated areas, but a milder slope requires a larger construction volume. Beach slopes between 1 to 30 and 1 to 50 are generally used for more open exposed coastal sites. A milder beach slope is more dissipative with spilling type of breaking waves resulting in less erosion and thus less maintenance works. The volume of sand required for a milder beach slope can be reduced by using a steeper lower beach slope. If high-quality beach sand is scarce, it may even be considered to construct a submerged sill/breakwater at the toe of the beach to reduce the construction volume of sand as much as possible, see **Figures 6** and **7**.

The main purpose of a submerged sill is: 1) to reduce the sand volume by enclosing the lower end of the beach and 2) to reduce the wave height attacking the beach resulting in lower erosion and thus maintenance. This latter type of solution with a submerged sill is often used along shallow lakes in the Netherlands to reduce the wave attack on traditional dikes. If the beach line is (almost) parallel to the main wave direction and the variation of the wave directions from year to year around the mean direction is limited, the net annual LST is relatively small resulting in minor beach changes in alongshore direction. In this case the crest level of the sill is mainly determined by cross-shore transport processes depending on the local wave climate (less erosion for higher crest levels). If the beach line is not perpendicular to the main direction, the crest level of the submerged sill should be relatively high (-0.5 or -1 m below MSL) to substantially reduce the wave height attacking the beach and thus beach erosion and beach rotation.

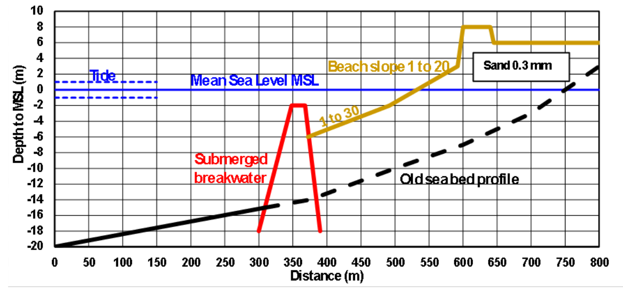

Figure 7. Alternative solution for an artificial beach in exposed conditions.

Herein, the following five alternative solutions are proposed and studied (**Figure 6**):

- A1: beach slope of 1 to 15 down to the old seabed;
- A2: beach slope of 1 to 20 down to the old seabed;
- A3: beach slope of 1 to 15 down to -4 m (upper beach) in combination with a milder lower slope of 1 to 20 down to the old seabed;
- A4: beach slope of 1 to 20 down to -4 m (upper beach) in combination with a steeper lower slope of 1 to 15 down to the old seabed;
- A5: upper beach slope of 1 to 20 in combination with a submerged sill with crest at -3 m.

Alternatives A2 and A4 have the largest volumes. Alternative A3 may also have a large volume of sand in the case that the lower slope part of the beach is represented by the equilibrium bed profile of Dean 1987 [35].

The design of an artificial beach along an exposed coast with a relatively steep and deep foreshore mostly requires a large-scale submerged breakwater (**Figure 7**) to enclose the lower end of the underwater beach, otherwise the required volume of sand may be excessively high. Often, two terminal groins are constructed on both ends of the planform of the beach, which are connected to the submerged breakwater.

3.4. Beach Runup and Crest Level

To prevent wave overtopping and flooding of the hinterland, the crest level of an artificial beach should be above the maximum runup level which depends on the maximum astronomical tide level (Δh_T), the wave-induced setup, the wind-induced setup (surge Δh_s) and the runup due to short and long waves, see **Figure 8**.

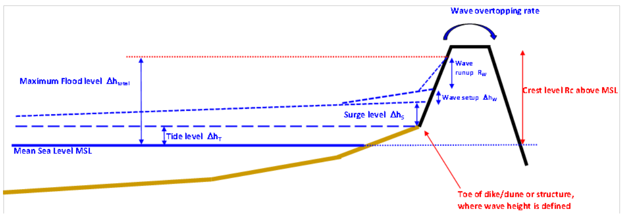

Figure 8. Maximum water level due to tide, storm surge, wave setup and wave runup.

Two sets of equations have been used to determine the wave-induced runup level, see **Figure 9**.

Figure 9 shows the computed runup level as function of the offshore significant wave height (at depth of 10 m) for a sheltered beach.

Equations (3) and (4) are the standard equation of the CROSMOR-model, which reads as:

$$R_s = 0.4 f_{runup}[\tanh(3.4\zeta_o)]H_{s,o} \quad \text{for } \zeta_o < 0.5 \tag{3}$$

$$R_s = 0.6 f_{runup}(\zeta_o)^{0.4}H_{s,o} \quad \text{for } \zeta_o \geq 0.5 \tag{4}$$

with: R_s = run-up level exceeded by 33% of the waves (= $0.7R_{2\%}$), $H_{s,o}$ = significant wave height at deep water, ζ_o = surf similarity parameter = tan $\beta(H_{s,o}/L_{s,o})^{-0.5}$, $L_{s,o}$ = wave length at deep water, $\tan\beta$ = beach slope, f_{runup} = input factor (default = 1).

The alternative Equations (5), (6), and (7) of Stockdon et al.[36] and Van Gent[37] are:

$$R_s = 0.7(0.043/\tan\beta)\zeta_o H_{s,o} \quad \text{for } \zeta_o \leq 0.3 \tag{5}$$

$$R_s = 0.7\zeta_o H_{s,o} \quad \text{for } 0.3 < \zeta_o < 1 \tag{6}$$

$$R_s = 0.7(\zeta_o)^{0.4}H_{s,o} \quad \text{for } \zeta_o \geq 1 \tag{7}$$

Given an offshore significant wave height in the range of 1 to 2 m at depth of 10 m, the runup level is of the order of 0.5 m for a beach slope of 1 to 20. Assuming a maximum surge level during extreme storm conditions of about 1 m and a maximum tide level of about 0.5 m, the maximum runup point along a sheltered beach is approximately 1 + 0.5 + 0.5 ≅ 2 m above MSL. Thus, beach erosion can be expected up to a level of 2 m above MSL. Using a margin of 1 m, the crest level of a sheltered beach is minimum 3 m above MSL.

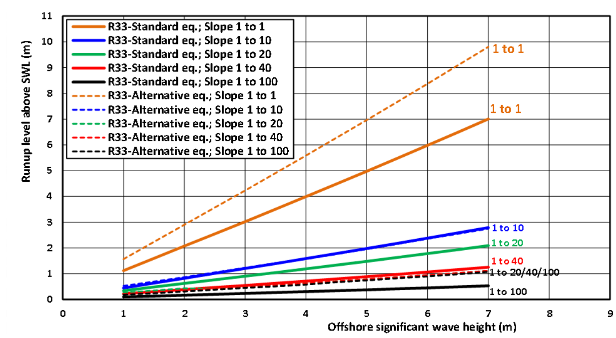

Figure 9. Wave runup as function of offshore significant wave height and beach slope (CROSMOR-model).

3.5. Required Beach-Dune Volume

In the case of a low-lying hinterland (flooding risk), the volume of sand of the new beach-dune system should always be larger than the erosion volume during extreme storm conditions. A rational method to determine the required dune volume for protection of the hinterland includes the following schematization of the beach-dune system[38, 39] into:

- residual dune profile/volume (**red line**, **Figure 10**); which is the profile that is supposed to remain to be present after an extreme design storm (return period >100 years); the residual volume ($V_{dune,res}$) is the volume enclosed by the residual profile and the dune toe line; minimum front slope of residual dune is 1 to 1; back slope of 1 to 2;
- dune storm erosion zone/volume; which is the erosion volume above the design storm level ($V_{dune,se}$; see yellow box in **Figure 10**) toe level (including all uncertainties represented by a safety factor);
- dune base volume; which is the volume ($V_{dune,base}$) between the dune toe level and the design storm level;
- dune wear zone/volume; which is the extra volume ($V_{dune,wear}$) in the dune zone that should be present above the dune toe to account for all erosion losses during the maintenance period (24 to 50 years);
- beach wear zone/volume, which is the extra volume ($V_{beach,wear}$) in the beach zone between the beach toe and the dune toe to account for beach losses during the main-

tenance period (5 to 10 years);

- dune-beach core zone; which is the volume (V_{core}) enclosed by the beach profile, the dune toe level, the dune-back profile and the original sea bottom.

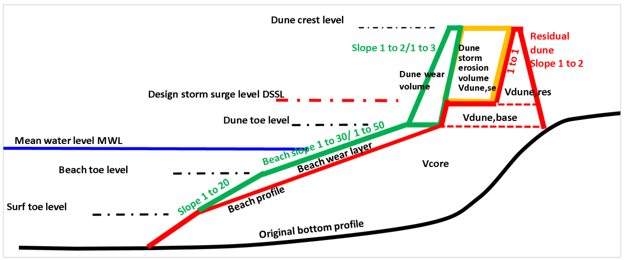

Figure 10. Cross-shore profile of beach-dune system.

The value of the dune erosion volume above the design water level during an extreme storm event ($V_{dune,se}$) can be determined by a dune erosion model (XBEACH[40], DUROS+[41], CROSMOR[19]). The computed value should be multiplied by a safety factor of 1.3 to include all relevant uncertainties[41]. Realistic dune erosion volumes for sand of 0.25 to 0.35 mm are about 75 m^3/m for moderate wave conditions (Mediterranean) up to 150 m^3/m for exposed conditions (North Sea)[19, 42].

3.6. Beach Line Orientation

To minimize beach erosion, the beach line orientation (planform) and the beach slopes should be close to the equilibrium values. If possible, the beach line orientation should be (almost) perpendicular to the main wave direction, otherwise the beach will try to adjust itself (rotate) to the main wave direction due to longshore transport processes. It may be necessary to build beach groynes for alongshore beach stabilization.

3.7. Practical and Economic Considerations

Finally, practical and economic considerations need to be taken into account. Two construction methods are mostly used: 1) hydraulic filling through a pipeline connected to dredging vessel and 2) dumping from a hopper vessel (through bottom doors) or from a barge. Using hydraulic filling, specific slopes will be generated which depend on the grain size[43]. Generally, slopes are steeper for coarser sediment. Above water, very gently slopes of 1 to 50 and flatter are obtained for sediment <0.12 mm. Underwater, beach slopes of 1 to15 to 1 to 30 can be expected for rough seas, while slopes of 1 to 10 for calm waters. For coarser material (0.2–0.6 mm), the slopes will be steeper: between 1 to 25 and 1 to 50 above water, while 1 to 10 to 1 to 15 under water for rough seas and 1 to 5 to 1 to 8 for calm waters.

Dumping from a vessel or barge can be used in the deeper parts of the beach profile. After the placing of the beach material, the slopes often need be further finalized by reshaping and trimming. Bulldozers and other equipment can only work above the low water line. Other equipment such as (long reach) excavators can be used for slope trimming, but also their reach is limited. Sometimes, temporary groynes can be constructed from which long reach excavators can also trim the deeper part of the slopes. It should be realized that such activities are time-consuming and thus costly. Alternatively, the placement of extra sand buffer in deeper water, which will be naturally reshaped afterwards, may be a cheaper solution.

In case of a submerged barrier, the interaction between the construction sequence of the beach and the submerged barrier is something to take into account. If the barrier is constructed first, one should be aware that floating equipment is hindered by the barrier. If the barrier is constructed afterwards, the beach will initially be exposed to much more severe conditions resulting in additional losses of beach sediment. If the beach toe has to be placed against the barrier, the beach construction always has to be performed in two phases, causing standby or mobilization costs.

Based on Van Rijn[42], the construction costs of a submerged sill/breakwater at the toe of the beach including maintenance over a period of 50 years are about the same that of beach fills including regular maintenance (beach width of the order of 100 m; **Figure 6**). Hence, the beach fill volume can be twice as large for a solution without a sill (same overall costs). So, if sand is sufficiently available locally (not scarce), the construction of a sill is not an attractive solution from an economic point of view.

4. Beach Erosion Due to Cross-Shore Processes

4.1. General

Beach erosion in the cross-shore direction is studied in this section based on the computed results by the morpho-dynamic CROSMOR-model for cross-shore sand transport processes. The effects of the runup level, sand size and grading on beach erosion are explained in Sections 4.2 and 4.3. Finally, the effect of the slope of the upper and lower beach and the presence of a submerged sill or breakwater on beach erosion are studied in Section 4.4.

4.2. Effect of Runup Level on Beach Erosion at Sheltered Beaches

The computed beach erosion depends on the runup level. This has been studied for a beach with slope of 1 to 20 and two wave conditions: 1) an extreme storm event of 1 year (return period of 100 years) and 2) annual waves over 1 year. The median sand diameter is d_{50} = 0.4 mm with uniformity coefficient $c_u = d_{60}/d_{10}$ = 2.6. The nearshore wave boundary conditions are given in **Table 4**. These relatively mild wave conditions are representative for the coast of Dubai in the Arabian Gulf. The main wave direction is from north-west (sector 270°–300° to North). In general, the north-west direction is the most dominant wave direction in the Arabian Gulf[44] . The tides along the coast of Dubai are semi-diurnal with a mean tidal range of about 1.3 m. Storm surge levels are about 0.5 m (annual) up to 1.0 m (once per 100 years). The maximum tidal currents near the shore are up to 0.3 m/s during springtide and below 0.1 m/s during neap tide.

Table 4. Nearshore annual wave climate and storm climate (s.n. = shore normal).

Time (days, s)	Annual Wave Climate			Storm Event (Return Period = 100 years)				
	H_{rms} (m)	T_p (s)	Dir to s.n. (°)	Days	H_{rms} (m)	T_p (s)	Dir to s.n. (°)	Surge Level (m)
0.	0.5	4	10	0	1.5	8.5	10	1
200; 17,280,000 s	0.5	4	10	1; 86400 s	1.5	8.5	10	1
201; 17,280,001 s	0.7	6	10					
300; 25,920,000 s	0.7	6	10					
301; 25,920,001 s	0.9	7	10					
360; 31,104,000 s	0.9	7	10					
361; 31,104,001 s	1.1	8	10					
365; 31,536,000 s	1.1	8	10					

The settings of the CROSMOR-model for this case are:

- artificial beach with straight slope of 1 to 20 between +4 m above MSL and −10 m below MSL;
- median sand diameter d_{50} = 0.3 to 0.5 mm; uniformity coefficient c_u = 2 to 3;
- water temperature = 25 °C; sea water salinity = 30 per mil (≅1030 kg/m^3);
- longshore current deep water = 0.2 m/s
- maximum tidal levels 0.6 and −0.6 m to MSL; storm surge level = 1.0 m
- number wave classes NHW = 10 (spectrum based on Rayleigh-distribution) per wave condition;
- coefficients: roller = 0.5; f_{smooth} = 10; f_{bed} = 0.5; f_{sus} = 1; f_{susw} = 0.

Figure 11 shows the computed beach erosion for three different runup levels due to an extreme storm event of 1 day (**Table 4**). The maximum significant wave height is H_s = 2.1 m (H_{rms} = 1.5 m). The initial beach slope is constant at 1 to 20. The standard runup equation is used with f_{runup} = 1, which gives a total beach erosion volume of about 25 m^3/m after 1 day. The maximum erosion depth is about 1 m. The eroded sand is deposited in a bar just below the mean sea level (MSL). The bar toe is situated at −3 m below MSL. The cases with $f_{runup}$of 1.5 and 2 (input values) mean that the runup values are multiplied by 1.5 and 2 resulting in higher runup levels. The computed beach erosion remains approximately the same, but it is more spread out over a longer runup length resulting in less deep erosion (maximum 0.5 m).

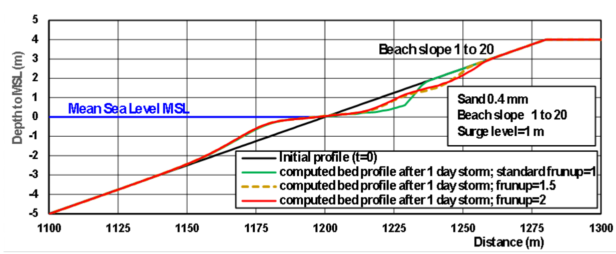

Figure 11. Computed beach erosion for different runup levels; extreme storm 1 day.

Figure 12 shows the computed beach erosion for three different runup levels and annual waves over 1 year.

The wave heights are much lower and thus the runup levels are lower. Using f_{runup} = 1 (default value, Equation 2a,b), the total beach erosion volume is about 35 m^3/m after 1 year.

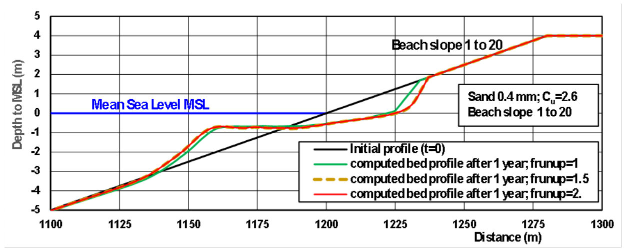

Figure 12. Computed beach erosion for different runup levels; annual waves over 1 year.

The computed bed profiles show the typical low gradient terrace with depths of −1 m to −0.5 m. The maximum computed erosion depth is about 1.1 m. The eroded sand is deposited in a bar just below the mean sea level (MSL). The bar toe is situated at −4 m below MSL. Using f_{runup} = 1.5 (standard runup value multiplied by 1.5) gives a higher runup level and erosion volume (15%). Using f_{runup} = 2, gives almost the same erosion volume as for f_{runup} = 1.5 (no further increase).

4.3. Effect of Beach Sand Size and Grading at Sheltered Beaches

The coastal erosion of a beach consisting of quasi-uniform natural sand depends on the median sand diameter (d_{50}) of the bed material and the representative size (d_s) of the suspended sediments (see Section 3.2.2). This latter parameter depends on the grading of the bed material (c_u-coefficient). The sand transport increases for more graded sand with higher c_u-coefficient and thus a smaller d_s-value (more fine sediment in suspension).

The effect of the c_u-coefficient on the computed coastal erosion along an artificial beach with slope of 1 to 20 has been studied for an extreme storm event of 1 day by performing a series of CROSMOR model runs with sand in the range of d_{50} = 0.3 to 0.5 mm and c_u-values in the range of 2 to 10. The model settings are similar to that of Section 4.2. The computed erosion results for d_{50} = 0.3, 0.4 and 0.5 mm are shown in **Figures 13–15** for the storm event of 1 day. The computed beach erosion is about 20 m^3/m after 1 day for c_u = 2. The erosion volume increases for increasing c_u-values (more graded sand). The effect of the c_u-value in the range of 2 to 5 on the computed erosion volume is relatively small (10% to 15%). The erosion volume increases substantially (>50%) for an extreme case of very graded sand with c_u = 10.

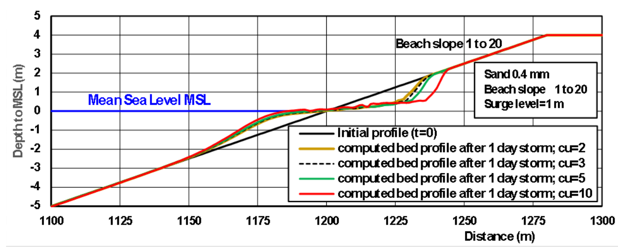

Figure 13. Computed beach erosion after 1 day; 0.4 mm sand; c_u = 2 to 10; storm event.

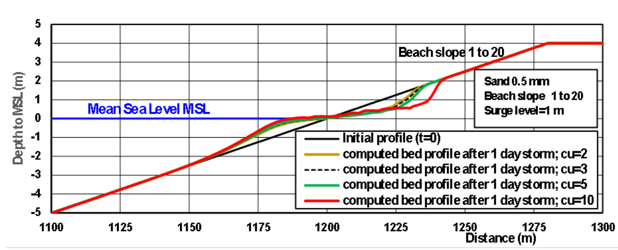

Figure 14. Computed beach erosion after 1 day; 0.5 mm sand; c_u = 2 to 10; storm event.

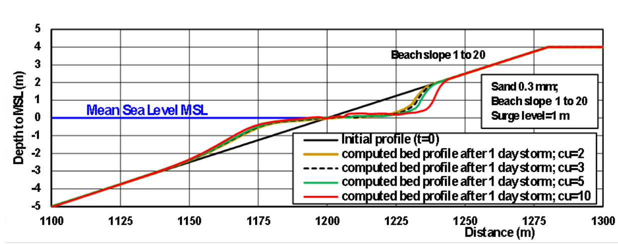

Figure 15. Computed beach erosion after 1 day; 0.3 mm sand; c_u = 2 to 10; storm event.

In addition, long term model runs over 1 year with annual waves have been performed for six types of sand: d_{50} = 0.3 mm sand with c_u = 2.5 and c_u = 2.3; d_{50} = 0.4 mm sand with c_u = 2 and c_u = 2.6; and d_{50} = 0.5 mm sand with c_u = 2 and c_u = 3. The results are presented in **Figures 16–19**. The most striking features are:

- d_{50} = 0.3 mm (**Figure 16**); the computed erosion after 1 year is relatively large (35 m^3/m/year) for uniform sand with c_u = 2; the erosion volume increases marginally (10%) for quasi-uniform sand with c_u = 2.3;

- d_{50} = 0.4 mm (**Figure 17**); the computed erosion after 1 year is smaller (25 m^3/m/year) for uniform sand with c_u = 2; the erosion volume increases slightly (20%) for quasi-uniform sand with c_u = 2.6;
- d_{50} = 0.5 mm (**Figure 18**); the computed erosion after 1 year is very small (12 m^3/m/year) for uniform sand with c_u = 2; the erosion volume increases substantially to about 22 m^3/m/year (80% increase) for quasi-uniform sand with c_u = 3.

Figure 16 clearly shows that the beach erosion is much lower for coarser sand with d_{50} = 0.5 mm and c_u = 3 than that for sand with d_{50} = 0.3 mm and c_u = 2.3. Thus, it is more economic (less maintenance) to use coarse sand with d_{50} = 0.5 mm and c_u = 3 than to use finer sand with d_{50} = 0.3 mm and c_u = 2.3. Ideally, almost uniform coarse sand with d_{50} = 0.5 mm and c_u = 2[6] should be used to obtain a stable beach with minimum erosion and maintenance. However, this type of almost uniform sand cannot easily be found at natural borrow sites. It can be produced artificially by removing the coarse fraction (>0.6–0.7 mm) from the borrow sand through special (expensive) sieving operations.

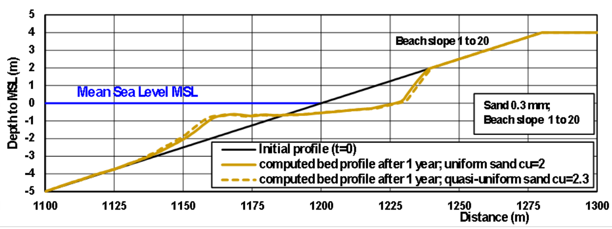

Figure 16. Computed beach erosion after 1 year annual waves; 0.3 mm sand; c_u = 2 and 2.3.

Figures 17 and **18** show a similar plots for sand of 0.4 and 0.5 mm sand. The computed erosion is smaller for coarser sand.

Figure 19 compares the erosion for 0.3 mm and 0.5 mm sand. Beach erosion is much lower for 0.5 mm sand.

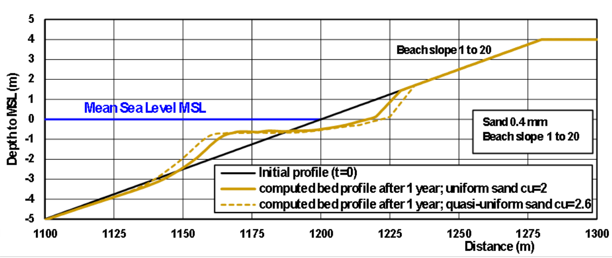

Figure 17. Computed beach erosion after 1 year annual waves; 0.4 mm sand; c_u = 2 and 2.6.

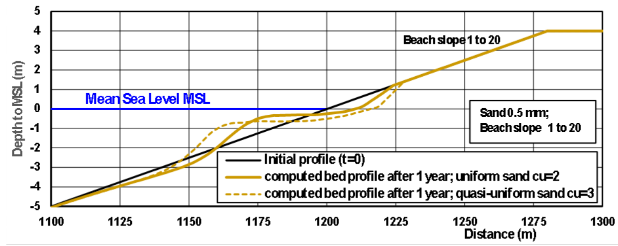

Figure 18. Computed beach erosion after 1 year annual waves; 0.5 mm sand; c_u = 2 and 3.0.

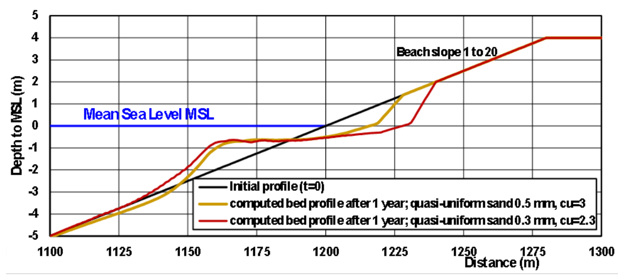

Figure 19. Computed beach erosion after 1 year; 0.5 mm sand with c_u = 2.6 and 0.3 mm sand with c_u = 2.3.

4.4. Effect of Beach Slopes and Submerged Sill at Sheltered Beaches

If sand is abundantly available, the artificial beach with a straight slope can be constructed down to the original seabed. However, at many locations the availability of high-quality beach sand is problematic. The volume of high-quality beach sand required may be reduced by constructing a steeper lower beach slope or placing a submerged sill in the nearshore zone (zone between −3 m and −5 m below MSL). Various alternative designs have been studied (Section 3.3, **Table 5**) and compared based on the computed bed profiles (CROSMOR). The model settings are similar to that of Section 3.3. The wave climate over 1 year followed by an extreme storm event of 1 day is given in **Table 6**. The sand characteristics are: d_{50} = 0.3 mm, c_u = 2.5 and d_{50} = 0.4 mm, c_u = 2.6.

The computed bed profiles after 1 year with annual waves including 1 extreme storm (return period 100 years) are shown in **Figures 20–23**. The computed erosion volumes are given in **Table 5**. Various sensitivity model runs were done to obtain a range of erosion volumes for different settings. Most simulations were done for a period of 1 year including 1 extreme storm event. Model simulations over 4 years without the extreme storm event were done for a straight beach with slope of 1 to 20 (see **Figure 21**).

Table 5. Cases CROSMOR-model runs.

Case	Computed Erosion Volume (m^3/m/year)		Files
	d_{50} = 0.3 mm, c_u = 2.5	d_{50} = 0.5 mm, c_u = 3.0	
A1. Slope 1 to 15, no sill	65 ± 7	17 ± 3	C-A1.inp
A2. Slope 1 to 20, no sill	60 ± 7	17 ± 3	C-A2.inp
A3. Slope upper 1 to 15 from 4 m to −4 m; Slope lower 1 to 20 from −4 m to −10 m	65 ± 7	17 ± 3	C-A3.inp
A4. Slope upper 1 to 20 from 4 m to −4 m; Slope lower 1 to 15 from −4 m to −10 m	55 ± 7	17 ± 3	C-A4.inp
A5. Slope 1 to 20; Sill with crest at −3 m	115 ± 15	80 ± 10	C-A5.inp
A5. Slope 1 to 20; Sill with crest at −2 m	110 ± 15	75 ± 7	C-A5.inp
A5. Slope 1 to 20; Sill with crest at −1 m	70 ± 7	45 ± 5	C-A5.inp
A5. Slope 1 to 20; Sill with crest at −0.5 m	25 ± 3	22 ± 3	C-A5.inp

Table 6. Wave climates (nearshore at −3 m MSL) of CROSMOR-model runs.

Days	Annual Wave Climate + 1 Extreme Storm During 1 Day			
	H_{rms} (m)	T_p (s)	Direction to North (deg.)	Storm Surge (m)
0.	0.5	4.0	10	0.
200; 17.,280,000 s	0.5	4.0	10	0.
201; 17,280,001 s	0.7	6.0	10	0.
300; 25,920,000 s	0.7	6.0	10	0.
301; 25,920,001 s	0.9	7.0	10	0.
360; 31,104,000 s	0.9	7.0	10	0.
361; 31,104,001 s	1.1	8.0	10	0.3
365; 31,536,000 s	1.1	8.0	10	0.3
366; 31,536,001 s	1.5	8.5	10	1.0
366; 31,622,400 s	1.5	8.5	10	1.0

The most striking features are:

- an almost horizontal (low gradient) terrace with bed level between −0.3 and −1 m is created along a straight beach profile, particularly for sand with d_{50} = 0.3 mm; the bed profile after 1 year is close to the 'equilibrium' profile, as the bed profile after 4 years is very similar to that after 1 year (**Figure 21**);
- the computed erosion volumes are much lower (factor 2 to 3) for a beach of coarse sand with d_{50} = 0.5 mm (c_u = 3) compared to medium fine sand with d_{50} = 0.3 mm (c_u = 2.5);
- the beach erosion along a straight beach with medium fine sand of d_{50} = 0.3 mm and slope of 1 to 15 (**Figure 20**) is slightly higher (10%) than that along a beach with slope of 1 to 20 (**Figure 21**); the upper beach slope (1 to 15 or 1 to 20) has almost no effect on the computed beach erosion for coarse sand with d_{50} = 0.5 mm;
- the annual beach erosion along a beach with a break in slope (1 to 20 down to −4 m and 1 to 15 down to the original seabed, see **Figure 22**, or 1 to 15 down to −4 m and 1 to 20 to the original sea bed, see **Figure 23**) is similar to that along a straight beach with slope of 1 to 20; the break in slope is quickly adjusted by local transport processes;
- the maximum erosion depth is about 2 m after 4 years for sand with d_{50} = 0.3 mm and about 1 m after 4 years for sand with d_{50} = 0.5 mm;
- the seabed activity along a straight beach is minimum below −6 m MS (closure depth); seaward directed transport processes occur on the landward flank of the bar and landward-directed transport processes on the seaward flank of the bar.

Overall, it is concluded that coarse sand (0.5 mm) is more stable (less erosion) than medium fine sand (0.3 mm). The effect of the upper beach slope (1 to 15 or 1 to 20) is marginal for coarse sand, but more pronounced for medium fine sand (upper slope of 1 to 15 leads to 10% more erosion). The effect of the lower beach slope (1 to 15 of 1 to 20) is marginal for all cases considered. The break in slope is quickly adjusted by transport processes. Hence, a lower beach slope reducing the overall volume of sand may be an attractive solution.

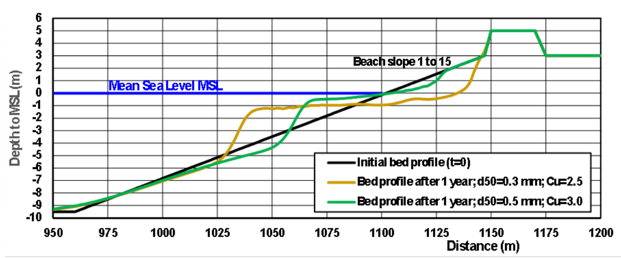

Figure 20. Straight bed slope 1 to 15 (A1).

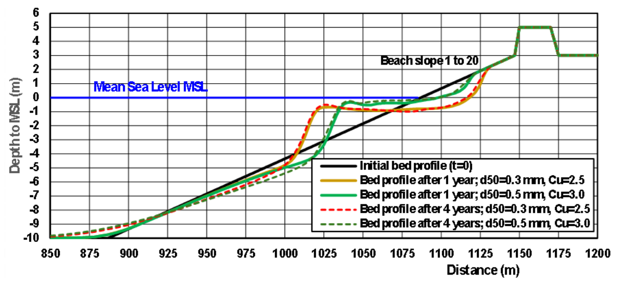

Figure 21. Straight bed slope 1 to 20 (A2).

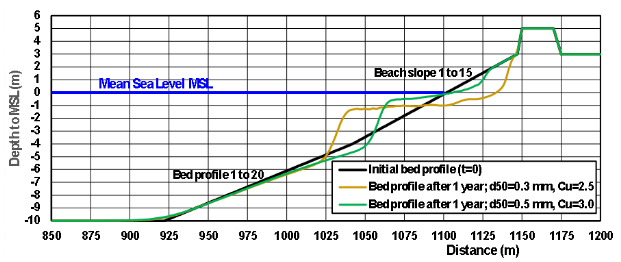

Figure 22. Break in slope with upper 1 to 15 lower 1 to 20 (A3.)

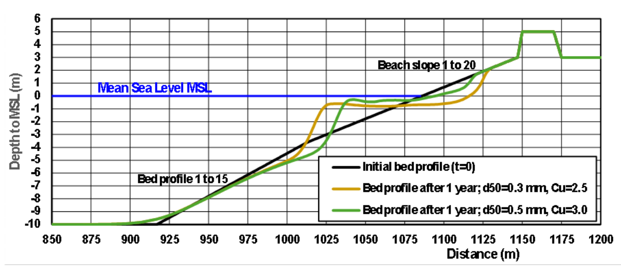

Figure 23. Break in slope with upper 1 to 20 lower 1 to 15 (A4).

If high-quality beach sand is scarcely available, it may be considered to construct a submerged sill at the toe of the beach. The sill extends to the original seabed, which may result in a rather high (and thus expensive) structure when the original seabed is deeplying (say at −10 m). **Figures 24** and **25** show the computed bed profiles after 1 year (waves, see **Table 4**) for the case with a submerged sill at the toe of the beach with slope of 1 to 20 and sand with d_{50} = 0.3 mm (c_u = 2.5) and d_{50} = 0.5 mm (c_u = 3.0). The maximum tide level is 0.6 m above MSL. The maximum water level including the surge level of 1 m is 1 + 0.6 = 1.6 m above MSL during the extreme storm event (t = 365 days to t = 366 days).

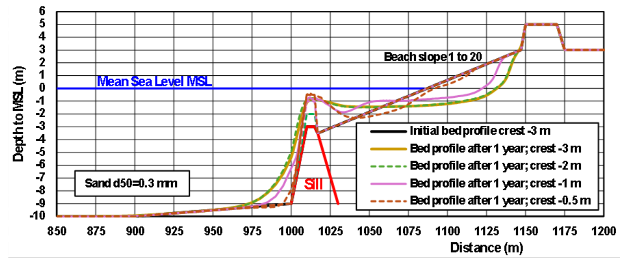

Figure 24. Beach with sill; erosion after 1 year; crest at −3, −2, −1 and −0.5 m; d_{50} = 0.3 mm, c_u = 2.5 (A5).

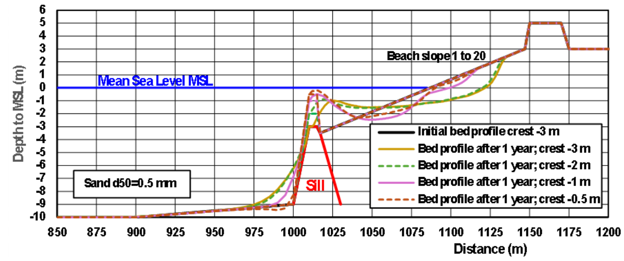

Figure 25. Beach with sill; erosion after 1 year; crest at −3, −2, −1 and −0.5 m; d_{50} = 0.5 mm, c_u = 3.0 (A5).

The computed beach erosion volumes are given in **Table 5**. The most characteristic features are:

- 0.3 mm sand: the beach erosion volume increases when a sill with crest at −3, −2 and −1 m is constructed at the toe of the beach, because the wave heights at the toe of the sill (in deep water) are relatively high; the beach erosion volume is a factor of 2 higher compared to that along a beach of 1 to 20 without a sill; a submerged sill with crest at −1 m below MSL also offers less protection against beach erosion than the subtidal low-gradient terrace (at about −0.8 m, see **Figure 21**) formed along a straight beach without sill;
- 0.5 mm sand: the beach erosion volume decreases by about 30% compared to that for sand of 0.3 mm; this decrease of beach erosion is much less than for the cases without a sill.

In micro-tidal conditions with a tidal amplitude of 0.6 m, the crest level should be rather high at −0.5 m below MSL. The model results show that a high sill crest at −0.5 m (Case A4) can reduce the beach erosion substantially to about 25 m^3/m after 1 year, (**Table 5**) which a factor of 2 lower than that along a straight beach slope of 1 to 20 without sill (Case A2). The computed local deposition of sand on top of the sill for low crest levels is not realistic, as it will be removed by extra turbulence due to wave breaking (not included in model).

Sills with crest-level at −3, −2 and −1 m are not very effective. The main reason is relatively high waves can pass over the sill in conditions with a tidal amplitude of 0.6 m resulting in a maximum water depth of 1 + 0.6 = 1.6 m. This was also found by Musumeci et al. [10] for a perched beach with sill crest at −2.5 m below MSL. at a coastal site in Italy. The observed beach erosion at the field site with sill (crest width = 10 m) was of the order of 10 to 15 m after 2 years. They found that beach erosion can be reduced by using an armour layer of 10 m behind the crest (wider crest of 20 m instead of 10 m) causing more wave damping. The effect of a higher crest level was not studied. Groenewoud et al. [8] made a scale model (1 to 15) of a sill protecting a beach with slope of 1 to 15 (sand d_{50} = 0.1 mm). The sill crest was at −1.5 m. The approach storm wave height was $H_{s,o}$ = 2 m at depth of 6 m (on seaward side of the sill). The beach erosion was about 55 m^3/m after about 32 hours (15,000 waves) in the case without a sill (straight beach only) and about 15% less in the case with sill, see **Figure 26**. The eroded sand was deposited against the sill slope, rather similar to the results of **Figures 24** and **25** (additional validation of CROSMOR-model for the case with a sill). It is concluded that a sill with crest at −1.5 m is not very effective (only 15% reduction of beach erosion).

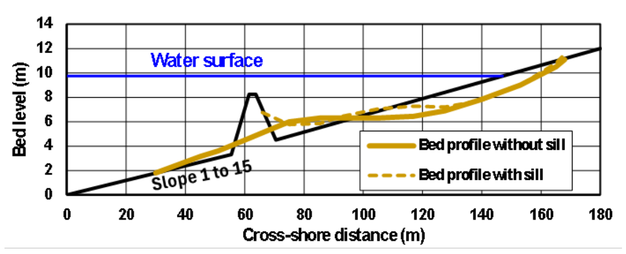

Figure 26. Bed profiles with and without sill after Groenewoud et al. [8].

If sand is sufficiently available, it may be more attractive (instead of a sill) to construct a straight beach with a slope of 1 to 20 or with a break in slope (upper: 1 to 20; lower: 1 to 15; no sill) to reduce on the total volume of sand. The upper beach can be made of high-quality sand whereas the lower beach can be made of low-quality fill sand. Using this latter approach, the construction of a massive (expensive) sill can be avoided.

Figure 27 shows the computed bed profiles at different time moments: after 300 days with waves up to H_{rms} = 0.7 m, after 365 days with waves up to H_{rms} = 1.1 m and after 366 days with 1 day of extreme storm waves of H_{rms} = 1.5 m and surge of 1 m high. The total beach erosion after 300 days is about 30 m^3/m and about 70 m^3/m after 365 days. Hence, most the erosion occurs during the time (65 days) with higher waves (H_{rms} = 0.9 and 1.1 m) The effect of the extra day with storm waves on the computed erosion is minor, because the bed profile at the start of the extreme storm is close to the equilibrium bed profile.

In a mild wave climate, it may be considered to construct straight beaches without a submerged sill. The slope of the upper beach can be safely designed as 1 to 15. An alternative solution is an upper beach at 1 to 20 in combination with a lower beach of 1 to 15. It is sufficient to extend the high-quality upper beach layer down to −4 m MSL, where the morpho-dynamic activity of the sea bed is low. The construction of straight beaches requires more sand (most coarse beach fill material), but saves the construction of the submerged sills. It is noted that the placement of more (graded) fill material may lead to slightly increased turbidity levels.

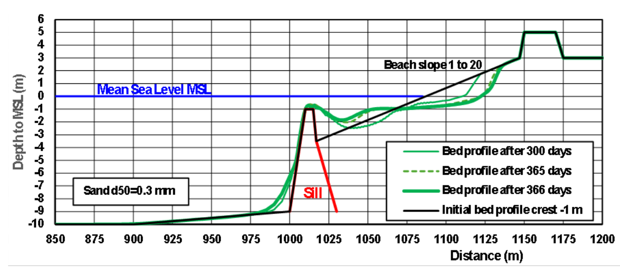

Figure 27. Beach with sill; erosion after 1 year; crest at −1 m; sand d_{50} = 0.3 mm, c_u = 2.5 (A5).

4.5. Effect of Beach Slopes and Submerged Breakwater at Exposed Beaches

Bijl et al. [11] have shown that the construction of a rock-type submerged breakwater with relatively high crest level just below MSL is also feasible in conditions with an energetic swell climate along the coast of Nigeria, Africa. The breakwater was constructed at a depth of about 6 m below MSL. The initial beach slope in the lee of the breakwater was set to 1 to 10, which was later reshaped by natural processes (slope of 1 to 30).

Herein, two other example cases are presented: 1) land reclamation beach at Mediterranean coast and 2) large-scale beach fill at Holland coast.

4.5.1. Mediterranean Coast

A major land reclamation of sand with d_{50} = 0.22 mm is situated along the coast of Egypt. The maximum coastal extension is 2200 m. The alongshore length of the beach is about 5000 m. The upper beach slope is 1 to 20 and the lower beach slope is 1 to 30. To protect the land reclamation against erosion and to reduce the sand fill volume as much as possible, a high submerged breakwater is built in deep water to enclose the beach, **Figure 28**. The offshore significant wave heights are up to 5 m with peak period of 10 s. Wave directions are up to 20° with respect to the shore normal (File: AQ1AN.inp). The maximum surge level is estimated to be 0.5 m during a storm event. Tidal variations are absent. **Figure 28** shows computed bed profiles after 1 year for a crest level of −2 m and −1 m. The beach erosion is very minor for a crest at −1 m. The deposited sand at the upper seaward flank of the structure is not realistic, because this part of the structure will be severely attacked by violent wave breaking with additional turbulence causing local scour and deposition at lower levels. These latter processes are not included in the model. The scour on the landward flank of the structure is realistic.

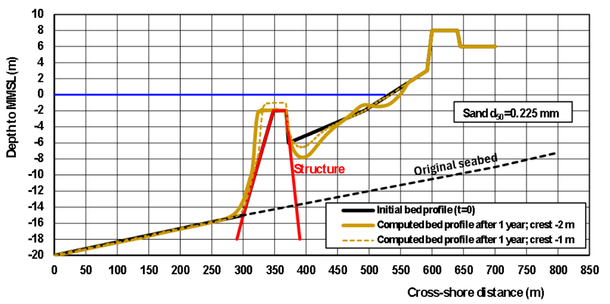

Figure 28. Computed cross-shore bed profiles, land reclamation Egypt coast, Mediterranean.

4.5.2. Large-Scale Beach Extension along North-Holland Coast, The Netherlands

A large-scale beach extension project was made in 2014 to replace the old sea dike by a natural beach-dune system over a distance of about 10 km. The maximum coastal extension of sand with d_{50} of about 0.2 to 0.25 mm is about 450 m, **Figure 29**. The upper beach slope above NAP (MSL) is 1 to 50 and the lower beach slope is 1 to 30. The construction of a submerged breakwater is no option, as fill sand is abundantly available at nearby borrow sites. The beach fill volume between the old sea bed and the dune crest is of the order of 5000 m^3/m resulting in a total volume of about 30 million m^3 over a distance of 10 km. The dune is designed to withstand a storm with a return period of 10,000 years ($H_{s,o}$ = 10 m, T_p = 16.2 s, surge level = 5.5 m above NAP). The crest level of the sand dune is at 12 m above NAP. The dune erosion volume during the design storm is estimated to about 375 m^3/m including 30% uncertainty. The total available dune volume above the maximum water level during the design storm (return period of 10,000 years) is about 450 m^3/m. As the beach fill area protrudes over a distance of about 450 m into the sea, the upper and lower beach show continuous erosion due to cross-shore and longshore transport processes requiring regular beach maintenance (placement of sand layer with thickness of about 2 m every 5 years). The total erosion is estimated to be in the range of 0.5 to 1 million m^3 per year. **Figure 29** shows the initial bed profiles including a beach wear layer and computed cross-shore bed profiles after 1, 3 and 5 years (CROSMOR-model) for a wave climate with offshore waves up to 6 m, peak periods up to 12 s, directions up to 30° with respect to the shore normal. The tidal range is about 2 m. The computed beach recession is 70 m after 1 year (erosion volume = 140 m^3/m) and 90 m after 5 years (erosion volume = 210 m^3/m). The eroded sand is deposited as a nearshore breaker bar.

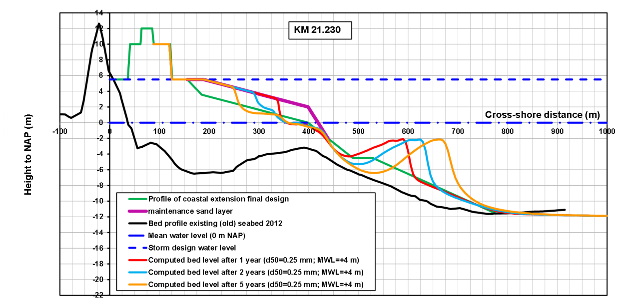

Figure 29. Computed cross-shore bed profiles, beach fill North-Holland coast, The Netherlands.

5. Beach Erosion Due to Longshore Processes

5.1. General

Beach erosion due to longshore transport processes is minimum if the beach line of the planform is perpendicular to the main wave direction (or equilibrium coastline orientation). If there are two main wave directions, the beach may show a rotational behavior around the main wave direction depending on the actual wave climate from year to year. It may not always be possible to construct the new beach line with the equilibrium coastline angle. Sometimes, it is more aesthetic to follow the existing coastline orientation. However, it should be realized that the larger the deviation from the equilibrium coastline, the larger the net longshore transport which may result in marked coastline changes (rotation). The new beach will try to gradually change (rotate) to the equilibrium orientation. This can only be prevented by regular maintenance works, moving sediments back to keep the original coastline intact or by groyne structures.

5.2. Equilibrium Beach Line Orientation

The equilibrium beach line orientation can be found by computing the net longshore sand transport (LST) as function of the beach line angle for the available long term wave climate. An example land reclamation with a submerged breakwater in Egypt is discussed herein. The mean wave direction is 313° to North (wave vector angle is 133° to N). The wave data are given in **Table 7**. Three longshore sand transport equations have been used: CERC (Shore Protection Manual[14], Kamphuis[15, 16] and Van Rijn[17]. The net LST-values (in m^3/year) are computed for shore normal angles of 128° to 140°. The basic input values are: sand with d_{50} = 0.25 mm, sand porosity = 0.4, beach slope of 1 to 50, wave breaking coefficient = 0.7, offshore water depth = 35 m. **Figure 30** shows the net LST-values of three equations for a long beach without submerged breakwater. Positive LST-values are to south-west and negative values to north-east. The net LST-value of the three equations is zero for shore normal angles in of 132°–134°. Let us assume that the beach is constructed with a shore normal angle of 133° with an inaccuracy of 1°. The LST of the CERC-equation is most sensitive to the coastline orientation. If the shore normal angle is 134° instead of 132°, the net LST changes from −60,000 m^3/year (to NE) to +100,000 m^3/year (to SW) based on the CERC-equation. The results of the other equations produce lower net LST-values. The LST-equation of Van Rijn[17] is also applied for d_{50} = 0.2 mm and 0.3 mm giving 15% to 20% higher and lower net LST-values compared to the values for d_{50} = 0.25 mm. It is noted that the actual net LST-values are substantially lower (factor 3) due to the presence of a submerged breakwater, which significantly reduces the wave height at the breaker line and thus the longshore transport. Taking this into account, the net LST-values along this beach are estimated to be in the range of +20,000 to −33,000 m^3/year (factor 3 lower). The precise direction of the net LST cannot be predicted given the variations of the three equations for shore-normal angles in the range of 132°–134°.

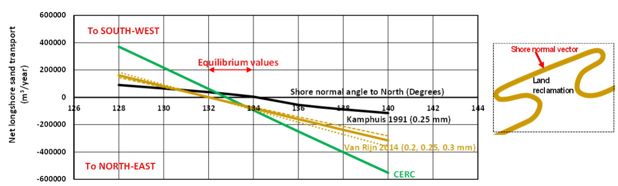

Figure 30. Net longshore sand transport as function of the shore-normal angle, land reclamation Egypt.

Table 7. Percentage of time (days per year) for a certain offshore significant wave height class per wave direction (coming from); values are mean values over 20 years.

	W.H	(m)	0.375	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	5.25	5.75	6.25	6.75	(m)	
W.D																		
(Deg. To north																		
0			3.285	7.008	1.57	0.402	0.102	0.029	0.011	0.007	0.007	0	0	0	0	0		
15			2.774	5.731	1.716	0.27	0.051	0.018	0	0	0	0	0	0	0	0		
30			3.066	7.738	2.154	0.365	0.044	0.007	0	0	0	0	0	0	0	0		
45			3.614	8.249	1.497	0.055	0	0	0	0	0	0	0	0	0	0		
60			2.774	1.679	0.007	0	0	0	0	0	0	0	0	0	0	0		
225			0.004	0	0	0	0	0	0	0	0	0	0	0	0	0		
240			1.059	1.205	0.438	0.139	0.029	0.011	0	0	0	0	0	0	0	0		
255			0.438	1.168	0.949	0.73	0.402	0.204	0.128	0.018	0.004	0	0	0	0	0		
270			0.475	1.57	1.789	1.46	0.949	0.584	0.314	0.128	0.062	0.018	0	0	0	0		
285			0.767	3.431	3.942	2.993	1.716	1.059	0.584	0.281	0.234	0.117	0.037	0.007	0	0		
300			2.409	19.42	17.59	7.556	2.884	1.424	0.767	0.438	0.201	0.117	0.062	0.033	0.007	0		
315			7.775	52.27	34.02	11.46	4.307	1.898	0.986	0.657	0.438	0.175	0.11	0.066	0.015	0.011		
330			8.103	40.77	24.2	8.578	3.103	1.46	0.657	0.339	0.201	0.08	0.018	0.007	0	0		
345			4.599	12.3	3.139	0.986	0.365	0.201	0.062	0.037	0.438	0	0	0	0	0		
Total			41.14	162.5	93.01	34.99	13.95	6.895	3.508	1.905	1.584	0.507	0.226	0.113	0.022	0.011		360.3974

5.3. Beach Rotation and Changes

Two examples are studied for exposed coasts: 1) land reclamation along Mediterranean coast and 2) beach extension along North-Holland coast, The Netherlands

5.3.1. Land Reclamation Along Mediterranean Egypt Coast

The angle of the shore normal of the beach is 133° to N. The results of **Figure 30** show that the net LST is approximately zero for a shore normal angle (equilibrium angle) in the range of 132° to 134°. Given this range, the beach orientation may adjust itself slightly (rotate) over an angle of 1° to get a new orientation perpendicular to the main wave direction, see **Figure 31**. The maximum beach change at the alongshore end of the beach is $\Delta y_{max} = 0.5 L_{beach} \tan(\beta_r)$ with L_{beach} = beach length, β_r = deviation angle from equilibrium shore normal angle (rotation angle). Using $\beta_r = 1°$ and $L_{beach} = 5000$ m, the maximum beach change is $\Delta y_{max} = 0.5 \times 0.017 \times 5000 \cong 45$ m. The time scale of beach adjustment (rotation) can be estimated from the sand balance: $Q_{LST}\ \Delta T = 0.25\ \Delta y_{max}\ L_{beach}\ h_a$ or $\Delta T = (0.25\ L_{beach}\ h_a)/Q_{LST}$, with: ΔT = time period (in years), Q_{LST} = net annual LST at mid beach point (in m^3/year), h_a = later thickness of active littoral zone (m). Using: $Q_{LST} = 33{,}000\ m^3$/year (situation with submerged breakwater), $L_{beach} = 5000$ m, $h_a = 6$ m, the time scale of beach adjustment (rotation) is $\Delta T \cong 0.25 \times 45 \times 5000 \times 6/33{,}000 \cong 10$ years.

The maximum beach change at the end of a long beach can be reduced significantly by the construction of short groynes to make smaller compartments. Using three groynes, the length of each compartment is $L_{compartment} = 1250$ m and the maximum beach change per compartment is $45/4 \cong 11$ m. The net LST in each short compartment will be much lower (factor 2 to 3) than that in a long compartment, because the wave-induced longshore current is reduced substantially and cannot fully develop due the presence of the short groynes. Using: $Q_{LST} = 15{,}000\ m^3$/year and $L_{compartment} = 1250$ m, the time scale for beach adjustment (rotation) is $\Delta T \cong 0.25 \times 11 \times 1250 \times 6/15{,}000 \cong 1.4$ years.

The LONGMOR-coastline model has been used to show the beach rotation for a deviation angle of 5°. The initial coastline is horizontal with terminal groynes at both ends (zero LST). The wave height is $H_{s,o} = 1.5$ m, $T_p = 6$ s (constant). The wave direction is set to 5° with respect to the shore normal (file: ABUQ1.inp). The maximum net longshore sand transport (LST-equation of Van Rijn[17] is calibrated to be 100,000 m^3/year.

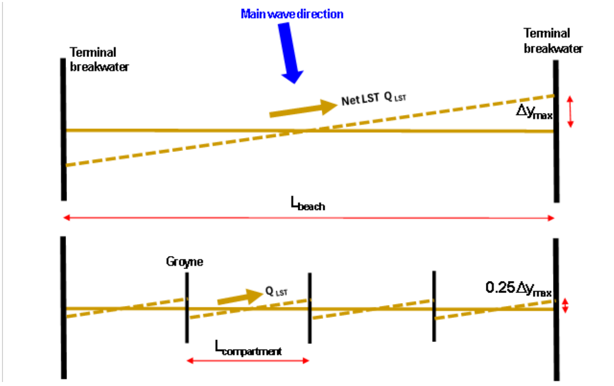

Figure 31. Beach adjustment (rotation) to the main wave direction; long beach without groynes (upper) and beach with compartments (lower).

Figure 32 shows the computed coastline after 15 years. The coastline has rotated over about 5° (tan5° = 0.0875) so that the new coastline is perpendicular to the wave direction. The maximum coastline change at the end is 210 m ($\tan\beta_r$ = 210/2500 = 0.084). The net LST averaged over 15 years is zero at both ends and maximum in the middle (parabolic distribution). The maximum coastline change can be reduced by placing groynes to create shorter compartments. This example shows that the coastline changes are minor if the beach line orientation is close to the equilibrium value. The time scale of adjustment is determined by the value of the net LST.

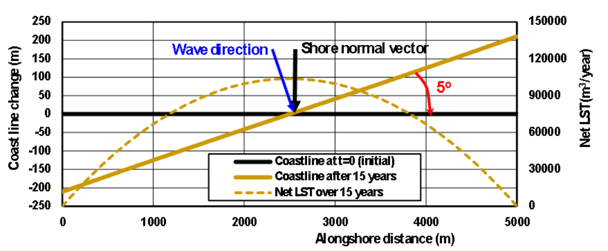

Figure 32. Computed beach rotation for deviation angle of 5°; d_{50} = 0.25 mm; maximum net longshore transport (LST) ≅ 100,000 m^3/year.

5.3.2. Beach Extension North-Holland Coast, The Netherlands

A new beach-dune system has been made seaward (extension of 450 m) of the sea dike (HBP) between the villages of Camperduin and Petten along the North-Hollands coast, The Netherlands, see **Figure 33** and **29**. The required volume of sand is about 5000 m^3/m resulting in a total volume of 30 million m^3 over the length of the extension. The seaward flank of the old HBP sea dike is now buried under a layer of sand, see also **Figure 29**. The new beach-dune system of sand (d_{50} = 0.21–0.25 mm) is parallel to the old sea dike which is far from the equilibrium coastline orientation with zero net LST. The shore normal vector (from sea to shore) of the old sea dike is 98° to north, whereas the equilibrium shore normal angle is about 80° to N. Hence, this relatively large deviation from the equilibrium angle leads to relatively large net LST-values in the range of 200,000 to 400,000 m^3/year to North[13].

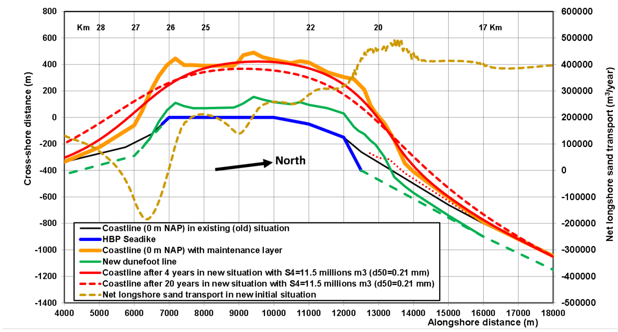

Figure 33. Computed net longshore sand transport (positive to North) and coastline changes, new beach-dune system, North-Holland coast, The Netherlands.

The LONGMOR-coastline model has been used to compute the net LST along the new coastline and the associated coastline changes over 20 years using the LST-equation of Van Rijn[17]. The effects of regular beach nourishment (scheme 4; S4) are included: an initial nourishment (buffer layer) of 4 million m^3 and 3 repeated nourishments of 2.5 million m^3 after 4, 9 and 15 years in the beach sections km 20–22 and km 25–27 (see **Figure 33**). The thickness of the active zone is set to 9 m.

Figure 33 shows the computed coastlines after 4 and 20 years for sand with d_{50} = 0.21 mm. The total maintenance volume is 4 + 3 × 2.5 = 11.5 million m^3 over 20 years. The net longshore sand transport for the new initial situation is shown on the right axis (positive values to North). The net LST is 200,000 m^3/year on the south boundary and 400,000 m^3/year on the north boundary. The maximum coastline recession is about 100 m at km 20.5 and about 150 m at km 26. The beach width remains at 150 m at these locations which is sufficient for safety and beach recreation. This example shows that massive beach nourishment at regular intervals is required to maintain the new beach system in a situation where the beach line orientation is far from the equilibrium value. This is only feasible if sand is abundantly available from nearby borrow sites.

6. Conclusions

The focus point (purpose) of this paper is the design of artificial (perched) beaches for recreation at sheltered sites, but examples for exposed sites are also presented. Highly sustainable sand is used as building material. Alternative building materials (dolomite or crushed concrete) are not considered.

The requirements for a well-designed artificial beach are: 1) safety against wave overtopping and flooding (sufficiently high crest level and beach-dune volume); 2) mild beach slopes to minimize beach erosion; 3) stable material with high erosion resistance (0.3–0.6 mm sand); 4) good permeability for drainage of the beach sand; 5) beach line orientation close to the equilibrium value (perpendicular to main wave direction); and 6) aesthetic appearance in accordance with that of local beaches.

One of the prime coastal management strategies is to minimize beach erosion (hold the line), which can be achieved by a design in which the beach line orientation and beach slope are close to the equilibrium values. If possible, the beach line orientation should be (almost) perpendicular to the main wave direction, otherwise the beach will try to adjust itself (rotate) to the main wave direction due to longshore transport processes. The design of the beach slope close to the equilibrium value (mild slopes in sandy conditions) requires a relatively large volume of sand. A milder beach slope is more dissipative with spilling type of breaking waves resulting in less erosion and thus less maintenance works. If high-quality beach sand is scarce, the volume of sand and beach erosion can be minimized by constructing a submerged sill/breakwater at the toe of the beach. The sill should have a high crest level (−1 m below MSL) and/or a wide crest (20 m) for sufficient wave damping. Sills with a low crest level are not effective[8, 10]. Analysis of costs shows that the construction costs of a submerged sill/breakwater at the toe of the beach including maintenance over a period of 50 years are about the same of that for beach fills including regular maintenance. This means that the beach fill volume can be twice as large for a solution without a sill (same overall costs). So, if sand is sufficiently available locally (not scarce), the construction of a sill at a sheltered coastal site with mild wave conditions is not an attractive solution from an economic point of view.

The design of an artificial beach along an exposed coast with a relatively steep and deep foreshore mostly requires a large-scale submerged breakwater to enclose the lower end of the underwater beach, otherwise the required volume of sand may be excessively high. Often, two terminal groins are constructed on both ends of the planform of the beach, which are connected to the submerged breakwater. Generally, this is only economically feasible for large-scale land reclamations.

A process-based numerical model (CROSMOR) for cross-shore sand transport and morpho-dynamics has been used to study the effects of sand size (d_{50}), grading (uniformity coefficient $c_u = d_{60}/d_{10}$), runup level, beach slopes and the effect of a submerged sill/breakwater on the beach erosion volume at the upper beach. Three field cases at sheltered sites have been used for calibration/validation of the CROSMOR-model. The CROSMOR-model produces realistic results for beach-dune erosion in mild and extreme wave conditions, but the model has not yet been validated for situations with a submerged sill/breakwater at the toe of a beach. So, the model may be less reliable for this case. Future work should focus on model validation for perched beaches with a sill.

Based on the modelling results, the beach erosion volume decreases for coarser sand. Beach erosion increases slightly for increasing c_u-values (more graded sand). Comparison of the erosion for a beach consisting of relatively coarse sand with d_{50} = 0.5 mm and c_u = 3 with that of a beach with sand of d_{50} = 0.3 mm and c_u = 2.3 shows much lower erosion for the coarse beach sand.

To prevent wave overtopping and flooding of the hinterland, the dune crest level of an artificial beach should be above the maximum runup level. Based on model computations, the maximum runup level for a sheltered site is approximately 2 m above mean sea level (MSL). Including a margin of 1 m, a safe beach crest level of a sheltered beach in micro-tidal conditions is minimum 3 m above MSL.

If high-quality sand is abundantly available, the slope of the artificial beach at sheltered sites is commonly in the range of 1 to 15 and 1 to 30 in conditions with a micro tidal range and mild waves. Slopes between 1 to 30 and 1 to 50 are used for more open exposed coastal sites. The beach width increases for a milder beach slope which is attractive for densily populated areas, but a milder slope requires a larger construction volume of sand.

The modelling results show that the effect of the upper beach slope (1 to 15 or 1 to 20) on beach erosion is marginal (<10%) for sand in the range of 0.3 to 0.5 mm. In the case of a beach with a break in slope, the effect of the lower beach slope (1 to 15 of 1 to 20) is marginal for all cases considered. The break in slope is quickly adjusted by transport processes.

If sand is abundantly available, the artificial beach can be constructed down to the original sea bed (without a sill). The volume of high-quality beach sand required may be reduced by constructing a steeper lower beach slope or placing a submerged sill at the toe of the beach. Various alternative designs have been studied and compared based on modelling results. A high sill crest at -0.5 m can reduce the beach erosion substantially. At exposed sites, a submerged breakwaters at the toe of an artificial beach is also feasible (Egypt, Mediterranean) but the dimensions of the structure are massive (expensive). The construction of an artificial beach without a submerged breakwater along an open, exposed coastal site is also feasible (North-Holland coast), but beach erosion generally is significant requiring massive regular beach nourishments (maintenance every 5 years).

Beach erosion due to alongshore transport processes is minimum if the beach line of the planform is perpendicular to the main wave direction (equilibrium coastline orientation). It may not always be possible to construct the new beach line at the equilibrium coastline angle. Sometimes, it is more aesthetic to follow the existing coastline orientation. However, it should be realized that the larger the deviation from the equilibrium coastline, the larger the net longshore transport which may result in marked coastline changes requiring maintenance works. The new beach will try to gradually change (rotate) to the equilibrium orientation. The equilibrium beach line orientation can be found by computing the net longshore sand transport (LST) as function of the beach line angle for the available long term wave climate. The maximum beach change at the alongshore end of the beach depends on the beach length and the deviation angle. The time scale of adjustment follows from the value of the net longshore sand transport. The maximum coastline change at the end of a long beach can be reduced by placing groynes to create shorter compartments.

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The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

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