



## **DESIGN OF BEACH-DUNE SYSTEM FOR COASTAL PROTECTION**

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**ANNEX A: Beach-Dune-Erosion (DR) model**

**ANNEX B: Longshore sand transport**

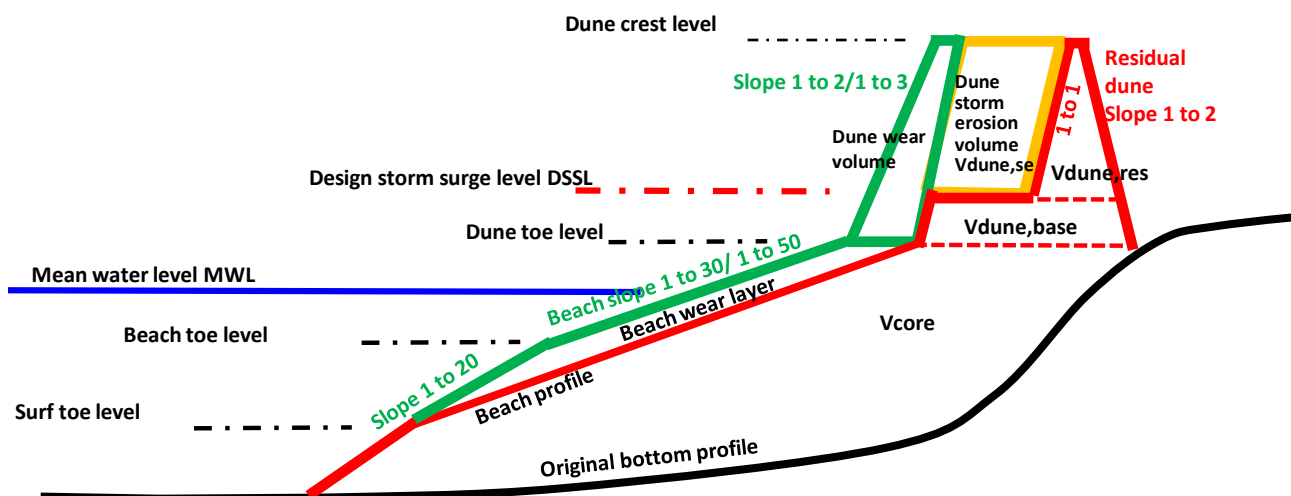
**ANNEX C: DUROS+ model**



## 1. Introduction

The design of a beach-dune system for protection of the land surface against flooding under extreme storm conditions requires the schematization of the cross-shore profile in various zones (**Figure 1.1**), as follows:

- residual dune profile/volume (**red line, Figure 1.1**); which is the profile that is supposed to remain to be present after an extreme design storm (with a return period in the range of 1000 to 10000 years); the residual volume ( $V_{\text{dune,res}}$ ) 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 ( $V_{\text{dune,se}}$ ) toe level (including all uncertainties);
- dune base volume; which is the volume ( $V_{\text{dune,base}}$ ) between the dune toe level and the design storm level and can be determined if the dune crest width, the dune front and back slopes and the dune toe level are known;
- dune wear zone/volume; which is the additional (extra) volume ( $V_{\text{dune,wear}}$ ) in the dune zone that should be present above the dune toe level to account for all erosion losses during a reasonable economic lifetime period (say 10 to 50 years);
- beach wear zone/volume, which is the additional (extra) volume ( $V_{\text{beach,wear}}$ ) in the beach zone between the beach toe level and the dune toe level to account for erosional beach losses during a reasonable maintenance period (say 5 to 10 years);
- dune-beach core zone; which is the volume ( $V_{\text{core}}$ ) enclosed by the beach profile, the dune toe level, the dune-back profile and the original sea bottom..



**Figure 1.1** Cross-shore profile of beach-dune system

Dunes protecting the coast should be relatively high. The dune crest should at least be at a level which is two times higher than the design storm surge level to prevent overwashing. Erosion due to overwashing is more severe than dune impact erosion.

The design conditions are defined for a return period of 1000 to 10000 years, depending on the economic values of the mainland facilities.

The total duration of an extreme storm event is defined to be in the range of about 24 hours. A storm related to the generation and movement of a low-pressure field generally consists of three phases:

- growing phase (of 6 to 12 hours);
- stabilisation phase with approximately constant wind speeds and wave heights (about 3 to 6 hours; peak of the storm);
- waning phase (6 to 12 hours).



The design storm parameters refer to the peak of the storm with duration of 6 to 12 hours. Sea level rise (order of 0.3 to 0.5 m) should be taken into account considering an economic life time period of say 50 years of the planned beach-dune construction.

The residual profile is the minimum profile that must remain present at the end of the design storm with maximum dune erosion. The minimum crest height of the residual dune above the storm level should be slightly higher than the wave-induced swash uprush height ( $R$ ), which is given by  $R \cong 0.375 \sin \alpha (H_{s,toe} L_{toe})^{0.5}$  with  $H_{s,toe}$ =significant wave height at toe of residual dune,  $L_{toe}$ =wave length at toe and  $\alpha$ = dune front slope angle (Stockdon et al. 2006). Assuming  $\sin \alpha \cong 0.7$  (steep slope),  $H_{s,toe} \cong 0.5 H_{s,o}$  and  $L_{toe} \cong 0.5 L_o$  with  $H_{s,o}$  and  $L_o = 1.56 T_p^2$  being the deep water values, it follows that  $R \cong 0.15 T_p H_{s,o}^{0.5}$  with  $T_p$ = peak wave period. Using:  $T_p = 7$  s and  $H_{s,o} = 3$  m, it follows that  $R \cong 2$  m. The dutch guidelines prescribe a minimum crest height of 2.5 m above the design storm level, minimum crest width of 3 m, minimum front slope of 1 to 1 and minimum back slope of 1 to 2.

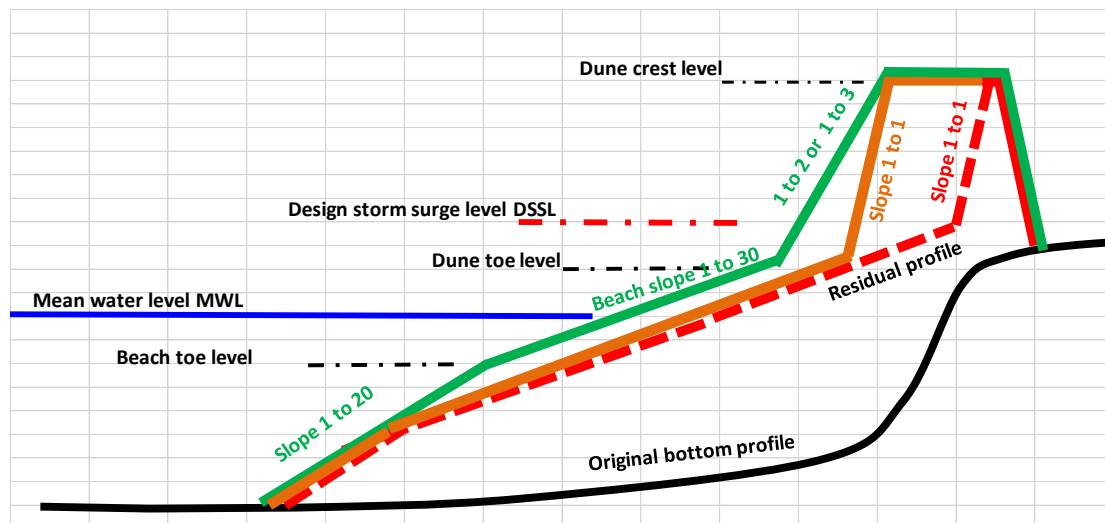
The design volume per unit width (in  $m^3/m$ ) is given by:

$$V_{\text{design}} = V_{\text{dune,se}} + V_{\text{dune,res}} + V_{\text{dune,base}} + V_{\text{dune,wear}} + V_{\text{beach,wear}} + V_{\text{core}} \quad (1.1)$$

(Note: erosion volumes are given in red).

The total design volume can be obtained by alongshore summation of the volumes per unit width of all location values. The design volume should also include the transition zones to the original shoreline (bay-type beach zones).

$$\text{The construction volume is: } V_{\text{construction}} = V_{\text{design}} + V_{\text{loss,fines}} + V_{\text{loss, compaction}} \cong 1.2 V_{\text{design}} \quad (1.2)$$



**Figure 1.2** Cross-shore beach-dune profiles;  
**Green profile**= construction profile including wear layer;  
**Brown profile** = safety profile just before extreme storm event (excl. wear layer);  
**Red profile** = residual profile after extreme storm

The construction volume is the volume that should be placed at the site by the dredging contractor, see **Figure 1.2**. It includes the loss of fine sediments ( $<100 \mu m$ ; beach sand of 0.2 to 0.25 mm contains about 10% of fines) and the volume loss due to compaction of the subsoil under the impact of the placed sand body and the compaction of the sand body itself. Detailed compaction/consolidation computations are required to get an estimate of the compaction losses. The compaction of the sand body is of the order of 5% to 10%. The compaction of the subsoil strongly depends on the presence of peat and clay layers. The compaction effect can be accounted for by using a construction profile with proper overheight (range of 0.5 to 1 m).



The total construction volume over the alongshore coastal section considered should be determined by using an alongshore grid of 100 to 300 m, depending on the irregularities of the original coastline and the sea bottom. The grid size can be relatively large in the case of very uniform sections. The new coastline should have a smooth appearance in planview; irregularities should be smoothed out as much as possible starting at the most protruding (seaward) locations.

Herein, a simplified method is proposed for the design of a beach-dune system of lake and sea coasts to protect the coastline.

## **2. Hydrodynamic conditions**

The required hydrodynamic data are:

- nearshore tidal water levels and current velocities (at edge of surf zone) during mean/spring tide;
- nearshore wind-driven velocities of storm events with return period of 1, 10 and 100 years;
- nearshore water level setup due to wind for return period of 1, 10, 100, 1000 and 10000 years;
- annual wave climate (significant wave height  $H_{s,0}$ , peak wave period  $T_p$ , wave incidence angle  $\theta_o$  to North or to the shore normal) at offshore depth;
- storm wave conditions at offshore depth ( $H_{s,0}$ ,  $T_p$ ,  $\theta_o$ , duration) for return period of 1, 10, 100, 1000 and 10000 years

Wave models are required to translate the offshore wave conditions to nearshore wave conditions.

## **3. Beach and dune characteristics**

The beach zone is defined as the zone between the beach toe level and the dune toe level. The dune toe level strongly depends on the tidal range and generally varies in the range of 2 to 4 m above mean sea level (MSL).

The beach toe level also depends on the tidal range and varies in the range of 1 to 3 m below MSL. The following values can be used:

Sea coasts: dune crest at +10 m MSL (mean sea level); dune toe at +3 m MSL; beach toe at -3 m MSL;

Lake coasts: dune crest at +5 m MSL (mean sea level); dune toe at +1 m MSL; beach toe at -1 m MSL.

Generally, beach and dune extensions/reinforcements are constructed using sandy materials from offshore borrow pits. Bore hole data should be used to determine the sand composition over the depth of the borrow pit. Often, finer sands are present in the top layers and coarser sands in the deeper layers of the borrow pit. The coarsest sand should be used for the beach and dune zones; the finer sands can be used for the surf zone bed below the beach toe level (< -1 m below mean sea level MSL). The sand fraction smaller than  $62 \mu\text{m}$  (fine sand and silt) in the surf zone below the beach toe level should not be larger than about 10% to prevent excessive erosional losses. The variation range of the  $d_{50}$ -values of beach and dune sands should be smaller than about  $100 \mu\text{m}$  (range of 200 to  $300 \mu\text{m}$ ).



TIDAL ENVIRONMENT	SAND SIZE (mm)	BEACH SLOPE +3/0 m lines	SURF ZONE SLOPES		BARS
			0/-3 m lines	-3/-6 m lines	
NON-TIDAL MICRO-TIDAL (0 - 2 M)	0.5 - 1	1:10	1:30	1:100	one/two
	0.2 - 0.5	1:20	1:50	1:150	multiple
	0.1 - 0.2	1:30	1:80	1:250	multiple
MESO-TIDAL (2 - 4 M)	0.5 - 1	1:10	1:30	1:100	one/two
	0.2 - 0.5	1:20	1:80	1:200	multiple
	0.1 - 0.2	1:30	1:100	1:300	multiple
MACRO-TIDAL (4 - 8 M)	0.2 - 0.5	1:30	1:80	1:250	flat (no bars)
	0.1 - 0.2	1:30	1:200/500	1:200/500	megaripples/ridges
MACRO-TIDAL (8 - 12 M)	0.2 - 0.5	1:30	1:100	1:300	flat (no bars)
	0.1 - 0.2	1:30	1:200/500	1:200/500	megaripples/ridges

- Remark 1 Bottom slopes in outer surf zone are often controlled by topographic and geologic factors (sediment availability, rigid layers, bed rock, canyons, shelf)
- Remark 2 Beach slopes generally are somewhat steeper during accretional stages and flatter during erosional stages
- Remark 3 Beach slope is defined as line between +3/0 m lines, etc.
- Remark 4 Upper beach slope of macro-tidal beaches consisting of very fine sediments (0.1 to 0.5 mm) may be rather steep (1:10), when relatively coarse materials are deposited on upper beach.

**Table 3.1** Beach and surf zone slopes along sandy coasts (Van Rijn 1993)

It is recommended to use the smallest  $d_{50}$ -value (lower limit) of the size range of the borrow pit sand for the determination of the dune erosion volume of the design storm. Using this approach, the most conservative estimate is obtained.

A conservative estimate can also be obtained using the expression:

$$d_{50,r} = \mu_{d50} - 5(\sigma_{d50}/\mu_{d50})\sigma_{d50}$$

with:  $\mu_{d50}$  = mean  $d_{50}$ -value of all samples from borrow site;  
 $\sigma_{d50}$  = standard deviation of  $d_{50}$  of all samples of borrow site.

The  $d_{50}$ -values of the beach material after construction should be verified by taking field samples (three samples per location at HW, MSL and LW-lines; alongshore spacing of 200 m). If the observed values are significantly smaller (> 20%) than the design values, the design computations should be repeated and the construction volume should be increased.

The equilibrium beach slope of sandy beaches depends on the beach material size, the wave climate and the tidal range and are given in **Table 3.1**.

The bed slope is steeper for increasing sediment size (coarser sand) and decreasing tidal range. Flatter beach slopes are present during erosional events (sand eroded from the dune front during a storm event is

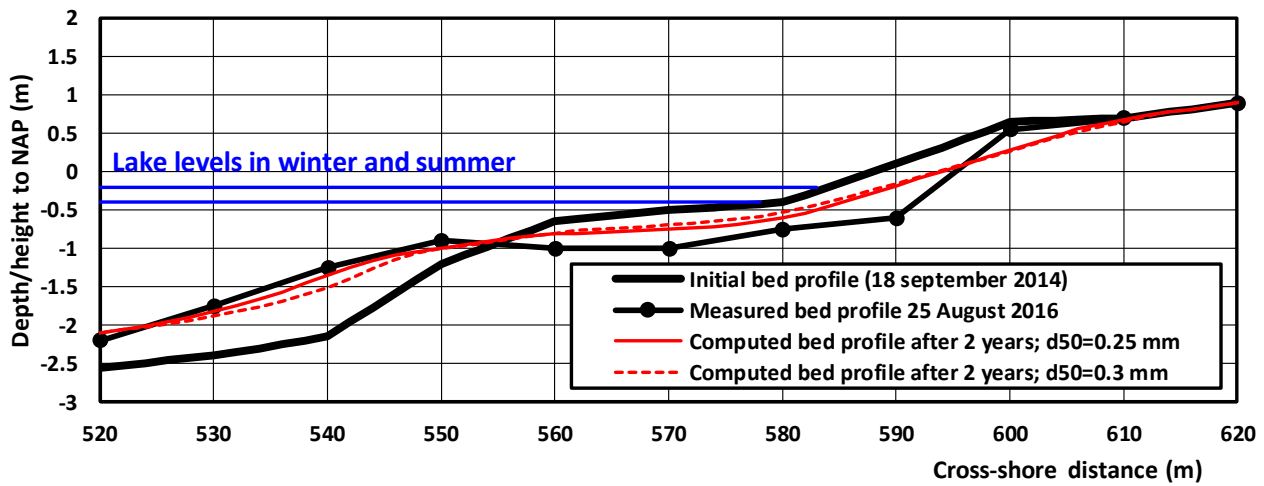


deposited on the beach face). Steeper slopes are present after a long period of beach accretion (after swell events).

Beach slopes of medium fine sand (0.2 to 0.3 mm) are in the range of 1 to 30 and 1 to 50. Given a tidal range of 2 m and a dune toe level of +3 m MSL, the beach width between the LW-line (at -1 m MSL) and the dune toe line at +3 m will then be about 120 to 200 m.

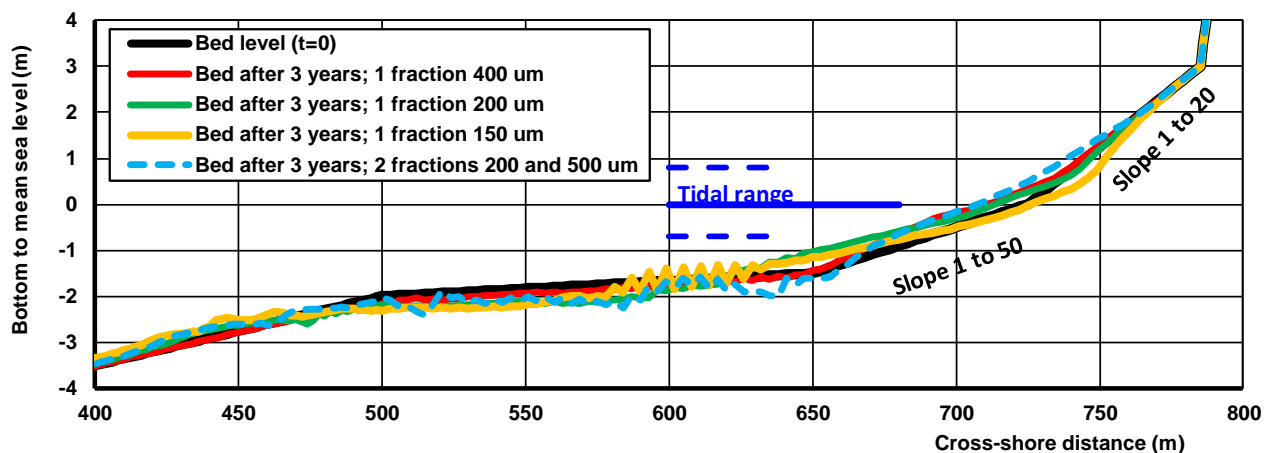
The dry beach width between the HW-line at +1 m and the dune toe line at +3 m MSL will be about 60 to 100 m.

When a new artificial beach is constructed (see **Figure 3.1**), the cross-shore beach profiles generally are non-natural and will be transformed into more natural profiles during a short period (about 1 to 2 years) after construction. Most often, the beach is eroded and sand is deposited at the beach toe. Computed results of the CROSMOR-model are also shown.



**Figure 3.1** Cross-shore profiles of an artificial beach in a lake (Houtribdijk, Markermeer, Netherlands)

**Figure 3.2** shows computed beach profiles based on the CROSMOR-model for a relatively mild lower beach of 1 to 50 and a steeper upper beach of 1 to 20 in sheltered wave conditions (annual waves between 0.3 and 1 m). Model runs over a period of 3 years were done for 1 sand fraction and 2 sand fractions. The initial bed profile consists of a beach section with a slope of 1 to 20 and and underwater section with a slope of 1 to 50. The beach slope is quite stable for sand between 200  $\mu\text{m}$  and 400  $\mu\text{m}$ , but some erosion (5  $\text{m}^3/\text{m}/\text{year}$ ) can be observed for sand of 150  $\mu\text{m}$ .



**Figure 3.2** Computed beach slopes for sheltered wave conditions (CROSMOR-model)



## 4. Design of cross-shore beach-dune profile

### 4.1 Definition of erosion and maintenance volumes

The design of the cross-shore beach-dune profile (see **Figure 1.1**) involves the determination of:

- residual profile volume ( $V_{\text{dune, res}}$ ); which is the volume in the zone between the storm level and the dune crest level that should remain to be present after an extreme storm event (residual dune volume above design level should be about 30 to 40 m<sup>3</sup>/m).
- dune erosion volume ( $V_{\text{dune, se}}$ ), which is the erosion volume in the zone between the design storm level and the dune crest level due to an extreme (design) storm; the residual profile plus the dune erosion profile is the (safety) profile which should be present just before the design storm event;
- dune base volume; which is the volume ( $V_{\text{dune, base}}$ ) between the dune toe level and the design storm level and can be determined if the dune crest width, the dune front and back slopes and the dune toe level are known;
- dune wear volume ( $V_{\text{dune, wear layer}}$ ), which is the additional (extra) volume in the zone between the dune toe level and the storm level to account for cross-shore storm erosion losses and longshore transport gradient losses over the economic lifetime period (say 50 years);
- beach wear layer ( $V_{\text{beach, wear layer}}$ ), which is the additional (extra) beach volume between the beach toe level and the dune toe level to account for beach erosion losses due to cross-shore and longshore transport processes over a given maintenance period (say 5 to 10 years);

### 4.2 Cross-shore transport and erosion processes during storms

#### 4.2.1 Cross-shore dune erosion processes during storm waves

When storm waves arrive at the beach, the wave crests will break continuously, resulting in large volumes of water running up the beach face (see **Figure 4.1**). Sand is dragged down the slope by the downrush causing erosion of the beach and dune faces and undermining of the dune toe. Part of the dune face may collapse when the local dune slope angle is larger than the equilibrium slope and lumps of sediment will slide downwards where it can be eroded again by wave-induced processes. The mass of sediment-laden water returning to the sea will drop its load at deeper water to form a bar. The sediments are carried in seaward direction by wave-induced near-bed return currents (undertow) and in longshore direction by wave-, wind- and tide-induced currents. The undertow currents bring the sediments to the nearshore breaker bar systems, whereas the rip currents carry the sediments over longer distances to the edge of the surf zone. Three-dimensional flow patterns are dominant in the inner surf zone, whereas vertical circulations are dominant in the outer surf zone.

The cross-shore profile between the toe of the surf zone (about -3 m below mean sea level MSL) and the dune crest (around + 10 m MSL), being present after an extreme storm event, is herein defined as the residual storm profile, see **redline** of **Figures 1.1** and **1.2**. The transition zone below the -3 m depth line (toe of inner surf zone) and the original sea bottom can have a relatively steep slope of 1 to 20.

During design storm conditions with a high water level above the dune toe level, the dune front is severely attacked by the waves and the dune front can be eroded over a considerable distance resulting in a cross-shore profile which is herein defined as the residual profile. The residual dune should have a crest width of 3 to 5 m and the crest should ideally be at the original crest level, but always well above the design storm level. The residual dune volume above the storm design level should be about 30 to 40 m<sup>3</sup>/m.





Figure 4.1 Wave impact at dune face

Figure 4.2 shows the residual profile for a storm erosion event in a large-scale wave flume (Vellinga, 1986). The dune front is severely eroded away over a horizontal distance of about 10 m and the eroded material is deposited on the beach face. The slope of the deposit zone will be relatively flat in nature (values smaller than 1 to 30; depending on the beach sand, see Table 3.1). The toe of the beach deposit is about 1.5 m (approximately equal to the incoming wave height) below the surge water level in the flume test. This level is well above the daily beach toe level. In reality (nature), the beach deposits may be washed away in longshore direction due to the presence of longshore currents which are not present in the flume.

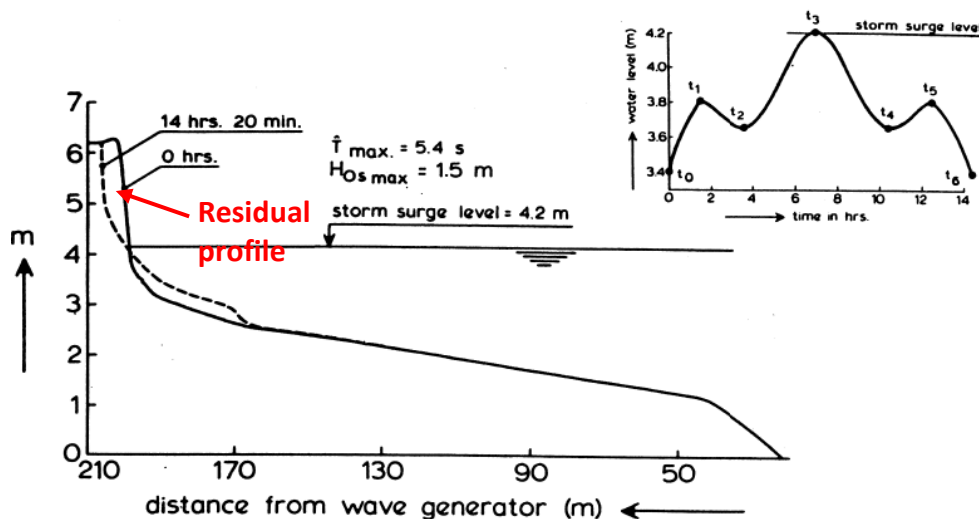


Figure 4.2 Residual profile after about 14 hours in large-scale wave flume after storm; Vellinga 1986





#### 4.2.2 Erosion models for cross-shore transport processes by storm waves

The erosion volume of the dune front in the zone above the design storm level due to cross-shore transport processes during the design storm event ( $V_{\text{dune,cross}}$ ) can be estimated by using dune erosion models such as:

- DUROS+ model (Deltares 2007; **ANNEX C**);
- XBEACH-model (Deltares.nl);
- DUROSTA-model (Steetzel 1993);
- CROSMOR-model (Van Rijn 2009).

A simplified DUNE RULE-model (DR-model) based on results of the CROSMOR-model is given by Van Rijn 2009 (**ANNEX A**).

The DR-model is implemented in the spreadsheet **Littoral.xls**. This model only yields the erosion volume above the considered water level for given input parameters: offshore storm wave height, period, angle, storm duration, design water level above mean sea level MSL,  $d_{50}$  of beach sand and beach slope.

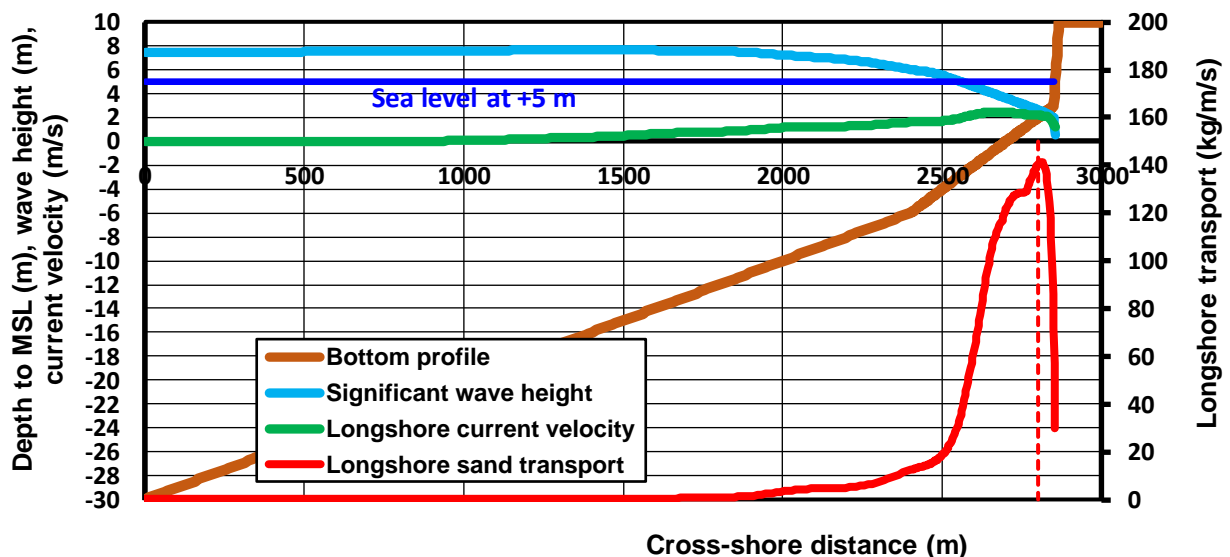
The DR-model is only valid for cases with a typical dune front and a crest level which is at least two times as high as the design storm level. If a submerged breakwater is present, the wave reduction of the breakwater should be neglected as the water level is relatively high during the design storm event.

The required dune volume above the design storm level should be larger than the computed dune erosion volume.

#### 4.3 Longshore transport processes and gradients

##### 4.3.1 Longshore transport processes

Longshore transport is the transport of sand in the surf zone between the outer breaker line and the water line due to longshore velocities generated by oblique breaking waves and including the longshore tide-induced velocities. Longshore sand transport primarily depends on the sand particle diameter, the beach slope, the wave heights and the wave angles in the surf zone.



**Figure 4.3** Cross-shore distribution of significant wave height, longshore current velocity, longshore sand transport for extreme storm event;  
water level at = +5 m MSL,  $H_{s,o}= 7.5\text{ m}$ ,  $T_p= 15\text{ s}$ , wave angle=  $30^\circ$ ,  $d_{50}=0.2\text{ mm}$

**Figure 4.3** shows the cross-shore distribution of the significant wave, longshore current velocity and longshore sand transport for an extreme storm event based on the CROSMOR-model. The bed consists of sand with  $d_{50}= 0.2\text{ mm}$ . The offshore boundary conditions are:  $H_{s,o}= 7.5\text{ m}$ ,  $T_p= 15\text{ s}$ , wave incidence angle=



30°. The storm surge level is 5 m above mean sea level (MSL). The breaker zone is between  $x=2000$  and the dune front. The computed maximum current velocity is about 2 m/s at  $x=2700$  m. The longshore current velocity in front of the dune zone reduces significantly due to the relatively small wave angles ( $<7^\circ$ ).

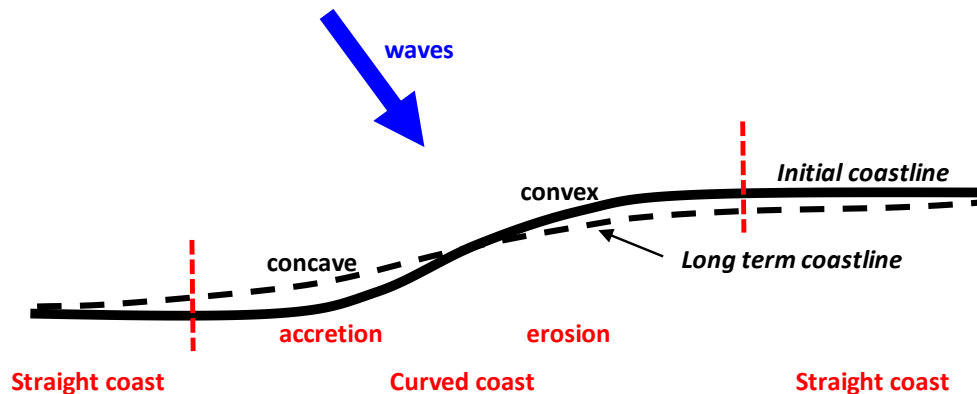
The longshore sand transport is concentrated in the inner surf zone (about 300 m wide) landward of the -6 m depth line. The maximum longshore sand transport (about 140 kg/m/s) occurs just in front of the duneface. The total longshore transport integrated over the surf zone is about 38000 kg/s (about 100,000 m<sup>3</sup>/hour). An estimate of the longshore transport in the upper beach and dune zone (assumed to be 50 m wide; to the right of the red dotted line) is about  $140 \times 50 = 7000$  kg/s, which is about 20% of the total longshore transport (38000 kg/s).

During an extreme storm event of short duration (about 1 day), the longshore transport will generally be in one direction depending on the wave incidence angle.

The net longshore transport for a given annual wave conditions with contributions from different wave directions consists of opposing contributions: positive and negative values, see **Figure 4.5**. The coastline is in equilibrium, if all positive values (over one year) are equal to all negative values (over one year) resulting in a net annual transport equal to zero.

Erosion and deposition occur if longshore transport gradients are present. Two types of longshore transport gradients can occur:

- straight coastal sections: local gradients at straight beach sections are caused by small variations of the sand particle diameter, beach slope, beach shape, wave parameters, etc;
- transition sections (curved coastline): gradients are caused by varying coastline angles, **Figure 4.4**.



**Figure 4.4** Plan view of curved coastal section (transition section)

#### 4.3.2 Longshore transport gradients due to local variations

The local gradients of the longshore transport events due to local variations (var) can be estimated by sensitivity computations of the longshore transport rate by varying the particle size, the beach slope and coastline angle. As this latter parameter has a strong influence, it is advised to vary the shore normal angle over  $\pm 15^\circ$  to account for uncertainties.

Based on experience, the longshore transport difference ( $\Delta Q_{s, \text{long}, \text{annual}}$ ) for annual wave conditions can be estimated by:

$$\Delta Q_{s, \text{long}, \text{annual}, \text{var}} = \alpha_g |Q_{s, \text{long}, \text{max}}| \quad (4.1)$$

with:

$\Delta Q_{s, \text{long}, \text{annual}, \text{var}}$  = difference of longshore transport for annual waves (m<sup>3</sup>/year);

$Q_{s, \text{long}, \text{max}}$  = largest value of the positive and negative annual transport contributions (m<sup>3</sup>/year);

$\alpha_g$  = proportionality coefficient ( $\cong 0.1-0.2$  for straight sections);

$L_{\text{gradient}}$  = alongshore length scale (m) of adjustment ( $5 W_{\text{beach}}$ );

$W_{\text{beach}}$  = beach width (m) between beach toe at -3 m below MSL and dune toe at +3 m above MSL.



Using Equation (4.1), it is assumed that the alongshore variation of the longshore transport is about 10% of the magnitude of longshore transport; the alongshore variation is assumed to occur over a length scale of about 5 times the beach width.

A priori, it is unknown where the gradients resulting in erosion will occur. Therefore, a wear (protection) layer should be present at all locations to compensate for erosion losses.

The longshore transport gradient due to local effects for annual wave conditions can be estimated by:

$$\Delta Q_{s, \text{long, annual, var}} / L_{\text{gradient}} = \alpha_g |Q_{s, \text{long, max}}| / L_{\text{gradient}} \quad (4.2)$$

The erosion/deposition at the beach and at the dune front due to longshore transport gradients for annual wave conditions can be estimated by:

$$V_{\text{dune, long, annual, var}} = \alpha_{\text{breakwater}} \alpha_{p, \text{dune}} \alpha_g |Q_{s, \text{long, max}}| / L_{\text{gradient}} \quad (4.3)$$

$$V_{\text{beach, long, annual, var}} = \alpha_{\text{breakwater}} \alpha_{p, \text{beach}} \alpha_g |Q_{s, \text{long, max}}| / L_{\text{gradient}} \quad (4.4)$$

with:

$V_{\text{dune, long, annual, var}}$  = dune erosion volume above dune toe level ( $\text{m}^3/\text{m}/\text{year}$ ) due to annual wave conditons;

$V_{\text{beach, long, annual, var}}$  = beach erosion volume between beach toe level and dune toe level ( $\text{m}^3/\text{m}/\text{year}$ ) due to annual wave conditons;

$L_{\text{gradient}}$  = length scale (m) over which longshore transport gradients are present ( $\cong 5 W_{\text{beach}}$ );

$W_{\text{beach}}$  = beach width between beach toe level and dune toe level (m);

$\alpha_g$  = coefficient longshore transport gradient ( $0 < \alpha_g < 1$ ;  $\cong 0.1$ - $0.2$  for annual wave conditions);

$\alpha_{p, \text{dune}}$  = coefficient representing the percentage of the longshore transport above the dune toe level ( $\alpha_{p, \text{dune}} \cong 0$  to  $0.1$  for annual wave conditions; **Figure 4.5** and **Table 4.1**);

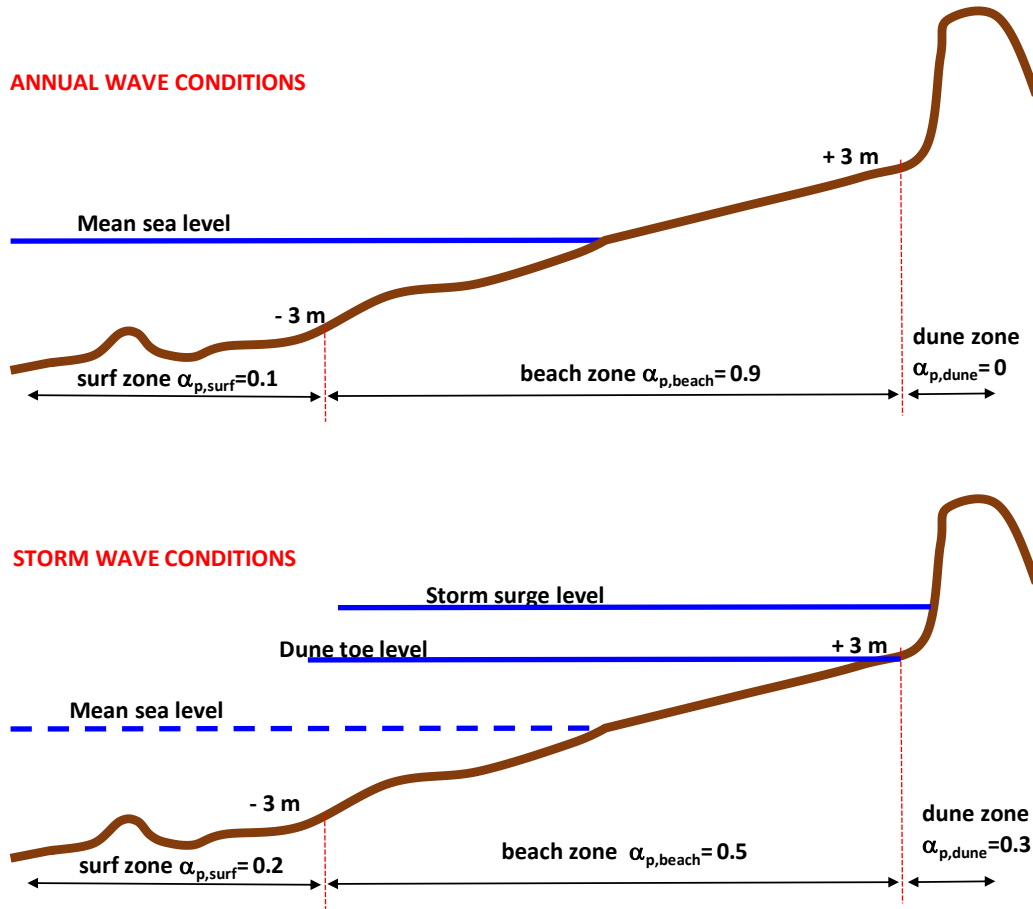
$\alpha_{p, \text{beach}}$  = coefficient representing the percentage of the longshore transport at the beach zone ( $\alpha_{p, \text{beach}} \cong 0.7$  to  $1$  for annual wave conditions; **Figure 4.5** and **Table 4.1**);

$\alpha_{\text{breakwater}}$  = reduction coefficient representing the effect of an offshore breakwater ( $0 < \alpha < 1$ ;  $\cong 0.1$  for an emerged breakwater;  $\cong 0.3$ - $0.5$  for a submerged breakwater;  $1$  for no breakwater).

Type of wave conditions	Coefficients
Annual wave conditions	$\alpha_{\text{breakwater}} = 0.1$ - $0.5$ (submerged/emerged breakwater); $= 1$ (no breakwater) $\alpha_g = 0.1$ - $0.2$ ; $\alpha_p = 0.7$ - $1$ for beach zone; (almost no longshore transport in dune zone)
Storm conditions	$\alpha_{\text{breakwater}} = 0.1$ - $0.5$ (submerged/emerged breakwater); $= 1$ (no breakwater) $\alpha_g = 0.2$ ; $\alpha_p = 0.5$ - $0.7$ for beach zone; $\alpha_p = 0.1$ - $0.3$ for dune zone
Extreme design storm (high water level)	$\alpha_{\text{breakwater}} = 1$ (Water level $\gg$ breakwater crest) $\alpha_g = 0.2$ ; $\alpha_p = 0.2$ for surfzone below beach toe level; $\alpha_p = 0.5$ for beach zone; $\alpha_p = 0.3$ for dune zone

**Table 4.1** Coefficients

It should be remarked that the erosion of the dune front due to annual wave conditions with low water levels is negligibly small in most cases.



**Figure 4.5** Division of longshore transport ( $\alpha_p$ -coefficients) over surf, beach and dune zones  
Upper: annual wave conditions; Lower: storm wave conditions

Equations (4.3) and (4.4) can also be applied to storm events, as follows:

$$V_{\text{dune,long,storm,var}} = \alpha_{\text{breakwater}} \alpha_{p,\text{dune}} \alpha_g \left| Q_{s,\text{long,storm}} \right| T_{\text{storm}} / L_{\text{gradient}} \quad (4.5)$$

$$V_{\text{beach,long,storm,var}} = \alpha_{\text{breakwater}} \alpha_{p,\text{beach}} \alpha_g \left| Q_{s,\text{long,storm}} \right| T_{\text{storm}} / L_{\text{gradient}} \quad (4.6)$$

with:

$Q_{s,\text{long,storm}}$  = longshore transport (in  $\text{m}^3/\text{hour}$ ) during a storm event;

$T_{\text{storm}}$  = peak storm duration of 6 to 12 hours (in hours);

$\alpha_g$  = coefficient longshore transport gradient ( $0 < \alpha_g < 1$ ;  $\cong 0.2$  for storm wave conditions);

$\alpha_{p,\text{dune}}$  = coefficient representing the percentage of the longshore transport above the dune toe level ( $\alpha_{p,\text{dune}} \cong 0.3$  for storm event; **Table 4.1**);

$\alpha_{p,\text{beach}}$  = coefficient representing the percentage of the longshore transport at the beach zone ( $\alpha_{p,\text{beach}} \cong 0.5$  for storm wave event).

#### 4.3.3 Longshore transport gradients in transition sections

The longshore transport gradient in a transition section (trs) is explained in **Figures 4.4** and **4.6**. Transition sections are sections where the coastline accretes in seaward direction (concave or hollow coastline) or erodes in landward direction (convex or rounded coastline). In the initial phase after construction, the adjustment length of the longshore transport is relatively small ( $\cong 10 W_{\text{beach}}$ ). On the long term, the coastline



will be smoothed out by opposing sand transport processes resulting in a much larger adjustment length ( $\approx 50 W_{\text{beach}}$ ) and smaller transport gradients.

**Figure 4.6** shows a coastline consisting of three straight sections. Section 3 is a local extension of the coast and protrudes into the sea over 2000 to 3000 m. Section 2 is a section with a length of 3000 m resulting in a coastline angle of about  $10^\circ$ . Sections 1-2 near point A and Section 2-3 near point B are transition sections with a length scale of the order of 500 m. The beach slope of all sections is 1 to 50. The total beach width between the dune toe at +3 m above MSL (mean sea level) and the beach toe at -3 below MSL is about 300 m. The wave climate of **Table 6.1** has been used to compute the longshore transport rates for sand of 0.21 mm (see **Figure 4.6**). The net annual longshore transport values are (based on **ANNEX B**):

- 250,000 m<sup>3</sup>/year at Sections 1 and 3;
- 60,000 m<sup>3</sup>/year at Section 2.

The positive (to the East) and the negative values (to the West) are also shown.

Accretion will occur around **Point A** due to the decreasing transport rate from 250,000 to 60,000 m<sup>3</sup>/year and erosion will occur around **Point B** due the increasing transport rate from 60000 to 250000 m<sup>3</sup>/year.

Hence, the longshore transport gradients ( $\Delta Q_{s,\text{long}}$ ) at both transition sections 1-2 and 2-3 are about 190,000 m<sup>3</sup>/year. The initial adjustment length is assumed to be about 10 times the beach width in the initial phase after construction of the coastline.

Using these values, the longshore transport gradient is about  $190,000/(10 \times 300) \approx 65 \text{ m}^3/\text{m}/\text{year}$ .

The erosion or deposition at the beach and at the dune front in the transition sections due to longshore transport gradients for annual wave conditions is:

$$V_{\text{dune, long, annual, trs}} = \alpha_{\text{breakwater}} \alpha_{p, \text{dune}} \left| \Delta Q_{s, \text{long, annual}} \right| / L_{\text{gradient}} \quad (4.7)$$

$$V_{\text{beach, long, annual, trs}} = \alpha_{\text{breakwater}} \alpha_{p, \text{beach}} \left| \Delta Q_{s, \text{long, annual}} \right| / L_{\text{gradient}} \quad (4.8)$$

$$\Delta Q_{s, \text{long, annual}} = Q_{s, \text{long, section 1}} - Q_{s, \text{long, section 2}}$$

$$L_{\text{gradient}} = 10 W_{\text{beach}} \text{ (initial situation)}$$

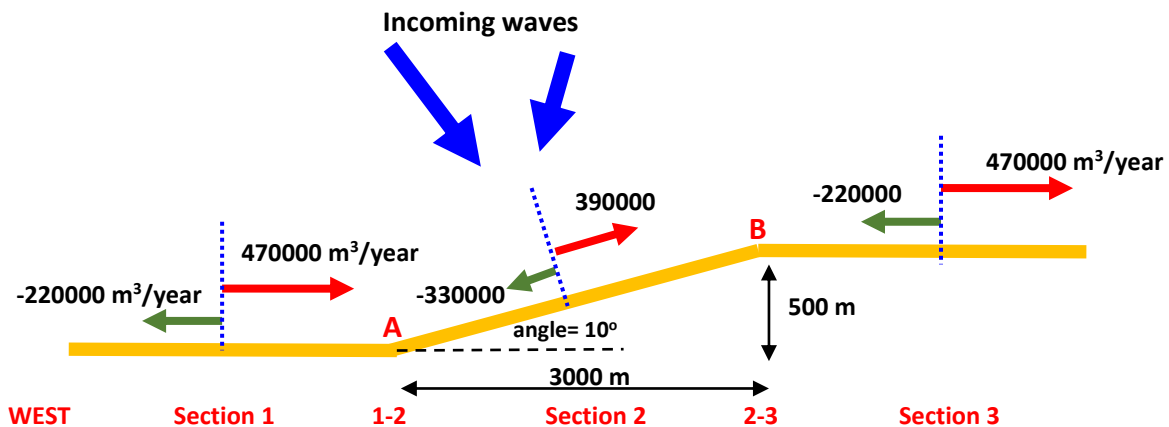
Equations (4.7) and (4.8) can also be applied to a single storm event, as follows:

$$V_{\text{dune, long, storm, trs}} = \alpha_{\text{breakwater}} \alpha_{p, \text{dune}} \left| \Delta Q_{s, \text{long, storm}} \right| T_{\text{storm}} / L_{\text{gradient}} \quad (4.9)$$

$$V_{\text{beach, long, storm, trs}} = \alpha_{\text{breakwater}} \alpha_{p, \text{beach}} \left| \Delta Q_{s, \text{long, storm}} \right| T_{\text{storm}} / L_{\text{gradient}} \quad (4.10)$$

$$\Delta Q_{s, \text{long, storm}} = Q_{s, \text{long, storm, section 1}} - Q_{s, \text{long, storm, section 2}}$$

$$L_{\text{gradient}} = 10 W_{\text{beach}} \text{ (initial situation)}$$



**Figure 4.6** Plan view of longshore transport (+ to the East and – to the West)



#### 4.4 Dune and beach erosion volume during storm events

##### 4.4.1 Dune erosion volume and dune wear volume due to design storm

###### **Required dune volume (design storm event with return period of 1000 to 10000 years)**

The return period of the design storm varies in the range of 1000 to 10000 years, depending on the land surface level (flooding risk) and the economic values (damage), see **Table 4.2**.

Land level	Low economic values	Medium economic values	High economic values
Land level < storm level	1000 years	5000 years	10000 years
Land level $\geq$ storm level	500	1000	3000
Land level > storm level	100	500	1000

**Table 4.2** *Return periods*

During an extreme storm event with a high water level above the dune toe level, the dune front will be eroded by attacking waves and currents.

Dune front erosion during extreme storm conditions proceeds by successive slope failures (dune front is relatively steep; steeper than 1 to 1).

The dune erosion process consists of two contributions:

- erosion of the cross-shore dune front ( $V_{\text{dune,cross,se}}$ ) due to undermining wave impact processes;
- erosion of the dune front zone ( $V_{\text{dune,long,se}}$ ) due to longshore transport gradients.

The cross-shore erosion volume of the dune front above the storm level during the design storm event ( $V_{\text{dune,cross,se}}$ ) can be estimated by using the simple methods:

- DUROS+ model (**ANNEX C**) for given input conditions of the design storm;;
- BEACH-DUNE EROSION model (**ANNEX A**) for given input conditions of the design storm.

The more sophisticated XBEACH-model ([www.deltares.nl](http://www.deltares.nl)) and the CROSMOR-model ([www.leovanrijn-sediment.com](http://www.leovanrijn-sediment.com)) can also be used.

The DR-model is implemented in the spreadsheet **Littoral.xls**. This model only yields the erosion volume above the considered water level. The input data are: offshore storm wave height, period, angle, storm duration, design water level above mean sea level MSL,  $d_{50}$  of beach sand and beach slope.

The simplified DR-model is only valid for a relatively high dune with a crest at a level equal to about 2 times the design storm level.

If a submerged breakwater is present, the wave reduction of the breakwater should be neglected as the water level is relatively high during the design storm event.

The dune volume present above the design storm level should be larger than the computed dune erosion volume.

The erosion ( $V_{\text{dune,long,se}}$ ) due to longshore transport gradients during the design storm event can be estimated by Equations (4.5) and (4.9).

Including a safety factor ( $\gamma_{sf}$ ) the total dune erosion volume in the zone between the design storm level and the dune crest level related to the design storm is:

$$V_{\text{dune,se}} = \gamma_{sf} (V_{\text{dune,cross,se}} + V_{\text{dune,long,se}} + V_{\text{dune,long,se,trs}}) \quad (4.11)$$

The safety factor represents the uncertainty effects. The safety factor should be relatively large ( $\geq 1.3$ ) as the residual profile plus dune profile should not fail during a storm event.





The required minimum dune volume above the design water level should be equal to that based on Equation (4.11). This volume should be present just before the occurrence of the extreme storm event. A certain reserve layer (wear layer or maintenance layer) should be included for compensation of erosion losses during minor storm events. Each 10 years, the available dune volume should be monitored to evaluate whether sufficient dune volume is present above the dune toe line. If not, the dune volume should be restored.

#### **Dune wear layer (50 years-storm event)**

The dune wear volume is the volume that needs to be present at the dune front to account for storm erosion losses during a given economic period (say 50 years) after construction of the new beach-dune profile. During a period of 50 years, the dune front is assumed to be attacked by a storm with a return period of 50 years. The surge level of this storm will most likely be somewhat higher than the dune toe level and may cause some dune erosion. Storms with surge levels lower than the dune toe level will not much affect the dune front.

Including a safety factor ( $\gamma_{sf}$ ), the total dune wear volume in the zone between the mean sea level and the dune toe level is:

$$V_{\text{dune,wear layer}} = \gamma_{sf} (V_{\text{dune,cross, 50y-storm}} + V_{\text{dune,long,50y-storm,var}} + V_{\text{dune,long,50y-storm,trs}}) \quad (4.12)$$

with:

$V_{\text{dune,cross,50y-storm}}$  = dune erosion volume due cross-shore processes during storm with return period of 50 years (computed by DR-Model);

$V_{\text{dune,long,50y-storm,var}}$  = dune erosion volume due to longshore transport gradients related to local variations for storm with  $T_{\text{return}} = 50$  years (based on Equation 4.5);

$V_{\text{dune,long,50y-storm,trs}}$  = dune erosion volume due to longshore transport gradients in transition sections (if present) for storm with  $T_{\text{return}} = 50$  years (based on Equation 4.9);

$\gamma_{sf}$  = safety factor to account for uncertainties (=1.1 to 1.2).

The dune wear volume ( $V_{\text{dune,wear layer}}$ ) will be about 20% of the design dune volume ( $V_{\text{dune,se}}$ ). It is advised to use a minimum value of 10% of the design dune volume ( $V_{\text{dune,wear,minimum}} = 0.1 V_{\text{dune,se}}$ ).

The dune wear volume should be evaluated regularly based on sounding measurements (on a alongshore grid of 200 m) and refilled if the dune wear volume is too small due to erosion. On the long term, the most appropriate dune wear volume will be found based on practical experience.

If regular monitoring and maintenance are done (after each storm event), the dune wear layer can be reduced/neglected. The design dune volume based on the erosion losses of the 10,000 year-storm is much larger than the dune erosion losses of storms with return period of 50 to 100 years. The design dune volume includes a safety volume which is sufficient for compensation of erosion losses related to minor storms. Monitoring and maintenance should be done immediately after each storm event affecting the dune zone above the dune toe level.

#### **4.4.2 Beach erosion and beach wear volume due to 10 years-storm event**

Given a maintenance period of about 10 years, it is most economic to determine the wear/maintenance volumes for a storm with a maximum return period of 10 years.

During a storm event with return period of 10 years along a natural coastal profile with a concave (hollow shape), the erosion of the beach zone below the dune toe level is mainly caused by longshore transport gradients. Some cross-shore beach erosion may also take. Major beach erosion will take place if a non-natural (artificial) convex-type beach profile is present, see **Figure 3.1**. Dune erosion generally is minor or absent for a 10 years-storm event.



The beach wear volume due to longshore transport gradients during a 10 years-storm event can be estimated by:

$$V_{\text{beach,wear layer}} = \gamma_{\text{sf}} (V_{\text{beach,cross, 10y-storm}} + V_{\text{beach,long,10y-storm,var}} + V_{\text{beach,long,10y-storm,trs}}) \quad (4.13)$$

with:

$V_{\text{beach,cross, 10y-storm}}$  = beach erosion volume ( $\text{m}^3/\text{m}$ ) during 10 years-storm event based cross-shore storm model ( $\cong 0$  for natural beach profile);

$V_{\text{beach,long,10y-storm,var}}$  = beach erosion volume ( $\text{m}^3/\text{m}$ ) during 10 years-storm event related to local variations based on Equation (4.6);

$V_{\text{beach,long,10y-storm,trs}}$  = beach erosion volume ( $\text{m}^3/\text{m}$ ) during 10 years-storm event in the transition zone based on Equation (4.10).

$\gamma_{\text{sf}}$  = safety factor ( $\cong 1.1$  to  $1.2$ ).

The beach wear volume related to a 10 years-storm event generally is much smaller (factor 5, see Section 5.2) than the beach wear volume due to the annual waves for a period of 10 years (as given in Section 4.5). The placement of the beach wear volume related to a 10 years-storm event can be neglected if beach monitoring is being done immediately after the occurrence of a 10 years-storm event and the beach erosion losses are restored immediately.

#### 4.5 Beach erosion and beach wear volume due to annual wave conditions

It is assumed that the erosion of the beach is mainly caused by:

- cross-shore beach erosion due to storms with return period of 1 year;
- longshore erosion due to longshore transport gradients during daily wave conditions of the mean annual wave climate.

Dune erosion will hardly take place as the maximum water level during a representative year will be below the dune toe level in most cases.

If a submerged breakwater is present, the wave reduction of the breakwater should be taken into account (wave transmission). Water level setup during storm events should be also taken into account. Wave angle variations due to diffractive effects can be neglected.

The cross-shore erosion volume of the beach face ( $\Delta V_{\text{beach,cross}}$ ) can be estimated by using the simplified DR-model (**ANNEX A**) for given input conditions of the storm with  $T_{\text{return}} = 1$  year. The DR-model is implemented in the spreadsheet **Littoral.xls**. The beach erosion due to longshore transport gradients of the mean annual wave climate can be estimated by Equation (4.4).

##### Beach wear volume (annual waves)

The total beach wear volume over the maintenance period and the thickness of the beach wear layer can be obtained from:

$$V_{\text{beach,wear layer}} = \gamma_{\text{sf}} [(V_{\text{beach,cross,1 year}})^2 + (V_{\text{beach,long,annual,var}})^2 + (V_{\text{beach,long,annual,trs}})^2]^{0.5} N_m \quad (4.14)$$

$$\delta_{\text{beach,wear layer}} = \gamma_{\text{sf}} [V_{\text{beach,wear layer}} / W_{\text{beach}}]$$

with:

$V_{\text{beach,cross,1 year}}$  = cross-shore beach erosion volume ( $\text{m}^3/\text{m}/\text{year}$ ) due to storm with return period of 1 year;

$V_{\text{beach,long,annual,var}}$  = erosion volume ( $\text{m}^3/\text{m}/\text{year}$ ) due to longshore gradients related to local variations caused by annual wave conditions based on Equation (4.4);



- $V_{\text{beach, long, annual, trs}}$  = erosion volume ( $\text{m}^3/\text{m}$ ) due to longshore gradients in transition sections caused by annual wave conditions based on Equation (4.8);
- $N_m$  = number of years of the maintenance period (years)
- $W_{\text{beach}}$  = beach width = width between dune toe and beach toe (m);
- $\delta_{\text{beach, wear layer}}$  = thickness of beach wear layer;
- $\gamma_{\text{sf}}$  = safety factor (= 1.1 to 1.2).

Equation (4.14) is based on quadratic summation as the cross-shore erosion during storms may be returned (partly) by onshore transport processes.

If beach vegetation is present locally, the longshore gradient may be substantially larger, which can be accounted for by a larger safety factor.

#### 4.6 Dune dimensions

The dune consists of (see **Figure 4.7**):

- dune volume ( $V_{\text{dune, se}}$ ) required to compensate the dune erosion losses in the zone above the design storm level during extreme storm conditions;
- dune residual volume of the residual profile ( $V_{\text{dune, res}}$ ) which should still be present in the zone above the storm level after the storm event;
- dune base volume ; which is the volume ( $V_{\text{dune, base}}$ ) between the dune toe level and the design storm level and can be determined if the dune crest width, the dune front and back slopes and the dune toe level are known;
- dune wear volume ( $V_{\text{dune, wear}}$ ) which is the maintenance volume to compensate annual erosion losses (due to waves, currents and wind transport) in the zone between the dune toe level and dune crest.

If these parameters are available, the dune dimensions can be determined.

The crest width ( $b_{\text{crest}}$ ) can be determined from:

$$V_{\text{dune, se}} + b_{\text{res}} h_{d1} + 0.5 h_{d1}^2 / \tan \alpha_2 + 0.5 h_{d1}^2 / \tan \alpha_3 = b_{\text{crest}} h_{d1} + 0.5 h_{d1}^2 / \tan \alpha_1 + 0.5 h_{d1}^2 / \tan \alpha_2$$

$$b_{\text{crest}} = (V_{\text{dune, se}}) / h_{d1} + b_{\text{res}} + 0.5 h_{d1} (1 / \tan \alpha_3 - 1 / \tan \alpha_1) \quad (4.15)$$

Assuming:  $b_{\text{res}} \cong 0.1 b_{\text{crest}}$  it follows that:

$$b_{\text{crest}} \cong 1.1 (V_{\text{dune, se}}) / h_{d1} + 0.55 h_{d1} (1 / \tan \alpha_3 - 1 / \tan \alpha_1) \quad (4.16)$$

with:

- $b_{\text{crest}}$  = crest width of dune;
- $b_{\text{res}}$  = crest width of residual profile ( $\cong 3-5$  m);
- $h_d = h_{d1} + h_{d2}$  = dune height between dune toe level and crest level;
- $h_{d1}$  = height of dune between design storm level and crest level;
- $h_{d2}$  = height of dune between dune toe level and design storm level;
- $\tan \alpha_1$  = tangens of front slope of dune (range 1/2 to 1/3);
- $\tan \alpha_2$  = tangens of back slope of residual profile (approximately 1/2);
- $\tan \alpha_3$  = tangens of front slope of residual profile (approximately 1/1).

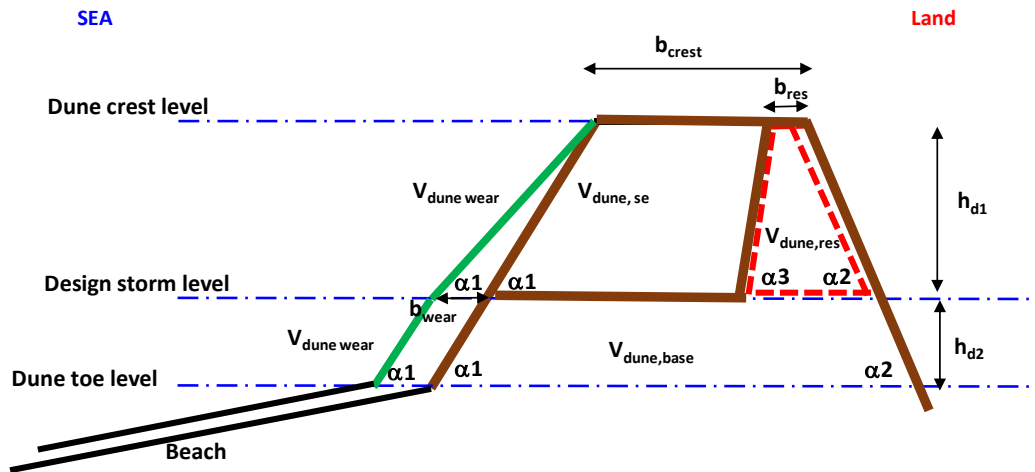


Figure 4.7 Schematization of dune profile

The width of the dune wear layer is:

$$b_{\text{dune wear}} = V_{\text{dune wear}} / (h_{d2} + 0.5 h_{d1}) \quad (4.17)$$

The width of the dune (without wear layer) at the design storm level is :

$$b_{\text{dune at DSL}} = b_{\text{crest}} + h_{d1} (1/\tan\alpha_1 + 1/\tan\alpha_2) \quad (4.18)$$

The width of the dune (without wear layer) at the dune toe level is:

$$b_{\text{dune at DTL}} = b_{\text{crest}} + (h_{d1} + h_{d2})(1/\tan\alpha_1 + 1/\tan\alpha_2) \quad (4.19)$$

The residual dune volume and the dune base volume are:

$$V_{\text{dune, res}} = b_{\text{res}} h_{d1} + 0.5(h_{d1})^2(1/\tan\alpha_3 + 1/\tan\alpha_2) \quad (4.20)$$

$$V_{\text{dune, base}} = 0.5 (b_{\text{dune at DTL}} + b_{\text{dune at DSL}}) h_{d2} \quad (4.21)$$

The total dune volume between the dune toe level and the dune crest level is:

$$V_{\text{dune total}} = V_{\text{dune wear}} + 0.5 (b_{\text{crest}} + b_{\text{dune at DTL}}) (h_{d1} + h_{d2}) \quad (4.22)$$

$$V_{\text{dune total}} = V_{\text{dune wear}} + 1.1 [((h_{d1} + h_{d2})/h_{d1}) V_{\text{dune, se}}] + 0.55 [((h_{d1} + h_{d2})h_{d1}) (1/\tan\alpha_3 - 1/\tan\alpha_1)] + 0.5 [(h_{d1} + h_{d2})^2 (1/\tan\alpha_1 + 1/\tan\alpha_2)] \quad (4.23)$$



### **Example 1**

Given:  $V_{\text{dune,se}} = 300 \text{ m}^3/\text{m}$ ;  $V_{\text{dune,wear}} = 30 \text{ m}^3/\text{m}$ ;  $h_{d1} = 5 \text{ m}$ ;  $h_{d1} = 2 \text{ m}$ ;  $\tan\alpha_1 = 1/3$ ;  $\tan\alpha_2 = 1/2$ ;  $\tan\alpha_3 = 1$ .

Computed:

$$b_{\text{crest}} = 1.1 \times 300 / 5 + 0.55 \times 5 \times (1-3) = 66 - 5.5 = 60.5 \text{ m};$$

$$b_{\text{dune wear}} = 30 / (2 + 0.5 \times 5) \cong 7 \text{ m};$$

$$b_{\text{dune at DSL}} = 60.5 + 5 \times (3+2) = 85.5 \text{ m};$$

$$b_{\text{dune at DTL}} = 60.5 + 7 \times (3+2) = 95.5 \text{ m};$$

$$V_{\text{dune total}} = 30 + 0.5 \times (60.5 + 95.5) \times (5+2) = 576 \text{ m}^3/\text{m};$$

$$V_{\text{dune total}} = 30 + 1.1 \times (7/5) \times 300 + 0.55 \times (7 \times 5) \times (1-3) + 0.5 \times (7)^2 \times (3+2) = 30 + 462 - 38.5 + 122.5 \cong 576 \text{ m}^3/\text{m}.$$

### **Example 2**

Given:  $V_{\text{dune,wear}} = 0 \text{ m}^3/\text{m}$  and  $h_{d1} = 5 \text{ m}$ ;  $h_{d1} = 2 \text{ m}$ ;  $\tan\alpha_1 = 1/3$ ;  $\tan\alpha_2 = 1/2$ ;  $\tan\alpha_3 = 1$ .

Computed:

$$V_{\text{dune total}} = 1.1 \times (7/5) \times V_{\text{dune,aboveDSL}} + 0.55 \times (7 \times 5) \times (1-3) + 0.5 \times (7)^2 \times (3+2) \cong 1.5 V_{\text{dune,se}} + 84 \text{ m}^3/\text{m}.$$

$$V_{\text{dune,se}} = 100 \text{ m}^3/\text{m} \text{ gives: } V_{\text{dune total}} \cong 225 \text{ m}^3/\text{m}.$$

$$V_{\text{dune,se}} = 200 \text{ m}^3/\text{m} \text{ gives: } V_{\text{dune total}} \cong 385 \text{ m}^3/\text{m}.$$

$$V_{\text{dune,se}} = 300 \text{ m}^3/\text{m} \text{ gives: } V_{\text{dune total}} \cong 535 \text{ m}^3/\text{m}.$$

$$V_{\text{dune,se}} = 400 \text{ m}^3/\text{m} \text{ gives: } V_{\text{dune total}} \cong 685 \text{ m}^3/\text{m}.$$

Thus:  $V_{\text{dune total}} \cong 1.7 \text{ to } 2.2 V_{\text{dune,se}}$



## 5. Example case 1: beach-dune system along lake coast

### 5.1 Available data

#### Beach and dune characteristics

The coast of a lake consisting of two sections, has to be protected against storm waves, see **Figure 5.1**.

The land surface is at +1.5 above the mean water level (MWL), see **Figure 5.2**.

The shore normal: angle of  $47^\circ$  to North in Section 1 and  $30^\circ$  to North in Section 2, see **Figure 5.1** and **5.3**.

Other available data:

Dune crest level +5 m above MWL; Dune toe level at +1 m above MWL; Beach toe level at -1 m below MWL

Beach sand  $d_{50} = 0.21$  mm (smallest  $d_{50}$  value of borrow pit sand; 0.21 to 0.25 mm).

Beach slope = 1 to 30 between the dune toe and the beach toe.

The design conditions are defined for a return period of 10,000 years.

The duration of an extreme design storm is defined to be  $T_{\text{storm}} = 12$  hours.

Sea level rise effect has been neglected.

No offshore breakwater.

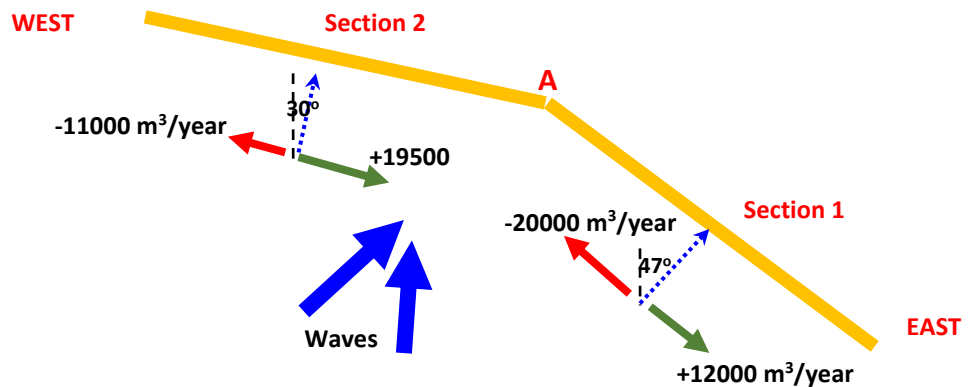


Figure 5.1 Plan view of longshore transport vectors *along* lake coast

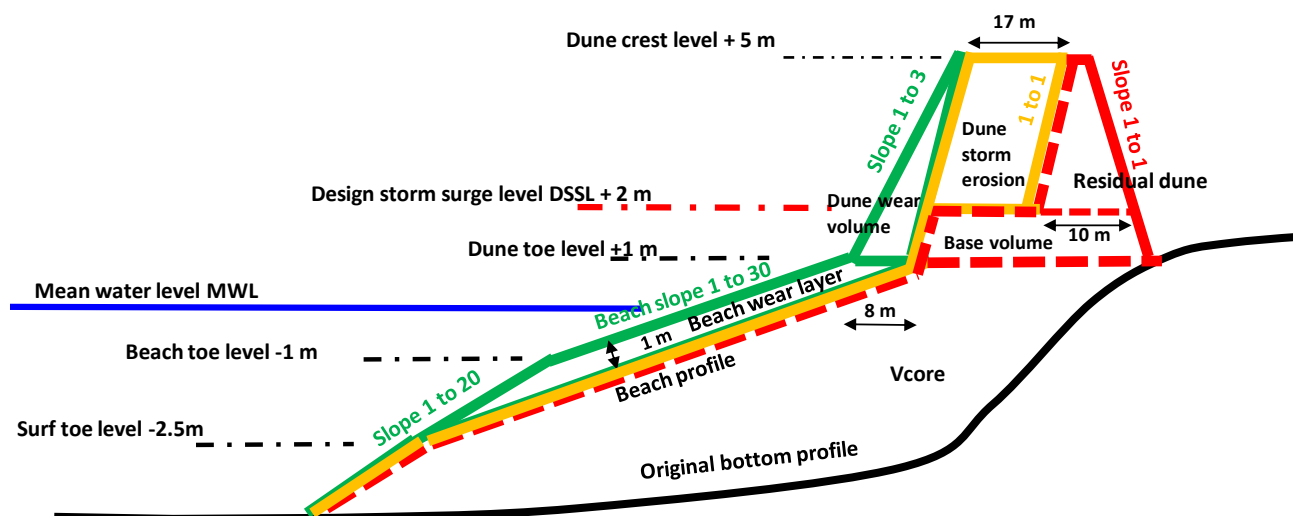


Figure 5.2 Cross-shore beach-dune profile





### Annual wave climate

Table 5.1 shows the annual wave data; Figure 5.3 shows the wave rose. The wave distribution is fairly symmetrical with respect to the line from North-East to South-West (235°).

Significant wave height classes (m)	AC 0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	Total
	AG 180°	210°	240°	270°	300°	330°	360°	30°	60°	90°	120°	150°	
< 0.2	11.1	6.4	7.9	7.3	9.1	7.6	7.1	7.0	11.7	9.6	9,7	7.2	101.6
0.2-0.4	10.3	8.9	10.8	8.3	9.8	8.3	9.4	10.2	18.9	13.5	9,0	4.9	122.3
0.4-0.6	3.6	3.6	5.2	4.3	5.3	7.8	9.8	12.9	21.2	4.0	2,3	1.0	80.9
0.6-0,8	0.6	0.6	1.1	1.1	1.8	3.4	6.5	9.6	13.3	1.2			39.4
0.8-1.0				0.1	0.2	0.9	3.4	6.0	6.2	0.3			17.1
1.0-1.2						0.1	0.6	1.1	1.2	0.1			3.1
1.2-1.4							0.1	0.2	0.2				0.5
> 1.4													
<b>Total</b>	<b>25.5</b>	<b>19.5</b>	<b>25.0</b>	<b>21.2</b>	<b>26.2</b>	<b>28.0</b>	<b>36.7</b>	<b>47.0</b>	<b>72.7</b>	<b>28.5</b>	<b>21.3</b>	<b>13.2</b>	<b>365 days</b>

AC= angle of direction vector from where the waves are coming with respect to North

AG= angle of direction vector where the waves are going to with respect to North

Table 5.1 Annual wave data

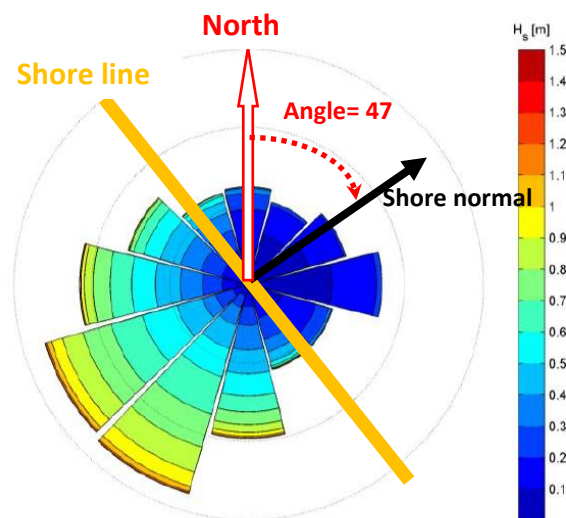


Figure 5.3 Wave rose with local shore line and shore normal; Section 1

### Storm wave data

Storm wave data are available for the period 1900 to 2000, which is period of 100 years. To obtain the return periods for extreme conditions, the available data have been extrapolated to return periods up to 10,000 years, see Figure 5.4.

The design conditions are defined to have a return period of 10,000 years resulting in design storm level of 2 m above mean water level of the lake.



Offshore water depth to mean level $h_o$ (m)	Offshore significant wave height $H_{s,o}$ (m)	Peak wave period $T_p$ (s)	Offshore wave angle to shore normal in Section 1 and 2 ( $^\circ$ )	Storm setup above mean level (m)	Return period (years)
4	0.5	2.5	30; 13	0.05	<1
4	0.7	2.8	30; 13	0.1	<1
4	0.8	3.2	30; 13	0.15	<1
4	0.9	3.5	30; 13	0.30	<1
4	1	3.7	30; 13	0.45	<1
4	1.1	4.0	30; 13	0.60	1
4	1.2	4.2	30; 13	0.75	3
4	1.3	4.5	30; 13	0.90	10
4	1.4	4.7	30; 13	1.00	20
4	1.5	5.0	30; 13	1.10	50
4	1.7	6.0	30; 13	1.30	100
4	1.85	6.5	30; 13	1.55	500
4	1.9	6.7	30; 13	1.65	1000
4	2.1	6.8	30; 13	1.90	5000
4	2.2	7.0	30; 13	2.0	10000

Table 5.2 Storm wave data

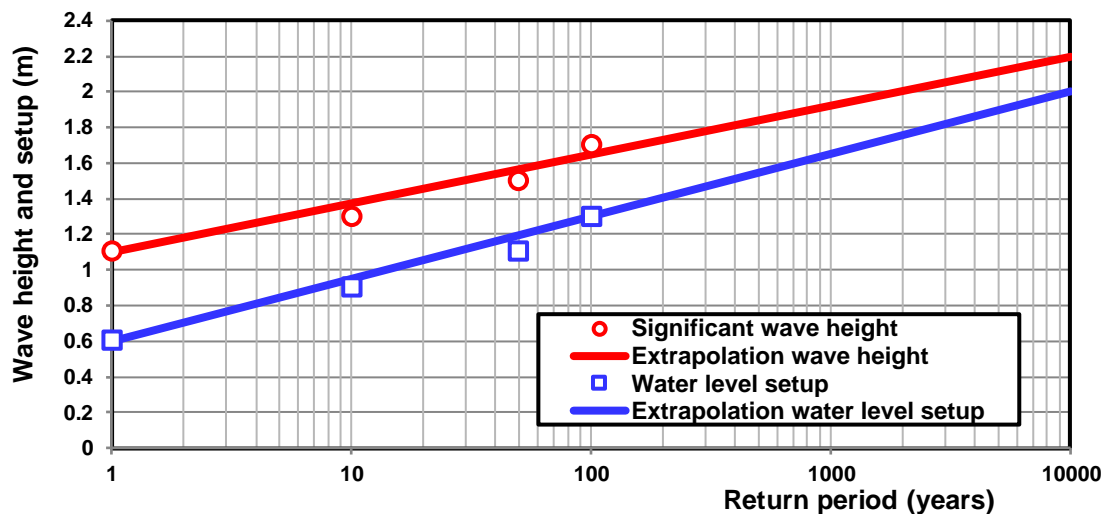


Figure 5.4 Extrapolation of wave height and water level setup

## 5.2 Design cross-shore beach-dune profile; method Van Rijn

### Dune erosion volume of design storm

The cross-shore erosion of the dune front can be estimated by using the simplified DR-model (**ANNEX A**) for given input conditions of Sections 1 and 2, see **Table 5.3**. The wave angles of Section 1 and 2 differ by  $17^\circ$  due to the varying coastline angle (column 3). The simplified DR-model is implemented in the spreadsheet **Littoral.xls**. **Figure 5.5** shows the computed dune erosion values (after 12 hours) for three beach sand diameters. The design storm level is  $S = 2$  m.



Offshore significant wave height	Peak wave period	Offshore wave angle to shore normal	Storm setup above mean level	Return period	Longshore sand transport $d_{50}=0.21$ mm beach 1 to 30 $\gamma_{br}=0.6$ $\rho_{bulk}=1600$ kg/m <sup>3</sup> $Q_{s,Long}$ (m <sup>3</sup> /hr)	Beach/Dune erosion volume $d_{50}=0.21$ mm beach slope 1 to 30 $V_{cross,storm}$ after 12 hrs (m <sup>3</sup> /m)
$H_{s,o}$ (m)	$T_p$ (s)	$\theta_o$ (°)	(m)	$T_{return}$ (years)	S1; S2	Section1; Section2
1.1	4.0	S1; S2	0.60	1	65; 35	4; 3.7
1.2	4.2	30; 13	0.75	3	85; 50	5.7; 5.3
1.3	4.5	30; 13	0.90	10	110; 60	7.8; 7.2
1.4	4.7	30; 13	1.00	20	135; 75	9.5; 8.8
1.5	5.0	30; 13	1.10	50	165; 95	11.5; 10.6
1.7	6.0	30; 13	1.30	100	240; 135	15.8; 14.7
1.85	6.5	30; 13	1.55	500	305; 175	21.7; 20.2
1.9	6.7	30; 13	1.65	1000	330; 190	23.8; 22.2
2.1	6.8	30; 13	1.90	5000	375; 250	31.2; 29.2
2.2	7.0	30; 13	2.0	10000	505; 290	35.5; 31.1

Table 5.3 Input and output data of simplified DR-MODEL (design conditions in red); Section 1 and 2

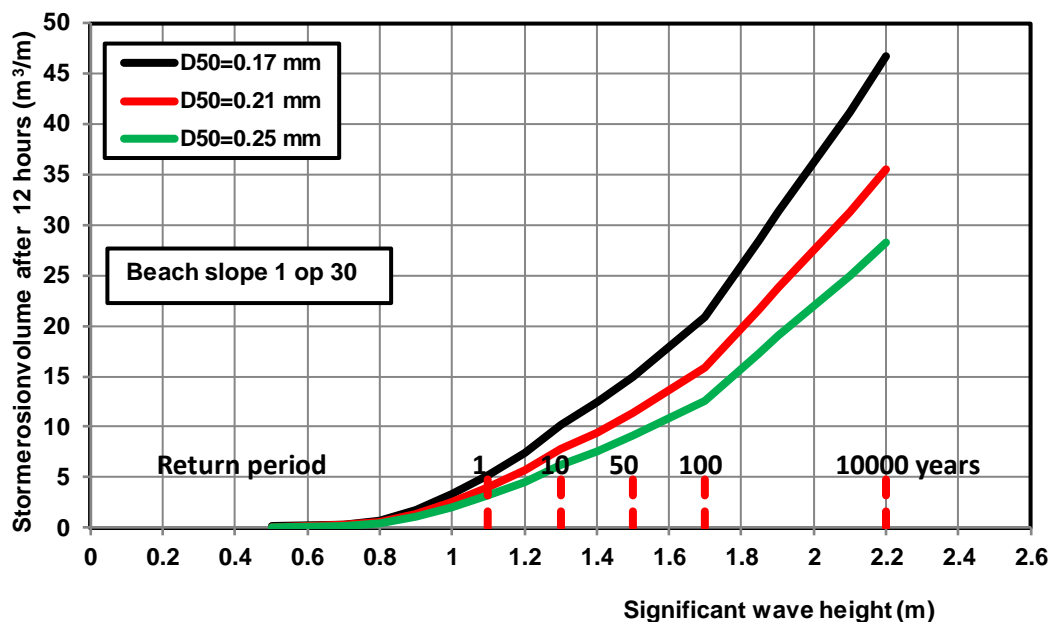


Figure 5.5 Erosion volumes above storm level; Section 1

Using beach sand  $d_{50}=0.00021$  m and beach slope= 1 to 30 (between beach toe level at -1 m and dune toe level at +1 m), the dune erosion volume above the design water level (DSL) of +2 m for an extreme storm with duration of 12 hours is:

Section 1:  $V_{dune,se,cross} = 36$  m<sup>3</sup>/m;

Section 2:  $V_{dune,se,cross} = 31$  m<sup>3</sup>/m;

The dune erosion due to longshore transport gradients during the design storm can be estimated by Equations (4.5) and (4.9):



Section 1: Using  $T_{\text{storm}}=12$  hrs,  $Q_{s,\text{long}}=505$  m<sup>3</sup>/hr,  $W_{\text{beach}}=60$  m:  
 $V_{\text{dune,long,storm,var}} = 0.3 \times 0.2 \times 505 \times 12 / (5 \times 60) \cong 1.2$  m<sup>3</sup>/m.

Section 2: Using  $T_{\text{storm}}=12$  hrs,  $Q_{s,\text{long}}=290$  m<sup>3</sup>/hr,  $W_{\text{beach}}=60$  m:  
 $V_{\text{dune,long,storm,var}} = 0.3 \times 0.2 \times 290 \times 12 / (5 \times 60) \cong 0.7$  m<sup>3</sup>/m.

Transition S1 to S2: Using  $T_{\text{storm}}=12$  hrs,  $W_{\text{beach}}=60$  m:  
 $V_{\text{dune,long,storm,trs}} = 0.3 \times (505-290) \times 12 / (10 \times 60) \cong 1$  m<sup>3</sup>/m.  
 $V_{\text{dune,long,storm,trs}} = 1$  m<sup>3</sup>/m.

Including a safety factor  $\gamma_{\text{sf}}=1.3$ , the dune erosion volume above the storm design level is:

Section 1:  $V_{\text{dune,se}} = \gamma_{\text{sf}} (V_{\text{dune,cross,storm}} + V_{\text{dune,long,storm,var}}) = 1.3 \times (36 + 1.2) = 48$  m<sup>3</sup>/m.

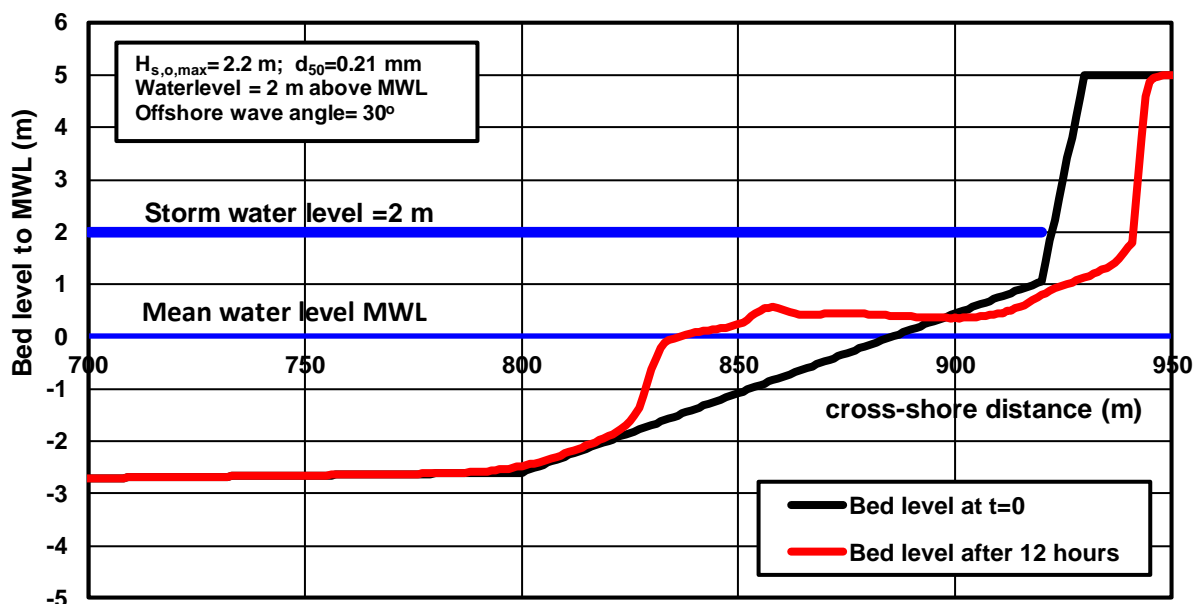
Section 2:  $V_{\text{dune,se}} = \gamma_{\text{sf}} (V_{\text{dune,cross,storm}} + V_{\text{dune,long,storm,var}}) = 1.3 \times (31 + 0.7) = 41$  m<sup>3</sup>/m.

Tran. S1-S2:  $V_{\text{dune,se}} = \gamma_{\text{sf}} (V_{\text{dune,cross,storm}} + V_{\text{dune,long,storm,var}} + V_{\text{dune,long,storm,trs}}) = 1.3 \times (33.5 + 1 + 1) = 46$  m<sup>3</sup>/m.

Given the dune crest level = 5 m above MWL and design storm level DSSL= 2 m, the dune height is given as:  
 $h_{\text{dune}} = 5 - 2 = 3$  m and the dune width is:  $W_{\text{dune}} = V_{\text{dune,se}} / h_{\text{dune}} \cong 50/3 \cong 17$  m.

The slopes of the dune erosion volume are assumed to be 1 to 1 (eroded dune fronts are relatively steep).

**Figure 5.6** shows the predicted storm erosion profile based on the CROSMOR-model. The input data are:  $H_{s,o}=2.2$  m (6 wave classes Rayleigh),  $T_p=7$  s, offshore wave angle=  $30^\circ$ , offshore water depth= 4 m below MWL,  $d_{50}=0.21$  mm, beach slope of 1 to 30, storm duration=12 hours, water level= 2 m above mean water level (constant over 12 hours). The dune erosion is about 45 m<sup>3</sup>/m above the storm level, which is about 25% larger than that (36 m<sup>3</sup>/m) based on the DR-model.



**Figure 5.6** Predicted storm erosion profile based on CROSMOR-model (File: hdjks5.inp)



### **Dune wear layer for 50 years-storm**

The dune wear volume is the volume that needs to be present to deal with storm erosion losses during a given economic period after construction of the new beach-dune profile. Herein, an economic period of 50 years is used.

The dune wear volume can be computed from Equations (4.5), (4.9), (4.12). The peak duration of the storm with return period of 50 years is assumed to be 12 hours. The minimum dune wear volume is  $V_{\text{dune,wear,minimum}} = 0.1 V_{\text{dune,se}} = 0.1 \times 50 = 5 \text{ m}^3/\text{m}$ .

Based on the data of **Table 5.3**, it follows that ( $\alpha_g=0.2$ ;  $\alpha_{p,\text{dune}}=0.3$ ):

Section 1:	$V_{\text{dune,cross,50y-storm}} = 11.5 \text{ m}^3/\text{m}$
	$V_{\text{dune,long,50y-storm,var}} = 0.2 \times 0.3 \times 165 \times 12 / (5 \times 60) \cong 0.4 \text{ m}^3/\text{m}$
Section 2:	$V_{\text{dune,cross,50y-storm}} = 10.6 \text{ m}^3/\text{m}$
	$V_{\text{dune,long,50y-storm,var}} = 0.2 \times 0.3 \times 95 \times 12 / (5 \times 60) \cong 0.2 \text{ m}^3/\text{m}$
Transition S1-S2:	$V_{\text{dune,cross,50y-storm}} = 11.0 \text{ m}^3/\text{m}$
	$V_{\text{dune,long,50y-storm,var}} = 0.5(0.2+0.4) = 0.3 \text{ m}^3/\text{m}$
	$V_{\text{dune,long,50y-storm,trs}} = 0.3 \times (165-95) \times 12 / (10 \times 60) \cong 0.5 \text{ m}^3/\text{m}$

Including a safety factor  $\gamma_{\text{sf}} = 1.3$ , the total dune wear volume is:

Section 1:	$V_{\text{dune,wear}} = \gamma_{\text{sf}} (V_{\text{dune,cross,50y-storm}} + V_{\text{dune,long,50y-storm,var}}) = 1.3 \times (11.5 + 0.4) = 16 \text{ m}^3/\text{m}$
Section 2:	$V_{\text{dune,wear}} = \gamma_{\text{sf}} (V_{\text{dune,cross,50y-storm}} + V_{\text{dune,long,50y-storm,var}}) = 1.3 \times (10.6 + 0.2) = 14 \text{ m}^3/\text{m}$
Tran. S1-S2:	$V_{\text{dune,wear}} = \gamma_{\text{sf}} (V_{\text{dune,cross,50y-storm}} + V_{\text{dune,long,50y-storm,var}} + V_{\text{dune,long,50y-storm,trs}}) = 1.3 \times (11 + 0.3 + 0.5) = 15 \text{ m}^3/\text{m}$

Using a triangular-type of wear profile, a front slope of 1 to 2, and a profile height of about 4 m (dune toe level to dune crest level), the base width of the dune wear volume is about 8 m, see **Figure 5.2**.

### **Beach wear layer for 10 years-storm**

The 10 years storm yielding a water level of about 0.9 m above MSL will erode the beach, but will most likely not much affect the dune zone.

The wear volume and thickness of the wear layer in the beach zone can be obtained from Equations (4.6), (4.10) and (4.13).

Based on the data of **Table 5.3**, the beach erosion volumes are ( $\alpha_g=0.2$ ;  $\alpha_{p,\text{beach}}=0.7$ ):

Section 1:	$V_{\text{beach,cross,10y-storm}} = 7.8 \text{ m}^3/\text{m}$
	$V_{\text{beach,long,10y-storm,var}} = 0.2 \times 0.7 \times 110 \times 12 / (5 \times 60) \cong 0.6 \text{ m}^3/\text{m}$
Section 2:	$V_{\text{beach,cross,10y-storm}} = 7.2 \text{ m}^3/\text{m}$
	$V_{\text{beach,long,10y-storm,var}} = 0.2 \times 0.7 \times 60 \times 12 / (5 \times 60) \cong 0.3 \text{ m}^3/\text{m}$
Transition S1-S2:	$V_{\text{beach,cross,10y-storm}} = 7.5 \text{ m}^3/\text{m}$
	$V_{\text{beach,long,10y-storm,var}} = 0.5 \text{ m}^3/\text{m}$
	$V_{\text{beach,long,10y-storm,trs}} = 0.7 \times (110-60) \times 12 / (10 \times 60) \cong 0.6 \text{ m}^3/\text{m}$ (deposition)

Including a safety factor  $\gamma_{\text{sf}} = 1.2$ , the total beach wear volume is:

Section 1:	$V_{\text{beach,wear}} = \gamma_{\text{sf}} (V_{\text{beach,cross,10y-storm}} + V_{\text{beach,long,10y-storm,var}}) = 1.2 \times (7.8 + 0.6) = 10 \text{ m}^3/\text{m}$
	$\delta_{\text{beach,wear}} = 10/60 = 0.15 \text{ m}$
Section 2:	$V_{\text{beach,wear}} = \gamma_{\text{sf}} (V_{\text{beach,cross,10y-storm}} + V_{\text{beach,long,10y-storm,var}}) = 1.2 \times (7.2 + 0.3) = 9 \text{ m}^3/\text{m}$
	$\delta_{\text{beach,wear}} = 9/60 = 0.15 \text{ m}$
Tran. S1-S2:	$V_{\text{beach,wear}} = \gamma_{\text{sf}} (V_{\text{beach,cross,10y-storm}} + V_{\text{beach,long,10y-storm,var}} + V_{\text{beach,long,10y-storm,trs}}) = 1.2 \times (7.5 + 0.5 + 0) = 10 \text{ m}^3/\text{m}$
	$\delta_{\text{beach,wear}} = 11/60 = 0.15 \text{ m}$



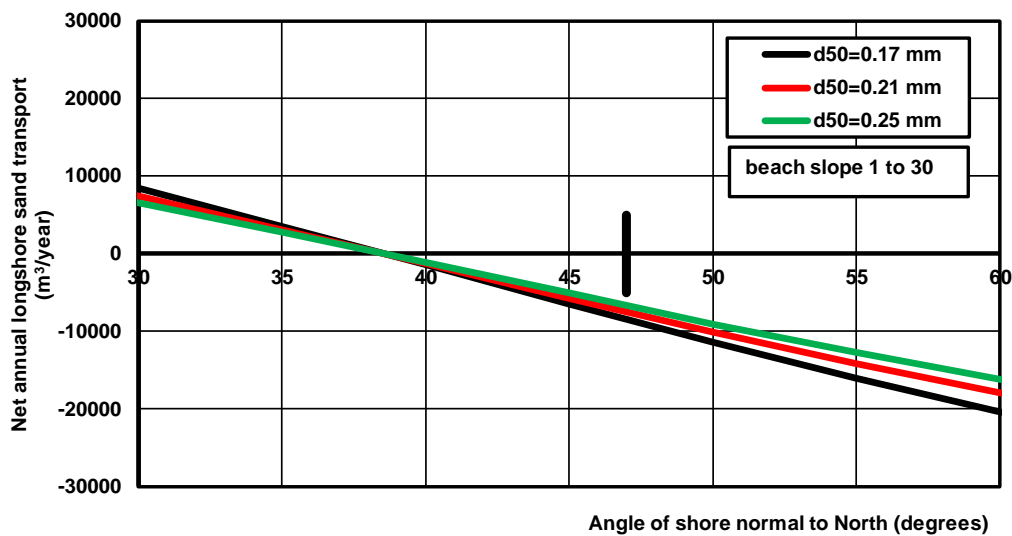
### Beach wear layer for annual wave conditions

The beach wear volume and the wear layer thickness can be determined by using the annual wave conditions, see Equations (4.4), (4.8) and (4.14).

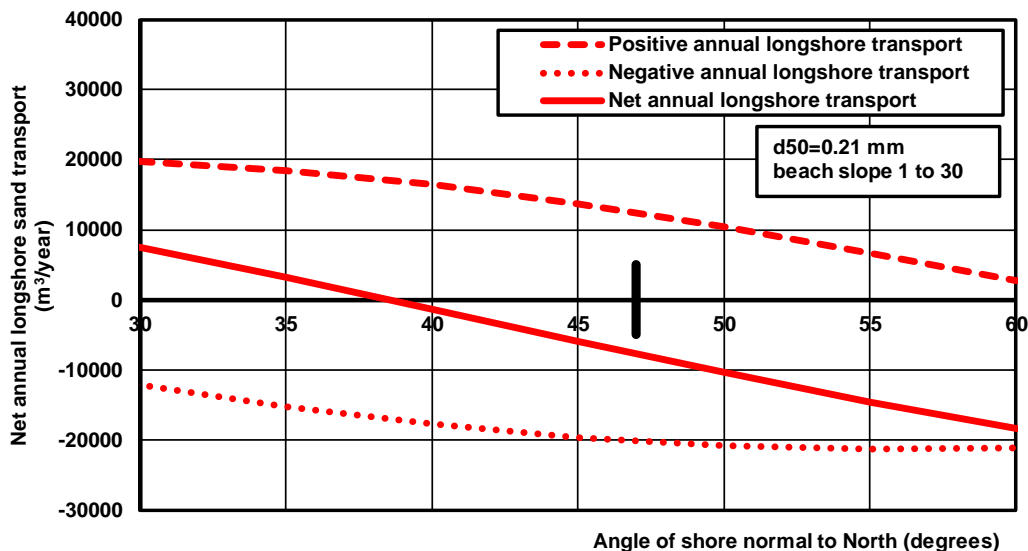
The mean annual longshore transport rate has been computed using the expression given in **ANNEX B**. The annual wave climate is given in **Table 5.1**. The beach sand is  $d_{50} = 0.21$  mm, the beach slope is 1 to 30, the bulk density is  $1600 \text{ kg/m}^3$ , the wave breaking coefficient is  $\gamma_{br} = 0.6$ . The shore normal =  $47^\circ$  to North; the shore normal has been varied in the range of  $30^\circ$  to  $60^\circ$  to include uncertainties.

**Figure 5.7** shows the computed net annual longshore sand transport rates for  $d_{50} = 0.17$ ,  $0.21$  and  $0.25$  mm.

**Figure 5.8** shows the positive, negative and net annual longshore transport rates for  $d_{50} = 0.21$  mm.



**Figure 5.7** Net annual longshore sand transport rates (+ to East; - to West)



**Figure 5.8** Positive, negative and net annual longshore sand transport rates (+ to East; - to West)





Using: beach sand  $d_{50} = 0.21$  mm, beach slope of 1 to 30, bulk density of  $1600 \text{ kg/m}^3$ , the longshore transport rates, are:

Section 1:  $Q_{s, \text{long}, \text{annual}, \text{max}} = 20000 \text{ m}^3/\text{year}$  (to West);  $Q_{s, \text{long}, \text{annual}, \text{net}} = 8000 \text{ m}^3/\text{year}$  (to West)

Section 2:  $Q_{s, \text{long}, \text{annual}, \text{max}} = 19500 \text{ m}^3/\text{year}$  (to East);  $Q_{s, \text{long}, \text{annual}, \text{net}} = 8500 \text{ m}^3/\text{year}$  (to East)

Based on this ( $\alpha_g = 0.1$ ;  $\alpha_{p, \text{beach}} = 1$ ;  $N_m = \text{maintenance period} = 10$  years):

Section 1:  $V_{\text{beach}, \text{cross}, \text{annual}} = 4 \text{ m}^3/\text{m}/\text{year}$

$V_{\text{beach}, \text{long}, \text{annual}, \text{var}} = 0.1 \times 1 \times 20000 / (5 \times 60) \cong 7 \text{ m}^3/\text{m}/\text{year}$

Section 2:  $V_{\text{beach}, \text{cross}, \text{annual}} = 4 \text{ m}^3/\text{m}/\text{year}$

$V_{\text{beach}, \text{long}, \text{annual}, \text{var}} = 0.1 \times 1 \times 19500 / (5 \times 60) \cong 7 \text{ m}^3/\text{m}/\text{year}$

Transition S1-S2:  $V_{\text{beach}, \text{cross}, \text{annual}} = 4 \text{ m}^3/\text{m}/\text{year}$

$V_{\text{beach}, \text{long}, \text{annual}, \text{var}} = 7 \text{ m}^3/\text{m}/\text{year}$  (deposition; no wear)

$V_{\text{beach}, \text{long}, \text{annual}, \text{trs}} = 1 \times (8000 + 8500) / (10 \times 60) \cong 28 \text{ m}^3/\text{m}/\text{year}$  (deposition; no wear)

Including a safety factor  $\gamma_{sf} = 1.1$ , the total beach wear volume is:

Section 1:  $V_{\text{beach}, \text{wear}} = \gamma_{sf} [(V_{\text{beach}, \text{cross}, \text{annual}})^2 + (V_{\text{beach}, \text{long}, \text{annual}, \text{var}})^2]^{0.5} N_m = 1.1 \times (4^2 + 7^2)^{0.5} \times 10 = 90 \text{ m}^3/\text{m}$

$\delta_{\text{beach}, \text{wear}} = 90 / 60 = 1.5 \text{ m}$

Section 2:  $V_{\text{beach}, \text{wear}} = \gamma_{sf} [(V_{\text{beach}, \text{cross}, \text{annual}})^2 + (V_{\text{beach}, \text{long}, \text{annual}, \text{var}})^2]^{0.5} N_m = 1.1 \times (4^2 + 7^2)^{0.5} \times 10 = 90 \text{ m}^3/\text{m}$

$\delta_{\text{beach}, \text{wear}} = 90 / 60 = 1.5 \text{ m}$

Transition S1-S2:  $V_{\text{beach}, \text{wear}} = \gamma_{sf} [(V_{\text{beach}, \text{cross}, \text{annual}})^2 + (V_{\text{beach}, \text{long}, \text{annual}, \text{var}})^2 + (V_{\text{beach}, \text{long}, \text{annual}, \text{trs}})^2]^{0.5} N_m =$   
 $= 1.1 \times (4^2 + 0)^{0.5} \times 10 = 45 \text{ m}^3/\text{m}$

$\delta_{\text{beach}, \text{wear}} = 45 / 60 = 0.75 \text{ m}$

The transition zone S1-S2 is an accretion zone with relatively large deposition rates of about  $28 \text{ m}^3/\text{m}/\text{year}$  over a period of 10 years. Assuming a length scale of about 600 m, the total deposition over 10 years in the transition zone will be of the order of  $28 \times 10 \times 600 \cong 170.000 \text{ m}^3$ .

In the case of an eroding transition section (convex coastline), additional measures are required to reduce the erosion rates: wooden pile screens at a spacing of 200 to 300 m; offshore breakwater ( $\alpha_{\text{breakwater}} \ll 1$ ) or a major local sand fill volume.

### **Total maintenance volume and construction volume**

**Table 5.4** shows a summary of computed erosion and wear volumes.

The volume between the residual profile and the original bottom is:  $V_{\text{res}} + V_{\text{base}} + V_{\text{core}} \cong 20 + 30 + 450 = 500 \text{ m}^3/\text{m}$ , see **Figure 5.2**.

The required dune volume above the design level is about  $V_{\text{dune}, \text{se}} = 50 \text{ m}^3/\text{m}$ .

Hence, the design volume per unit width (excl. dune and beach wear volumes) is  $V_{\text{design}} = 500 + 50 = 550 \text{ m}^3/\text{m}$ .

The construction volume is  $V_{\text{construction}} = 1.2 \times 550 \cong 660 \text{ m}^3/\text{m}$  (including construction losses, see Equation 1.2).

The dune wear volume is about  $15 \text{ m}^3/\text{m}$  for 50 years.

If dune monitoring is being done after each major storm event with water levels near or higher than the dune toe level, the dune wear volume can be left out.

The beach maintenance volume at the straight sections is:

$$[(V_{\text{beach}, \text{wear}, 10 \text{ years}})^2 + (V_{\text{beach}, \text{wear}, \text{annual}})^2]^{0.5} = [10^2 + 120^2]^{0.5} \cong 120 \text{ m}^3/\text{m} \text{ for 10 years.}$$

If regular beach monitoring and maintenance (every 5 years) is being done, the beach wear volume can be set to:  $V_{\text{beach}, \text{wear}, \text{annual}} \cong 60 \text{ m}^3/\text{m}$ .

Wind erosion losses will occur if no vegetation is present at the dune front and crest.



Type of erosion	Straight Section 1 L= 3 km	Accreting Transition Section 1-2 L= 0.5 km	Straight section 2 L= 4 km
Design storm with return period of 10000 years (safety)	<u>Dune zone</u> $V_{Cross} = 36 \text{ m}^3/\text{m}$ $V_{Long,var} = 1.2 \text{ m}^3/\text{m}$  $V_{dune, se, required} = 48 \text{ m}^3/\text{m}$ above design storm level	<u>Dune zone</u> $V_{Cross} = 35 \text{ m}^3/\text{m}$ $V_{Long,var} = 1 \text{ m}^3/\text{m}$ $V_{Long, trs} = 1 \text{ m}^3/\text{m}$ $V_{dune, se, required} = 46 \text{ m}^3/\text{m}$ above design storm level	<u>Dune zone</u> $V_{Cross} = 31 \text{ m}^3/\text{m}$ $V_{Long,var} = 0.7 \text{ m}^3/\text{m}$  $V_{dune, se, required} = 41 \text{ m}^3/\text{m}$ above design storm level
Storm with return period of 50 years	<u>Dune zone</u> $V_{Cross} = 11.5 \text{ m}^3/\text{m}$ $V_{Long,var} = 0.4 \text{ m}^3/\text{m}$  Wear volume (50 years) $V_{wear} = 16 \text{ m}^3/\text{m}$ in zone between dune toe and storm level	<u>Dune zone</u> $V_{Cross} = 11 \text{ m}^3/\text{m}$ $V_{Long,var} = 0.3 \text{ m}^3/\text{m}$ $V_{Long, trs} = 0.5 \text{ m}^3/\text{m}$  Wear volume (50 years) $V_{wear} = 15 \text{ m}^3/\text{m}$ in zone between dune toe and storm level	<u>Dune zone</u> $V_{Cross} = 10.6 \text{ m}^3/\text{m}$ $V_{Long,var} = 0.2 \text{ m}^3/\text{m}$  Wear volume (50 years) $V_{wear} = 14 \text{ m}^3/\text{m}$ in zone between dune toe and storm level
Storm with return period of 10 years	<u>Beach zone (60 m)</u> $V_{Cross} = 7.8 \text{ m}^3/\text{m}$ $V_{Long,var} = 0.6 \text{ m}^3/\text{m}$  Wear volume (10 years) $V_{wear} = 10 \text{ m}^3/\text{m}$ $\delta_{wear} = 10/60 = 0.15 \text{ m}$ in beach zone	<u>Beach zone (60 m)</u> $V_{Cross} = 7.5 \text{ m}^3/\text{m}$ $V_{Long,var} = 0.5 \text{ m}^3/\text{m}$ (deposition) $V_{Long, trs} = 0.6 \text{ m}^3/\text{m}$ (deposition)  Wear volume (10 years) $V_{wear} = 10 \text{ m}^3/\text{m}$ $\delta_{wear} = 10/60 = 0.15 \text{ m}$ in beach zone	<u>Beach zone (60 m)</u> $V_{Cross} = 7.2 \text{ m}^3/\text{m}$ $V_{Long,var} = 0.3 \text{ m}^3/\text{m}$  Wear volume (10 years) $V_{wear} = 9 \text{ m}^3/\text{m}$ $\delta_{wear} = 9/60 = 0.15 \text{ m}$ in beach zone
Long term erosion due annual wave conditions	<u>Beach zone</u> (width= 60 m) erosion $V_{Cross} = 4 \text{ m}^3/\text{m/year}$ $V_{Long,var} = 7 \text{ m}^3/\text{m/year}$  Wear volume (for 10 years) $V_{wear} = 90 \text{ m}^3/\text{m}$ $\delta_{wear} = 90/60 = 1.5 \text{ m}$ in beach zone	<u>Beach zone</u> (width= 60 m) deposition $V_{Cross} = 4 \text{ m}^3/\text{m/year}$ $V_{Long,var} = 7 \text{ m}^3/\text{m/year}$ (deposition) $V_{Long, trs} = 28 \text{ m}^3/\text{m/year}$ (deposition)  Wear volume (for 10 years) $V_{wear} = 45 \text{ m}^3/\text{m}$ $\delta_{wear} = 45/60 = 0.75 \text{ m}$ in beach zone	<u>Beach zone</u> (width= 60 m) erosion $V_{Cross} = 4 \text{ m}^3/\text{m/year}$ $V_{Long,var} = 7 \text{ m}^3/\text{m/year}$  Wear volume (for 10 years) $V_{wear} = 90 \text{ m}^3/\text{m}$ $\delta_{wear} = 90/60 = 1.5 \text{ m}$ in beach zone
Wind erosion (without vegetation)	$3 \text{ m}^3/\text{m/jr}$	$2 \text{ m}^3/\text{m/jr}$	$4 \text{ m}^3/\text{m/jr}$

**Table 5.4** Summary of erosion volumes and wear volumes



## 6. Example case 2: beach-dune system coastal section Camperduin-Petten, Netherlands

### 6.1 Coastal section Camperduin-Petten, North-Holland, Netherlands

The seadike “Hondsbossche en Pettemer Zeedijk” (HBPZ; KM17-28 from Den Helder, see **Figure 6.1**) along the coastal section between Camperduin and Petten has been replaced by a natural beach-dune system of sand in the period 2012-2014 resulting in a coastline shift of about 500 m at the location of the seadike, see **Figure 6.2**. The sand was dredged from an offshore borrow pit beyond the -20 m depth contour.



**Figure 6.1** HBPZ from South to North before (upper) and after construction of new beach-dune system.

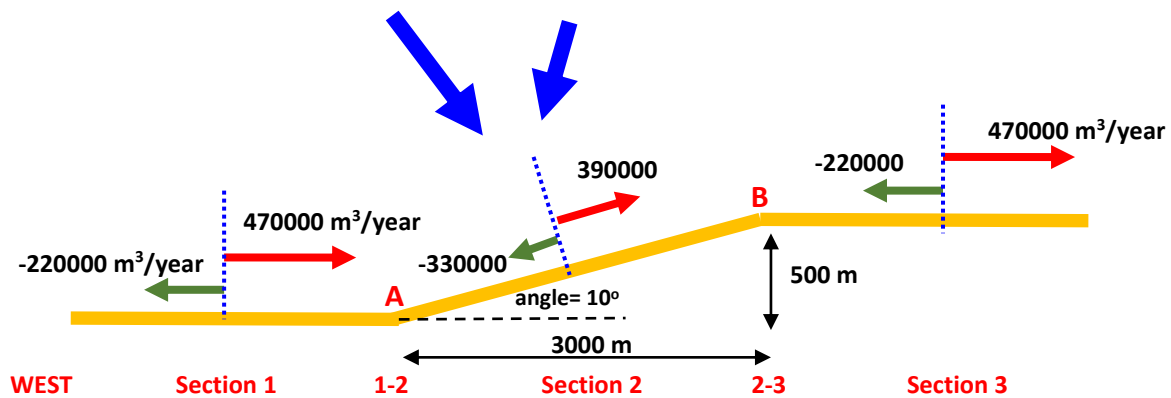


Figure 6.2 Plan view of longshore transport vectors (+ to the North and – to the South)

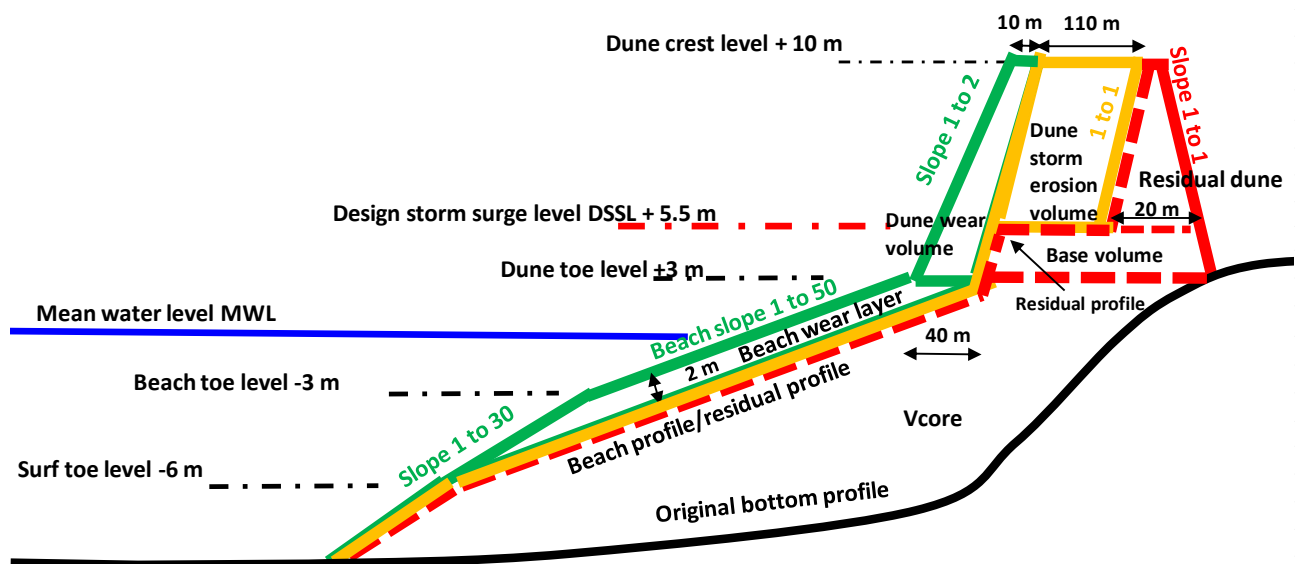


Figure 6.3 Cross-shore beach-dune profile (green=construction profile; yellow=profile without maintenance volumes; red= residual profile after extreme storm)

## 6.2 Available data

The dominant waves come from the sector South-West. Conditions with waves larger than 0.5 m occur during 75% of the time. Two breaker bars are present in the surf zone landward of the -6 m/-8 m (to mean sea level MSL). The tidal wave runs from South to North. The mean tidal range at the site is about 2 m. The maximum flood flow to the North is about 0.5 to 0.6 m/s; the maximum ebb flow to the South is about 0.4 to 0.5 m/s at deeper water. The tidal currents in the surf zone are of the order of 0.1 m/s. The highest measured storm surge level including tide is about +4 m above MSL. The wind-driven velocities at deeper water are about 1 m/s at BF 8.

The net annual longshore sand transport is in the range of 0.2 to 0.3 millions m<sup>3</sup>/year to the North (Deltares, 1995, 2009, Van Rijn 2013).



The local beach sand is in the range of 0.2 to 0.25 mm. The beach slope is about 1 to 50 between -1 m and +3 m MSL.

Other available data, see **Figure 6.3**:

Shore/Coast normal at the HBPZ sea dike makes an angle of 102° to North;

Dune crest level at +10 m above MSL.

Dune toe level at +3 m above MSL.

Beach toe level at -3 m below MSL.

Beach sand  $d_{50} = 0.21$  mm; Beach slope = 1 to 50 between the dune toe and the beach toe.

Sea level rise effect= 0.5 m (for coming 50 years)

The design conditions are defined for a return period of 10,000 years.

The peak duration of an extreme design storm is defined to be 12 hours.

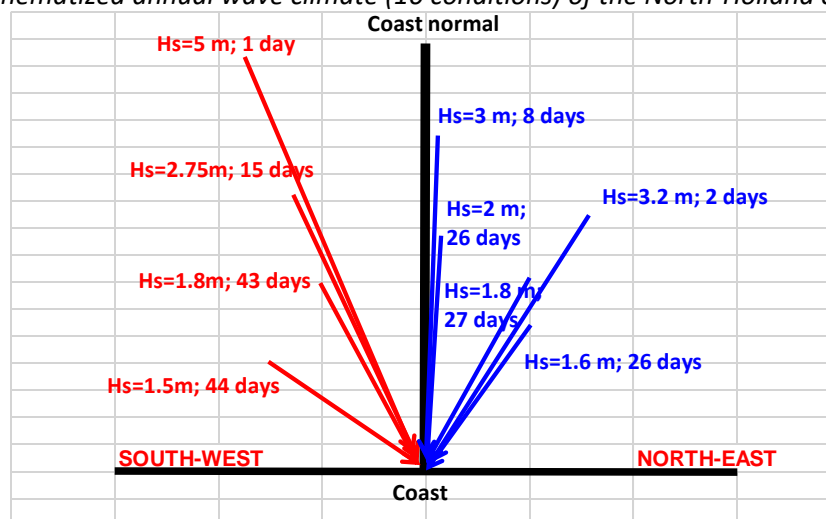
### Annual wave climate table

Table 6.1 shows the annual wave data; Figure 6.4 shows the wave vectors.

Duration (days)	Significant wave height at deep water $H_{s,o}$ (m)	Peak wave period $T_p$ (s)	Angle wave direction at deep water to coast normal (degrees)	Storm surge to MSL (m)
44	1.5	4.9	58	0
43	1.8	5.4	28	0
15	2.75	6.6	28	0.5
26	2.0	5.7	-2	0
27	1.8	5.4	-32	0
26	1.6	5.1	-32	0
8	3.0	6.9	-2	0.5
2	3.2	7.2	-32	0.5
1	5.0	10	30	2
173	<1 m (no wind)	0.5	5.	0

+ from south-west to north-east; - from north-east to south-west

**Table 6.1** Schematized annual wave climate (10 conditions) of the North-Holland coast (1980-1988)



**Figure 6.4** Plot of annual wave vectors



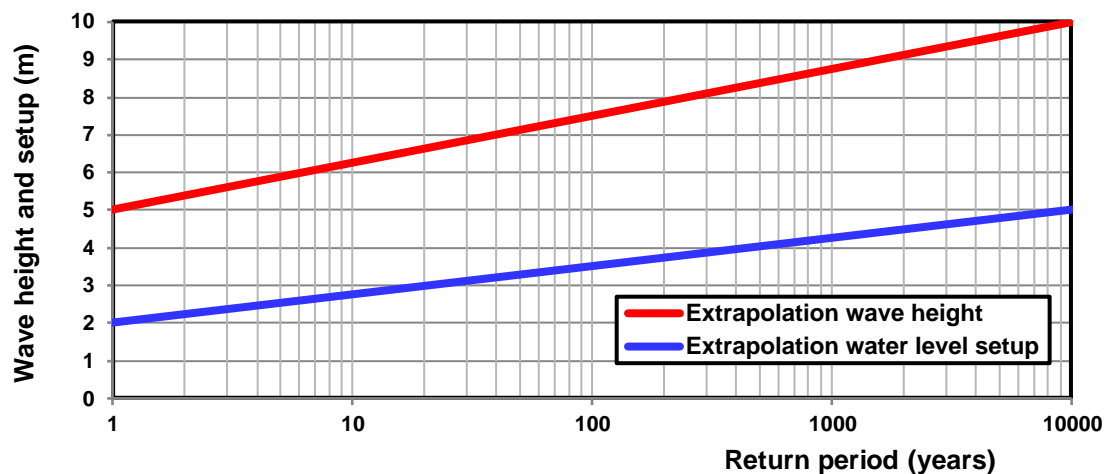
### Storm wave data

Storm wave data are available for the period 1900 to 2000, which is period of 100 years. To obtain the return periods for extreme conditions, the available data have been extrapolated to return periods up to 10,000 years, see **Table 6.2** and **Figure 6.5**.

The design conditions are defined to have a return period of 10,000 years.

Offshore water depth to mean level $h_o$ (m)	Offshore significant wave height $H_{s,o}$ (m)	Peak wave period $T_p$ (s)	Offshore wave angle to shore normal (°)	Storm setup above mean level incl. sea level rise (m)	Return period (years)
30	5.0	10.0	30	2.0	1
30	6.2	11.0	30	2.7	10
30	7.1	11.5	30	$3.2+0.5=3.7$	50
30	7.5	12.0	30	$3.5+0.5=4.0$	100
30	8.7	14.0	30	$4.3+0.5=4.8$	1000
30	10	16.2	30	$5.0+0.5=5.5$	10000

**Table 6.2** Storm wave data



**Figure 6.5** Extrapolation of wave height and water level setup

### 6.3 Design cross-shore beach-dune profile; method Van Rijn

**Figure 6.3** shows the basic zones of the design beach-dune profile including dune wear and beach wear volumes.

#### Dune erosion volume of design storm (10,000 years)

The cross-shore erosion of the dune front can be estimated by using the DR-model (ANNEX A) for given input conditions, see **Tables 6.2, 6.3** and **6.4**. The DR-model is implemented in the spreadsheet **Littoral.xls**.

Given:

Beach sand  $d_{50} = 0.00021$  m;

Beach slope = 1 to 50 (between surf toe level -3 m and dune toe level +3 m);

Surge level for return period of 10,000 years = 5m; sea level rise for 50 years = 0.5 m;

Design water level  $S = 5 + 0.5 = 5.5$  m above mean sea level MSL.

Based on **Tables 6.3, 6.4**, the dune erosion volume above the design water level (DSSL) of +5.5 m for an extreme storm with duration of 12 hours is:





Section 1:  $V_{\text{dune,se,cross}} = 345 \text{ m}^3/\text{m}$   
 Section 2:  $V_{\text{dune,se,cross}} = 330 \text{ m}^3/\text{m}$   
 Section 3:  $V_{\text{dune,se,cross}} = 345 \text{ m}^3/\text{m}$

The erosion in the dune zone due to local longshore transport gradients during the design storm can be estimated by the Equations (4.5), (4.9).

Section 1: Using  $\alpha_{p,\text{dune}}=0.3$ ,  $\alpha_g=0.2$ ,  $T_{\text{storm}}=12 \text{ hrs}$ ,  $Q_{s,\text{long}}=52000 \text{ m}^3/\text{hr}$ ,  $W_{\text{beach}}=300 \text{ m}$  (-3 m to +3 m NAP):  
 $V_{\text{dune,long,storm,var}} = 0.3 \times 0.2 \times 52000 \times 12 / (5 \times 300) \cong 25 \text{ m}^3/\text{m}$ .  
 Section 2: Using  $\alpha_{p,\text{dune}}=0.3$ ,  $\alpha_g=0.2$ ,  $T_{\text{storm}}=12 \text{ hrs}$ ,  $Q_{s,\text{long}}=41000 \text{ m}^3/\text{hr}$ ,  $W_{\text{beach}}=300 \text{ m}$ :  
 $V_{\text{dune,long,storm,var}} = 0.3 \times 0.2 \times 41000 \times 12 / (5 \times 300) \cong 20 \text{ m}^3/\text{m}$ .  
 Section 3: Using  $\alpha_{p,\text{dune}}=0.3$ ,  $\alpha_g=0.2$ ,  $T_{\text{storm}}=12 \text{ hrs}$ ,  $Q_{s,\text{long}}=52000 \text{ m}^3/\text{hr}$ ,  $W_{\text{beach}}=60 \text{ m}$ :  
 $V_{\text{dune,long,storm,var}} = 0.3 \times 0.2 \times 52000 \times 12 / (5 \times 300) \cong 25 \text{ m}^3/\text{m}$ .

Transition S1 to S2: Using  $\alpha_{p,\text{dune}}=0.3$ ,  $T_{\text{storm}}=12 \text{ hrs}$ ,  $W_{\text{beach}}=300 \text{ m}$ :  
 $V_{\text{dune,long,storm,trs}} = 0.3 \times (52000 - 41000) \times 12 / (10 \times 300) \cong 13 \text{ m}^3/\text{m}$  (deposition).  
 $V_{\text{dune,long,storm,var}} = 0.5(25 + 20) = 22 \text{ m}^3/\text{m}$ .  
 Transition S2 to S3: Using  $\alpha_{p,\text{dune}}=0.3$ ,  $T_{\text{storm}}=12 \text{ hrs}$ ,  $W_{\text{beach}}=300 \text{ m}$ :  
 $V_{\text{dune,long,storm,trs}} = 0.3 \times (57000 - 41000) \times 12 / (10 \times 300) \cong 13 \text{ m}^3/\text{m}$  (erosion).  
 $V_{\text{dune,long,storm,var}} = 0.5(25 + 20) = 22 \text{ m}^3/\text{m}$ .

Including a safety factor  $\gamma_{\text{sf}}=1.3$ , the total dune erosion volume above the design storm level is:

Section 1:  $V_{\text{dune,se}} = \gamma_{\text{sf}} (V_{\text{dune,cross,storm}} + V_{\text{dune,long,storm,var}}) = 1.3 \times (345 + 25) = 480 \text{ m}^3/\text{m}$ .  
 Section 2:  $V_{\text{dune,se}} = \gamma_{\text{sf}} (V_{\text{dune,cross,storm}} + V_{\text{dune,long,storm,var}}) = 1.3 \times (330 + 20) = 455 \text{ m}^3/\text{m}$ .  
 Section 3:  $V_{\text{dune,se}} = \gamma_{\text{sf}} (V_{\text{dune,cross,storm}} + V_{\text{dune,long,storm,var}}) = 1.3 \times (345 + 25) = 480 \text{ m}^3/\text{m}$ .  
 Tran. S1-S2:  $V_{\text{dune,se}} = \gamma_{\text{sf}} (V_{\text{dune,cross,storm}} + V_{\text{dune,long,storm,var}} + V_{\text{dune,long,storm,trs}}) = 1.3 \times (335 + 22 + 13) = 480 \text{ m}^3/\text{m}$ .  
 Tran. S2-S3:  $V_{\text{dune,se}} = \gamma_{\text{sf}} (V_{\text{dune,cross,storm}} + V_{\text{dune,long,storm,var}} + V_{\text{dune,long,storm,trs}}) = 1.3 \times (335 + 22 + 13) = 480 \text{ m}^3/\text{m}$ .

Given the dune crest level = 10 m above MSL and design storm level DSSL = 5.5 m to MSL, the dune height  $h_{\text{dune}} = 10 - 5.5 = 4.5 \text{ m}$  and the mean dune width  $W_{\text{dune}} = V_{\text{dune}}/h_{\text{dune}} = 480/4.5 \cong 105 \text{ m}$ .

The slopes of the dune erosion volume are assumed to 1 to 1 (eroded dune fronts are relatively steep).

Offshore significant wave height	Peak wave period	Offshore wave angle to shore normal	Storm setup above mean level (incl. sea level rise)	Return period	Longshore sand transport $d_{50}=0.21 \text{ mm}$ $\gamma_{br}=0.6$ beach 1 to 50 $\rho_{\text{bulk}}=1600 \text{ kg/m}^3$ $Q_{s,\text{Long}}$ (kg/s); (m <sup>3</sup> /hr)	Dune erosion volume $d_{50}=0.21 \text{ mm}$ beach slope 1 to 50  $V_{\text{dune,cross,storm}}$ (m <sup>3</sup> /m) after 5      12 hours	
$H_{s,o}$ (m)	$T_p$ (s)	$\theta_o$ (°)	(m)	$T_{\text{return}}$ (years)			
5.0	10	30	2.0	1	2950    6650	45	55
6.2	11	30	2.7	10	5550    12500	80	95
7.1	11.5	30	3.2+0.5=3.7	50	8950    20000	130	155
7.5	12	30	3.5+0.5=4.0	100	9700    22000	150	180
8.7	14	30	4.3+0.5=4.8	1000	15200    34000	225	270
<b>10</b>	<b>16.2</b>	<b>30</b>	<b>5.0+0.5=5.5</b>	<b>10000</b>	<b>23000    52000</b>	<b>290</b>	<b>345</b>

Table 6.3 Input and output data for DR-model (design conditions in red); Section 1 and 3



Offshore significant wave height	Peak wave period	Offshore wave angle to shore normal	Storm setup above mean level (incl. sea level rise)	Return period	Longshore sand transport $d_{50}=0.21$ mm $\gamma_{br}=0.6$ beach 1 to 50 $\rho_{bulk}=1600$ kg/m <sup>3</sup> $Q_{s,Long}$ (kg/s); (m <sup>3</sup> /hr)		Dune erosion volume $d_{50}=0.21$ mm beach slope 1 to 50 $V_{dune,cross,storm}$ (m <sup>3</sup> /m) after 5 12 hours	
$H_{s,o}$ (m)	$T_p$ (s)	$\theta_o$ (°)	(m)	$T_{return}$ (years)				
5.0	10	20	2.0	1	2320	5200	45	55
6.2	11	20	2.7	10	4385	9900	75	90
7.1	11.5	20	3.2+0.5=3.7	50	7040	16000	125	150
7.5	12	20	3.5+0.5=4.0	100	8300	19000	145	175
8.7	14	20	4.3+0.5=4.8	1000	12060	27000	215	260
<b>10</b>	<b>16.2</b>	<b>20</b>	<b>5.0+0.5=5.5</b>	<b>10000</b>	<b>18320</b>	<b>41000</b>	<b>275</b>	<b>330</b>

Table 6.4 Input and output data for DR-model (design conditions in red); Section 2

Figure 6.6 shows the predicted storm erosion profile based on the CROSMOR-model. The input data are:  $H_{s,o}=10$  m (6 wave classes Rayleigh),  $T_p=16.2$  s, offshore wave angle=  $0^\circ$  and  $30^\circ$ , offshore water depth= 50 m below MWL,  $d_{50}=0.21$  mm, beach slope of 1 to 50, storm duration=12 hours (wave parameters are constant during the storm), water level= 5.5 m above mean water level (constant over 12 hours). The dune erosion is about 150 m<sup>3</sup>/m above the storm level for an offshore wave angle of  $0^\circ$  and about 400 m<sup>3</sup>/m for an offshore wave angle of  $30^\circ$ . This latter value is about 15% larger than that (345 m<sup>3</sup>/m; Table 6.4) based on the DR-model. The total dune and beach erosion increases enormously (to about 1000 m<sup>3</sup>/m above MWL) in the case with oblique waves due to the generation of a strong longshore current and associated increase of the sand concentrations and hence the cross-shore transport capacity. The erosion is less (green curve, Figure 6.6) for a time-varying storm cycle of 36 hours. The wave height increases linearly from 2 to 10 m in 15 hours, remains constant at 10 m for 6 hours and reduces to 2 m during the last 15 hours of the storm cycle. The storm water level has a similar cycle with values between 1 and 5.5 m. The offshore wave angle varies from  $-30^\circ$  to  $0^\circ$  and then to  $+30^\circ$  simulating the passage of a storm.

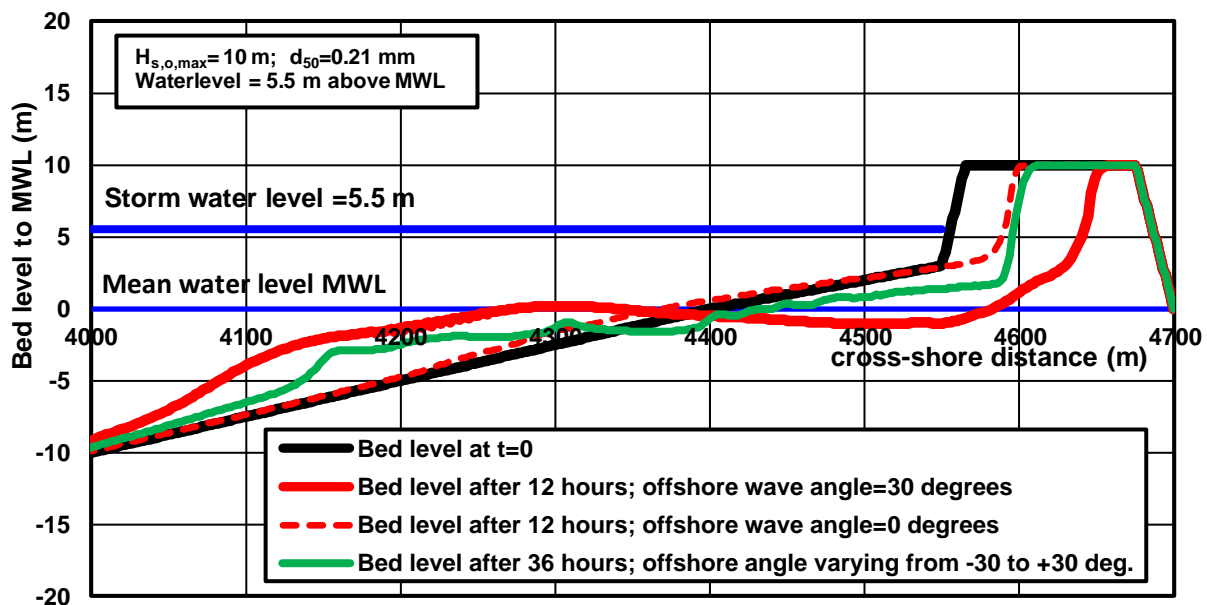


Figure 6.6 Predicted storm erosion volume based on CROSMOR-model (File: hbpz1.inp; hbpz2.inp)



### **Dune wear layer for 50 years-storm event**

The dune wear volume is the volume that needs to be present to deal with storm erosion losses during a given economic period after construction of the new beach-dune profile. Herein, an economic period of 50 years is used.

The dune wear volume can be computed from Equation (4.12). The peak duration of the storm with return period of 50 years is assumed to be 12 hours.

The minimum dune wear volume is  $V_{\text{dune,wear,minimum}} = 0.1 V_{\text{dune,se}} = 0.1 \times 480 = 48 \text{ m}^3/\text{m}$ .

Based on the data of **Tables 6.3, 6.4**, it follows that ( $\alpha_g=0.2$ ;  $\alpha_{p,\text{dune}}=0.3$ ):

Section 1:	$V_{\text{dune,cross,50y-storm}}$	$= 155 \text{ m}^3/\text{m}$
	$V_{\text{dune,long,50y-storm,var}}$	$= 0.2 \times 0.3 \times 20000 \times 12 / (5 \times 300) \cong 10 \text{ m}^3/\text{m}$
Section 2:	$V_{\text{dune,cross,50y-storm}}$	$= 150 \text{ m}^3/\text{m}$
	$V_{\text{dune,long,50y-storm,var}}$	$= 0.2 \times 0.3 \times 16000 \times 12 / (5 \times 300) \cong 8 \text{ m}^3/\text{m}$
Section 3:	$V_{\text{dune,cross,50y-storm}}$	$= 155 \text{ m}^3/\text{m}$
	$V_{\text{dune,long,50y-storm,var}}$	$= 0.2 \times 0.3 \times 20000 \times 12 / (5 \times 300) \cong 10 \text{ m}^3/\text{m}$
Transition S1-S2:	$V_{\text{dune,cross,50y-storm}}$	$= 150 \text{ m}^3/\text{m}$ (by interpolation)
	$V_{\text{dune,long,50y-storm,var}}$	$= 0.5(10+8)=9 \text{ m}^3/\text{m}$ (by interpolation)
	$V_{\text{dune,long,50y-storm,trs}}$	$= 0.3 \times (20000-16000) \times 12 / (10 \times 300) \cong 5 \text{ m}^3/\text{m}$
Transition S2-S3:	$V_{\text{dune,cross,50y-storm}}$	$= 150 \text{ m}^3/\text{m}$ (by interpolation)
	$V_{\text{dune,long,50y-storm,var}}$	$= 0.5(8 + 10)= 9 \text{ m}^3/\text{m}$ (by interpolation)
	$V_{\text{dune,long,50y-storm,trs}}$	$= 0.3 \times (20000-16000) \times 12 / (10 \times 300) \cong 5 \text{ m}^3/\text{m}$

Including a safety factor  $\gamma_{\text{sf}} = 1.1$ , the total dune wear volume is:

Section 1:	$V_{\text{dune,wear}} = \gamma_{\text{sf}} (V_{\text{dune,cross,50y-storm}} + V_{\text{dune,long,50y-storm,var}})$	$= 1.1 \times (155+10) = 180 \text{ m}^3/\text{m}$ .
Section 2:	$V_{\text{dune,wear}} = \gamma_{\text{sf}} (V_{\text{dune,cross,50y-storm}} + V_{\text{dune,long,50y-storm,var}})$	$= 1.1 \times (150+8) = 175 \text{ m}^3/\text{m}$ .
Section 3:	$V_{\text{dune,wear}} = \gamma_{\text{sf}} (V_{\text{dune,cross,50y-storm}} + V_{\text{dune,long,50y-storm,var}})$	$= 1.1 \times (155+10) = 180 \text{ m}^3/\text{m}$ .
Tran. S1-S2:	$V_{\text{dune,wear}} = \gamma_{\text{sf}} (V_{\text{dune,cross,50y-storm}} + V_{\text{dune,long,50y-storm,var}} + V_{\text{dune,long,50y-storm,trs}})$	$= 1.1 \times (150+9+5) = 180 \text{ m}^3/\text{m}$ .
Tran. S2-S3:	$V_{\text{dune,wear}} = \gamma_{\text{sf}} (V_{\text{dune,cross,50y-storm}} + V_{\text{dune,long,50y-storm,var}} + V_{\text{dune,long,50y-storm,trs}})$	$= 1.1 \times (150+9+5) = 180 \text{ m}^3/\text{m}$ .

Using a trapezoidal-type of wear profile, a front slope of 1 to 2, and a profile height of about 7 m (Dune toe level at +3 m to dune crest at =10 m MSL), the width of the dune wear volume at the dune toe level is about 40 m, see **Figure 6.3**.

### **Beach wear layer for annual waves**

The beach wear volume and the wear layer thickness can be determined by using the annual wave conditions, see Equation (4.14).

The mean annual longshore transport rate has been computed using the expression given in **ANNEX B**. The annual wave climate is given in **Table 6.1**. The beach sand is  $d_{50} = 0.21 \text{ mm}$ , the beach slope is 1 to 50, the bulk density is  $1600 \text{ kg/m}^3$ , the wave breaking coefficient is  $\gamma_{\text{br}} = 0.6$ .

Using: beach sand  $d_{50} = 0.21 \text{ mm}$ , beach slope of 1 to 50, bulk density of  $1600 \text{ kg/m}^3$ , the longshore transport rates (see **Figure 6.2**), are:

Section 1:	$Q_{s,\text{long,annual,max}} = 470,000 \text{ m}^3/\text{year}$ (to northeast); $Q_{s,\text{long,annual net}} = 250,000 \text{ m}^3/\text{year}$ (to northeast)
Section 2:	$Q_{s,\text{long,annual,max}} = 390,000 \text{ m}^3/\text{year}$ (to northeast); $Q_{s,\text{long,annual net}} = 60,000 \text{ m}^3/\text{year}$ (to northeast)
Section 3:	$Q_{s,\text{long,annual,max}} = 470,000 \text{ m}^3/\text{year}$ (to northeast); $Q_{s,\text{long,annual net}} = 250,000 \text{ m}^3/\text{year}$ (to northeast)



Based on this ( $\alpha_g = 0.1$ ;  $\alpha_p = 1$ ;  $N_m$  = maintenance period = 5 years):

Section 1:  $V_{\text{beach,cross,annual}} = 55 \text{ m}^3/\text{m/year}$

$$V_{\text{beach,long,annual,var}} = 0.1 \times 1 \times 470,000 / (5 \times 300) \cong 32 \text{ m}^3/\text{m/year}$$

Section 2:  $V_{\text{beach,cross,annual}} = 55 \text{ m}^3/\text{m/year}$

$$V_{\text{beach,long,annual,var}} = 0.1 \times 1 \times 390,000 / (5 \times 300) \cong 26 \text{ m}^3/\text{m/year}$$

Section 3:  $V_{\text{beach,cross,annual}} = 55 \text{ m}^3/\text{m/year}$

$$V_{\text{beach,long,annual,var}} = 0.1 \times 1 \times 470,000 / (5 \times 300) \cong 32 \text{ m}^3/\text{m/year}$$

Tran. S1-S2:  $V_{\text{beach,cross,annual}} = 55 \text{ m}^3/\text{m/year}$

$$V_{\text{beach,long,annual,var}} = 0.5(26+32) \cong 30 \text{ m}^3/\text{m/year}$$

$$V_{\text{beach,long,annual,trs}} = 1 \times (250,000 - 60,000) / (10 \times 300) \cong 65 \text{ m}^3/\text{m/year (deposition)}$$

Tran. S2-S3:  $V_{\text{beach,cross,annual}} = 55 \text{ m}^3/\text{m/year}$

$$V_{\text{beach,long,annual,var}} = 0.5(26+32) \cong 30 \text{ m}^3/\text{m/year}$$

$$V_{\text{beach,long,annual,trs}} = 1 \times (250,000 - 60,000) / (10 \times 300) \cong 65 \text{ m}^3/\text{m/year (erosion)}$$

Including a safety factor  $\gamma_{sf} = 1.1$ , the total beach wear volume is:

$$\text{Section 1: } V_{\text{beach,wear}} = \gamma_{sf} [(V_{\text{beach,cross,annual}})^2 + (V_{\text{beach,long,annual,var}})^2]^{0.5} N_m = 1.1 \times (55^2 + 32^2)^{0.5} \times 5 = 350 \text{ m}^3/\text{m}$$

$$\delta_{\text{beach,wear}} = 350/300 \cong 1.2 \text{ m}$$

$$\text{Section 2: } V_{\text{beach,wear}} = \gamma_{sf} [(V_{\text{beach,cross,annual}})^2 + (V_{\text{beach,long,annual,var}})^2]^{0.5} N_m = 1.1 \times (55^2 + 26^2)^{0.5} \times 5 = 335 \text{ m}^3/\text{m}$$

$$\delta_{\text{beach,wear}} = 335/300 = 1.1 \text{ m}$$

$$\text{Section 3: } V_{\text{beach,wear}} = \gamma_{sf} [(V_{\text{beach,cross,annual}})^2 + (V_{\text{beach,long,annual,var}})^2]^{0.5} N_m = 1.1 \times (55^2 + 32^2)^{0.5} \times 5 = 350 \text{ m}^3/\text{m}$$

$$\delta_{\text{beach,wear}} = 350/300 \cong 1.2 \text{ m}$$

Tran.S1-S2: accretion section; neglecting the longshore transport gradient due to the transition effect, the beach wear layer should be based on:

$$V_{\text{beach,wear}} = \gamma_{sf} [(V_{\text{beach,cross,annual}})^2 + (V_{\text{beach,long,annual,var}})^2 + (V_{\text{beach,long,annual,trs}})^2]^{0.5} N_m$$

$$= 1.1 \times (55^2 + 30^2 + 0)^{0.5} \times 5 = 340 \text{ m}^3/\text{m};$$

$$\delta_{\text{beach,wear}} = 340/300 \cong 1.15 \text{ m}.$$

Tran. S2-S3: erosion section;

$$V_{\text{beach,wear}} = \gamma_{sf} [(V_{\text{beach,cross,annual}})^2 + (V_{\text{beach,long,annual,var}})^2 + (V_{\text{beach,long,annual,trs}})^2]^{0.5} N_m$$

$$= 1.1 \times (55^2 + 30^2 + 65^2)^{0.5} \times 5 = 500 \text{ m}^3/\text{m};$$

$$\delta_{\text{beach,wear}} = 500/300 \cong 1.7 \text{ m}.$$

The transition zone S1-S2 is an accretion section with relatively large deposition volumes of about  $5 \times 65 = 325 \text{ m}^3/\text{m}$  over a period of 5 years. Assuming a length scale of about  $10 \times 300 = 3000 \text{ m}$ , the total deposition over 5 years in the transition zone will be of the order of  $325 \times 3000 \cong 1,000,000 \text{ m}^3$  (1 million  $\text{m}^3$ )

The transition zone S2-S3 is an erosion section (convex coastline) with a very large erosion volume of about  $500 \text{ m}^3/\text{m}$  over 5 years, which requires a beach wear layer of 1.7 m. This latter value may not be feasible in practice (maximum wear layer of about 1.5 m), which can be overcome by using a maintenance period of 3 years reducing the beach wear layer thickness to about 1 m. Another additional measure can be the construction of a very large fill volume of about 1 million  $\text{m}^3$  in the zone between -3 and -6 m MSL over a length scale of 3 km.

### **Total maintenance volume and construction volume**

The volume between the residual profile and the original bottom is:  $V_{\text{res}} + V_{\text{base}} + V_{\text{core}} = 60 + 350 + 3000 \cong 3400 \text{ m}^3/\text{m}$ , see **Figure 6.5**.

The required dune volume above the design level ( $1 \times 10,000$  years) is about  $V_{\text{dune,se}} = 500 \text{ m}^3/\text{m}$ , see **Table 6.5**. Hence, the total design volume per unit width (excl. wear layers) is  $V_{\text{design}} = 3400 + 500 = 3900 \text{ m}^3/\text{m}$ .

The construction volume per unit width is  $V_{\text{construction}} = 1.2 \times 3900 \cong 4700 \text{ m}^3/\text{m}$  (including construction losses, see Equation 1.2).



The dune wear volume in all Sections is about  $180 \text{ m}^3/\text{m}$  for 50 years.

This value can be left out, if dune monitoring is being done after each major storm event with water levels near or higher than the dune toe level.

The beach maintenance volume in Section 1, 1-2, 2 and 3 is about  $350 \text{ m}^3/\text{m}$  for 5 years.

The beach wear volume in the eroding transition Section 2-3 is about  $500 \text{ m}^3/\text{m}$  for 5 years, which is a maintenance layer of about 1.7 m.

Figure 6.7 shows the beach-dune profile including wear layers.

Type of erosion	Straight Section 1	Accreting Transition Section 1-2 L= 3 km	Straight section 2	Eroding Transition Section 2-3 L= 3 km	Straight section 2
Design storm with return period of 10000 years (safety)	<u>Dune zone</u> $V_{\text{Cross}} = 345 \text{ m}^3/\text{m}$ $V_{\text{Long,var}} = 25 \text{ m}^3/\text{m}$  $V_{\text{dune,se,required}} = 480 \text{ m}^3/\text{m}$ above design storm level	<u>Dune zone</u> $V_{\text{Cross}} = 340$ $V_{\text{Long,var}} = 22$ $V_{\text{Long,trs}} = 13$ $V_{\text{dune,se,required}} = 480$	<u>Dune zone</u> $V_{\text{Cross}} = 330 \text{ m}^3/\text{m}$ $V_{\text{Long,var}} = 20 \text{ m}^3/\text{m}$  $V_{\text{dune,se,required}} = 455$	<u>Dune zone</u> $V_{\text{Cross}} = 340$ $V_{\text{Long,var}} = 22$ $V_{\text{Long,trs}} = 13$ $V_{\text{dune,se,required}} = 480$	<u>Dune zone</u> $V_{\text{Cross}} = 345$ $V_{\text{Long,var}} = 25$  $V_{\text{dune,se,required}} = 480$
Storm with return period of 50 years	<u>Dune zone</u> $V_{\text{Cross}} = 155 \text{ m}^3/\text{m}$ $V_{\text{Long,var}} = 10 \text{ m}^3/\text{m}$  Wear volume (50 years) $V_{\text{wear}} = 180 \text{ m}^3/\text{m}$ in zone between dune toe and storm level	<u>Dune zone</u> $V_{\text{Cross}} = 150 \text{ m}^3/\text{m}$ $V_{\text{Long,var}} = 8 \text{ m}^3/\text{m}$ $V_{\text{Long,trs}} = 5 \text{ m}^3/\text{m}$  Wear volume (50 years) $V_{\text{wear}} = 180 \text{ m}^3/\text{m}$ in zone between dune toe and storm level	<u>Dune zone</u> $V_{\text{Cross}} = 150 \text{ m}^3/\text{m}$ $V_{\text{Long,var}} = 8 \text{ m}^3/\text{m}$  Wear volume (50 years) $V_{\text{wear}} = 175 \text{ m}^3/\text{m}$ in zone between dune toe and storm level	<u>Dune zone</u> $V_{\text{Cross}} = 150$ $V_{\text{Long,var}} = 8$ $V_{\text{Long,trs}} = 5$  Wear volume (50 years) $V_{\text{wear}} = 180$ in zone between dune toe and storm level	<u>Dune zone</u> $V_{\text{Cross}} = 155$ $V_{\text{Long,var}} = 10$  Wear volume (50 years) $V_{\text{wear}} = 180$ in zone between dune toe and storm level
Long term erosion due annual wave conditions	<u>Beach zone</u> (width= 300 m) erosion $V_{\text{Cross}} = 55 \text{ m}^3/\text{m/y}$ $V_{\text{Long,var}} = 32 \text{ m}^3/\text{m/y}$  Wear volume (for 5 years) $V_{\text{wear}} = 350 \text{ m}^3/\text{m}$ $\delta_{\text{wear}} = 350/300 = 1.2 \text{ m}$	<u>Beach zone</u> (width= 300 m) deposition $V_{\text{Cross}} = 55 \text{ m}^3/\text{m/y}$ $V_{\text{Long,var}} = 30 \text{ m}^3/\text{m/y}$ (D) $V_{\text{Long,trs}} = 65 \text{ m}^3/\text{m/y}$ (D)  Wear volume (for 5 years) $V_{\text{wear}} = 340 \text{ m}^3/\text{m}$ $\delta_{\text{wear}} = 340/300 = 1.15 \text{ m}$	<u>Beach zone</u> (width= 300 m) erosion $V_{\text{Cross}} = 55 \text{ m}^3/\text{m/y}$ $V_{\text{Long,var}} = 26 \text{ m}^3/\text{m/y}$  Wear volume (for 5 years) $V_{\text{wear}} = 335 \text{ m}^3/\text{m}$ $\delta_{\text{wear}} = 335/300 = 1.1 \text{ m}$	<u>Beach zone</u> (width= 300 m) erosion $V_{\text{Cross}} = 55$ $V_{\text{Long,var}} = 30$ (E) $V_{\text{Long,trs}} = 65$ (E)  Wear volume (for 5 years) $V_{\text{wear}} = 500 \text{ m}^3/\text{m}$ $\delta_{\text{wear}} = 500/300 = 1.7 \text{ m}$	<u>Beach zone</u> (width= 300 m) erosion $V_{\text{Cross}} = 55$ $V_{\text{Long,var}} = 32$  Wear volume (for 5 years) $V_{\text{wear}} = 350$ $\delta_{\text{wear}} = 350/300 = 1.2 \text{ m}$

D= deposition; E=erosion

**Table 6.5** Summary of erosion volumes and wear volumes

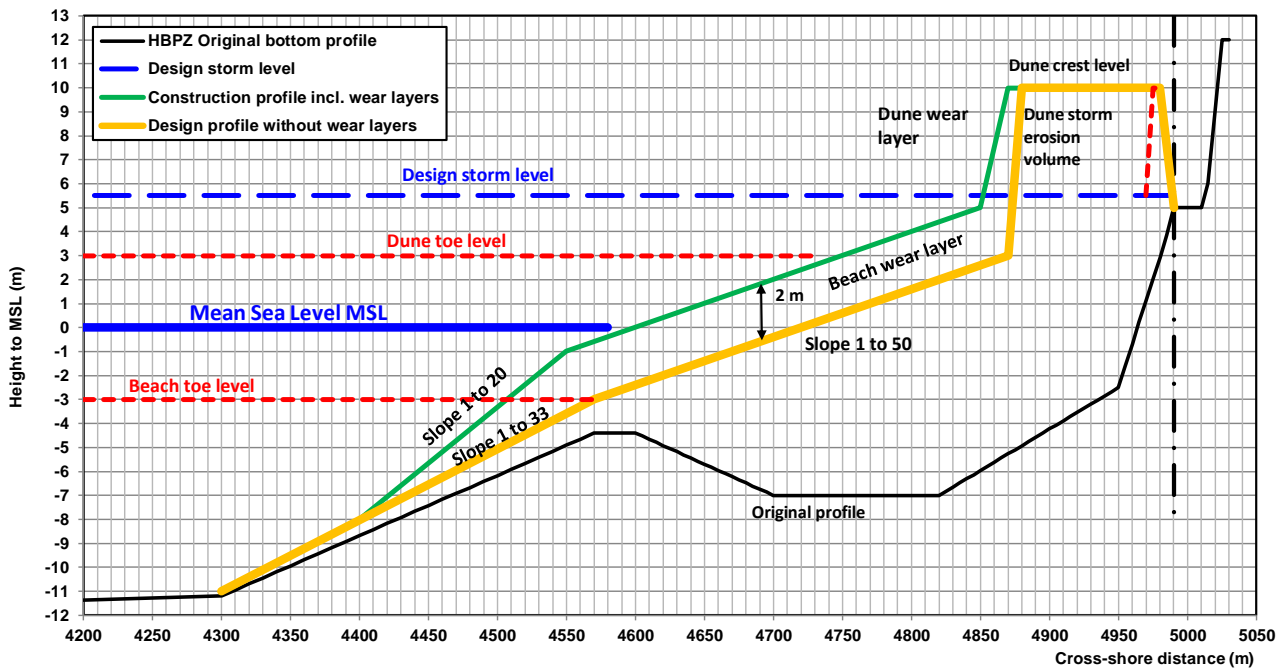


Figure 6.7 Cross-shore beach-dune profile; coast Camperduin-Petten, North-Holland, The Netherlands

#### 6.4 Design cross-shore beach-dune profile; method DUROS+ model of Deltares/Rijkswaterstaat

The DUROS+ model of Deltares/Rijkswaterstaat is described in ANNEX C. This method has been applied to the design profile minus the wear layers, see Figure 6.6 (yellow profile).

The input data are (Table 6.2):

design storm surge level DSSL=+5.5 m MSL,

$H_{s,0} = 10$  m,  $T_p = 16.2$  s,  $\theta_0 = 0^\circ$ ,

$d_{50} = 0.21$  mm (fall velocity  $w_s = 0.0225$  m/s).

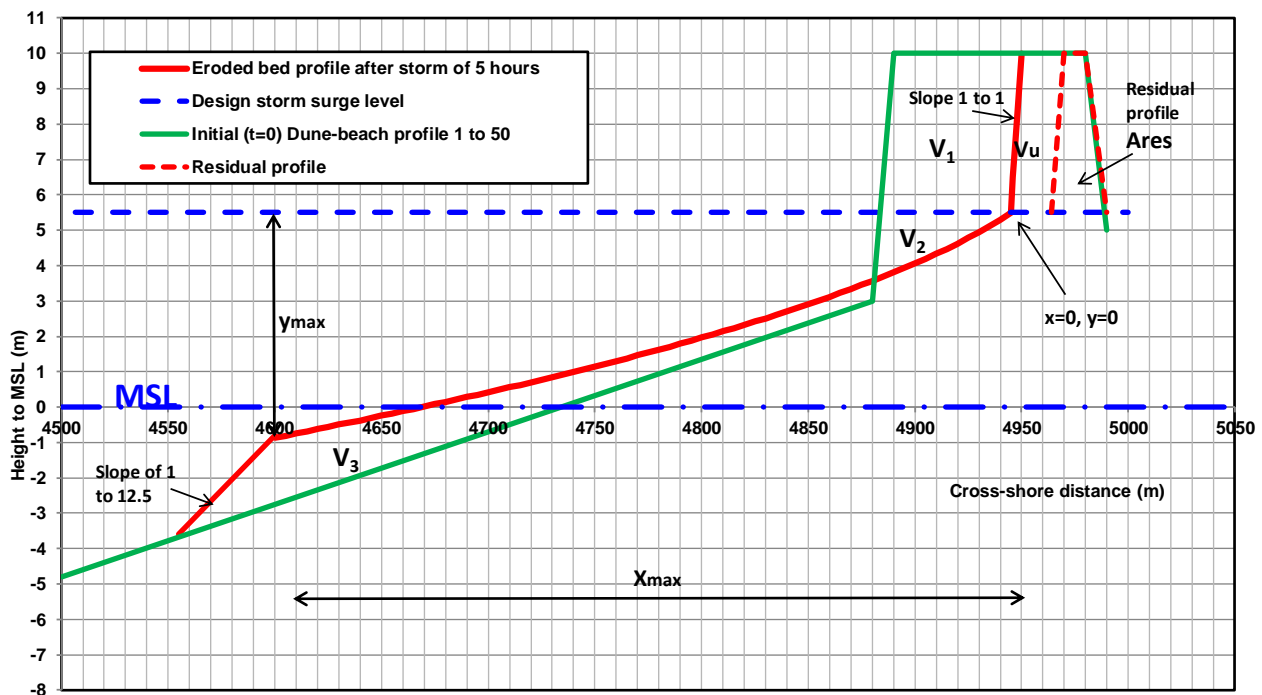
The results are shown in Figure 6.8 and in Table 6.6.

The computed dune erosion volume above the design storm level is about  $V_1 = 240$  m<sup>3</sup>/m (after storm with 5 hours). This method does not take the offshore wave angle into account. Hence, the results are only valid for waves normal to the coast. The volume related to uncertainties  $V_u = 0.25 \times 240 = 60$  m<sup>3</sup>/m.

The method of Van Rijn yields a dune storm erosion volume of 250 m<sup>3</sup>/m after 5 hours for an offshore wave angle of  $\theta_0 = 0^\circ$  (waves normal to the coast). Hence, both methods yield very similar results for the same input data.

The method of Van Rijn yields a dune storm erosion volume of 290 m<sup>3</sup>/m after 5 hours and  $\theta_0 = 30^\circ$  (see Table 6.6).

The method of Van Rijn is more conservative if the offshore wave angle is included. Furthermore, the dune wear layer is included to account for storm erosion losses over a maintenance period of 10 years.



**Figure 6.8** Storm erosion profile based on DUROS+ model; coast Camperduin-Petten, North-Holland

Predicted dune volumes	Method DUROS+ waves normal coast Storm duration= 5 hrs	Method Van Rijn		
		Waves normal coast (0°) Duration= 5 hrs	Waves oblique coast (30°) Duration= 5 hrs	Waves oblique coast (30°) Duration= 12 hrs
Predicted dune volume (m <sup>3</sup> /m)	240 m <sup>3</sup> /m	250 m <sup>3</sup> /m	290 m <sup>3</sup> /m	350 m <sup>3</sup> /m
Uncertainty volume (m <sup>3</sup> /m)	60 m <sup>3</sup> /m (25%)	75 m <sup>3</sup> /m (30%)	90 m <sup>3</sup> /m (30%)	100 m <sup>3</sup> /m (30%)
Total volume (m <sup>3</sup> /m)	300 m <sup>3</sup> /m	325 m <sup>3</sup> /m	380 m <sup>3</sup> /m	450 m <sup>3</sup> /m

**Table 6.6** Predicted dune erosion volumes of DUROS+ method and Van Rijn-method



## ANNEX A: DUNE RULE-model (DR-model)

The erosion volume of a dune due to storm waves can be computed from the simplified erosion model (Van Rijn 2009), as follows (see **Figure A1**):

$$A_{d,t=5} = A_{d,ref} (d_{50,ref}/d_{50})^{\alpha_1} (S/S_{ref})^{\alpha_2} (H_{s,o}/H_{s,o,ref})^{\alpha_3} (T_p/T_{p,ref})^{\alpha_4} (\tan\beta/\tan\beta_{ref})^{\alpha_5} (1+\theta_o/100)^{\alpha_6} \quad (A1)$$

with:

$A_{d,t=5}$  = dune erosion area (or volume per unit width) above storm surge level after 5 hours ( $m^3/m$ ),

$A_{d,ref}$  = dune erosion area (volume per unit width) above  $S$  storm surge level after 5 hours in Reference Case= 170 ( $m^3/m$ ),

$S$  = storm surge level above mean sea level (m),

$S_{ref}$  = storm surge level above mean sea level in Reference Case= 5 (m),

$H_{s,o}$  = offshore significant wave height (m),

$H_{s,o,ref}$  = offshore significant wave height in Reference Case= 7.6 (m),

$T_p$  = peak wave period (s),

$T_{p,ref}$  = peak wave period (s) in Reference Case= 12 (s),

$d_{50}$  = median bed material diameter (m),

$d_{50,ref}$  = median bed material diameter in Reference Case= 0.000225 (m),

$\tan\beta$  = coastal slope gradient defined as the slope between the -3 m depth contour (below mean sea level) and the dune toe (+3 m),

$\tan\beta_{ref}$  = coastal slope gradient defined as the slope between the -3 m depth contour and the dune toe (+3 m) for the Reference Case= 0.0222 (1 to 45),

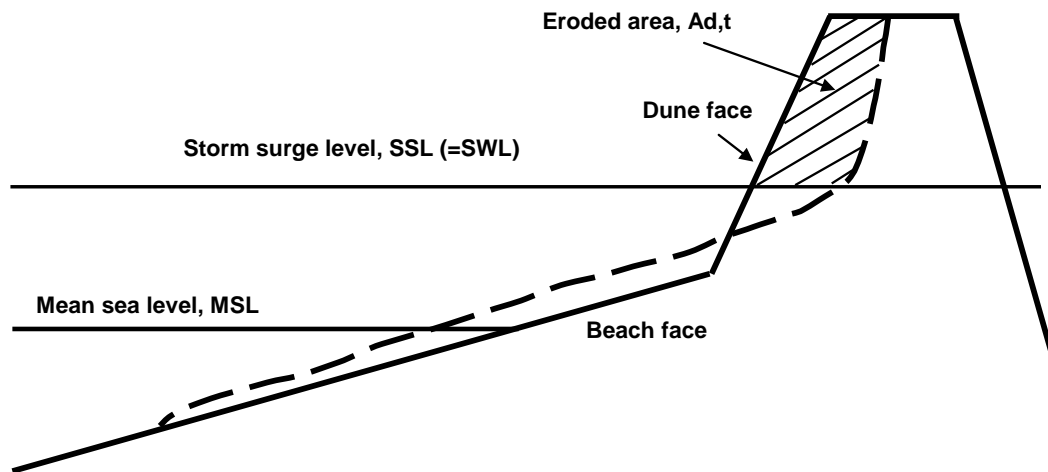
$\theta_o$  = offshore wave incidence angle to coast normal (degrees),

$\alpha_1$  = exponent=1.3,

$\alpha_2$  = exponent=1.3 for  $S < S_{ref}$  and  $\alpha_2=0.5$  for  $S > S_{ref}$ ,

$\alpha_3 = \alpha_4 = \alpha_6 = 0.5$  (exponents),

$\alpha_5$  = exponent=0.3.



**Figure A1** Sketch of dune erosion

Equation (A1) yields zero erosion for  $S=0$  (no storm surge set-up).

The average horizontal dune recession ( $R_d$ ) can be estimated from:

$$R_d = A_d / (h_d - S) \quad (A2)$$





The maximum horizontal dune recession ( $R_{d,max}$ ) at storm surge level can be estimated from:

$$R_{d,max} \cong 1.5 R_d \quad (A3)$$

with:

$R_d$  = average horizontal dune recession (m),

$R_{d,max}$  = maximum horizontal dune recession at storm surge level (m),

$h_d$  = height of dune crest above mean sea level (m).

The time development over 100 hours can be estimated from:

$$A_{d,t} = A_{d,t=5} (t/t_{ref})^{\alpha_6} \quad (A4)$$

with:

$t$  = time in hours ( $t_{ref} = 5$  hours),

$\alpha_6$  = exponent = 0.5 for  $t < t_{ref}$  and 0.2 for  $t > t_{ref}$ .

Basically, the proposed method produces dune erosion values with respect to a defined Reference Case (storm with a constant storm surge level, wave height and duration of 5 hours). According to the CROSMOR-model, the dune erosion area above storm surge level in the Reference Case is approximately  $A_{d,ref} = 170 \text{ m}^3/\text{m}$ . According to the experimental values (Vellinga, 1986), this value is in the range of 250 to  $300 \text{ m}^3/\text{m}$ . The storm surge level ( $S$ ) above mean sea level and the bed material diameter ( $d_{50}$ ) are the most influential parameters. Equation (A7) is especially suitable for probabilistic computations to represent the natural variations of the controlling parameters.

As an example, the following storm values are used:

$S=4 \text{ m}$ ,  $H_{s,0}=5 \text{ m}$ ,  $T_p=10 \text{ s}$ ,  $d_{50}=0.0002 \text{ m}$ ,  $\alpha_o=20^\circ$ ,  $h_d=15$ ,  $\tan\beta=0.02$  yielding:

$A_d = 170 (0.000225/0.0002)^{1.3} (4/5)^{1.3} (5/7.6)^{0.5} (10/12)^{0.5} (0.02/0.0222)^{0.3} (1+20/100)^{0.5} = 115 \text{ m}^3/\text{m}$  after 5 hours.

$A_d = 82 \text{ m}^3/\text{m}$  after 2.5 hours and  $135 \text{ m}^3/\text{m}$  after 10 hours.

$R_d = 115/(15-4) = 10.5 \text{ m}$  after 5 hours;  $7.5$  after 2.5 hours and  $12.5 \text{ m}$  after 10 hours.

$R_{d,max} = 16 \text{ m}$  after 5 hours;  $11 \text{ m}$  after 2.5 hours and  $19 \text{ m}$  after 10 hours.



## ANNEX B: Longshore sand transport

The longshore sand transport rate can be computed by (Van Rijn, 2013):

$$Q_{t, \text{mass}} = 0.00018 \rho_s g^{0.5} (\tan\beta)^{0.4} (d_{50})^{-0.6} (H_{s, \text{br}})^{3.1} \sin(2\theta_{\text{br}}) \quad (\text{B1})$$

$Q_t$  = total longshore sediment transport (in kg/s),

$\rho_s$  = sediment density (kg/m<sup>3</sup>),

$d_{50}$  = median grain size (m),

$H_{s, \text{br}}$  = significant wave height at breakerline (m),

$\theta_{\text{br}}$  = wave angle at breakerline,

$g$  = acceleration of gravity (m/s<sup>2</sup>),

$\tan\beta$  = slope of beach/surf zone.

Equation (B1) does not account for the effect of the wave period on the longshore transport rate. However, low-period swell waves in the range of 1 to 2 m produce significantly larger transport rates (factor 1.5 compared to wind waves of the same height ( $H_{\text{rms}}=H$ )). This effect can to some extent be taken into account by using a correction factor to the longshore transport rate, if the percentage of swell waves (in terms of wave height) of the total wave height record is known. Herein, it is proposed to use a swell factor, as follows:

$$K_{\text{swell}} = 1.5(p_{\text{swell}}/100) + 1 (1-p_{\text{swell}}/100) = 0.015p_{\text{swell}} + (1-0.01p_{\text{swell}}) \quad (\text{B2})$$

with:

$p_{\text{swell}}$  = percentage of low-period swell wave heights of the total wave height record (about 10% to 20% for sea coasts and 20% to 30% for ocean coasts).

Some values are:  $K_{\text{swell}}=1.05$  for  $p_{\text{swell}}=10\%$ ;  $K_{\text{swell}}=1.1$  for  $p_{\text{swell}}=20\%$  and  $K_{\text{swell}}=1.5$  for  $p_{\text{swell}}=100\%$ .

If swell is absent (or unknown), then  $K_{\text{swell}}=1$ .

Using this approach, the longshore transport rate increases slightly with increasing percentage of swell.

Based on this, Equation (B1) reads, as:

$$Q_{t, \text{mass}} = 0.00018 K_{\text{swell}} \rho_s g^{0.5} (\tan\beta)^{0.4} (d_{50})^{-0.6} (H_{s, \text{br}})^{3.1} \sin(2\theta_{\text{br}}) \quad (\text{B3})$$

Equation (B3) can also be expressed, as:

$$Q_{t, \text{mass}} = 0.0006 K_{\text{swell}} \rho_s (\tan\beta)^{0.4} (d_{50})^{-0.6} (H_{s, \text{br}})^{2.6} V_{\text{wave}} \quad (\text{B4})$$

$$V_{\text{wave}} = 0.3 (gH_{s, \text{br}})^{0.5} \sin(2\theta_{\text{br}}) \quad (\text{B5})$$

with:  $V_{\text{wave}}$  = wave-induced longshore current velocity (m/s) averaged over the cross-section of the surf zone based on the work of Bagnold (1963) and Komar (1979).

Equation (B4) is linear in velocity. Additional velocities in the surf zone due to tide and wind can be simply taken into account by schematizing the tidal period in two blocks, as follows:

$$V_{\text{total}} = V_{\text{wave}} + 0.01p_1 V_1 + 0.01p_2 V_2 \quad (\text{B6})$$

with  $V_1$  = representative velocity in positive longshore direction due to wind and tide;  $V_2$  = representative tidal velocity in negative longshore direction due to wind and tide;  $p_1$  = percentage of time with positive flow (about 50%),  $p_2$  = percentage of time with negative flow (about 50%). The peak longshore velocities in the surf zone due to wind and tide are approximately in the range of 0.1 m/s for micro-tidal to 0.5 m/s for macro-



tidal conditions. Generally, there is a slight asymmetry in the wind-generated velocities in the main wave (wind) direction. Using this approach, a slight asymmetry in the velocities due to wind and tide ( $V_1$  larger than  $V_2$  or reversed) can be taken into account. The effect is zero in fully symmetric tidal flow ( $p_1=50\%$ ,  $p_2=50\%$ ,  $V_1=-V_2$ ).

### Wave refraction for uniform coasts

Equation (B1) or (B3) depends on the basic wave parameters at the breaker line. If only the offshore wave parameters are known, the values at the breakerline can be determined from refraction theory (Van Rijn, 1990/2011). Assuming a straight uniform coast with parallel depth contours, the water depth at the breakerline (location where 5% of the waves are breaking) can be estimated from:

$$h_{br} = [(H_{s,o}^2 c_o \cos\theta_o) / (\alpha \gamma^2 g^{0.5})]^{0.4} \quad (B7)$$

The wave incidence angle at the breakerline ( $\theta_{br}$ ) can be determined from:

$$\sin\theta_{br} = (c_{br}/c_o) \sin\theta_o \quad (B8)$$

with:

$H_{s,o}$  = significant wave height at deep water;

$h_{br}$  = water depth at breakerline;

$c_o, c_{br}$  = wave propagation speed at deep water and at breakerline;

$\theta_o, \theta_{br}$  = wave incidence angle (to shore normal) at deep water and at breakerline;

$\gamma = H_{s,br}/h_{br}$  = breaking coefficient based on 5% breaking= 0.6 to 0.8;

$\alpha = 1.8$  = calibration coefficient based on Egmond data;

$L_o$  = wave length in deep water ( $h_o$ ),  $c_o = L_o/T_p$ ,  $T_p$  = peak wave period.

### Example computation

The following offshore values are given:

$h_o = 20$  m (water depth deep water),

$H_{s,o} = 3$  m,  $T_p = 10$  s,  $\theta_o = 30$  degrees; no swell ( $K_{swell}=1$ ).

The wave breaking coefficient is:  $\gamma=0.6$ .

The sediment size is  $d_{50}=0.0003$  m.

The surf zone slope is  $\tan\beta = 0.02$ .

The wind- and tide induced velocities in the surf zone are:  $v_1=+0.2$  m/s during  $p_1=50\%$  of the time and  $V_2=-0.1$  m/s during  $p_2=50\%$  of the time.

This results in:

$L_o = 121.2$  m (wave length in water depth of 20 m),

$c_o = L_o/T_p = 12.1$  m/s,

$h_{br} = 4.65$  m (water depth at breakerline),

$H_{br} = 2.79$  m,  $\theta_{br} = 15.7$  degrees,  $\sin(2\theta_{br}) = 0.52$ ,

$V_{wave} = 0.815$  m/s,  $V_{total} = 0.864$  m/s

The computed longshore transport rate is  $Q_t=630$  kg/s (including tide-induced velocity) and  $Q_{t'}=507$  kg/s (excluding tide-induced velocities).



### ANNEX C: DUROS+ model

The certified method to compute dune erosion in the Netherlands is known as the DUROS+ method.

The DUROS+method was initially developed by **Vellinga (1986)** basd on many laboratory data sets and later improved by others (**Deltares,2007**).

The eroded bed profile at the end of the design storm is described by (see **Figure C1**):

$$\begin{aligned} Y &= 0.4714 (H_{o,s}/7.6) [(H_{o,s}/7.6)^{1.28} (12/T_p)^{0.45} (w_s/0.0268)^{0.56} x + 18]^{0.5} - 2 \\ X_{\max} &= 250 (H_{o,s}/7.6)^{1.28} (0.0268/w_s)^{0.56} \\ Y_{\max} &= [0.4714 \{250(12/T_p)^{0.45} + 18\}^{0.5} - 2] (H_{o,s}/7.6) \end{aligned} \quad (C1)$$

$$^{10}\log (1/w_s) = 0.476(^{10}\log d_{50})^2 + 2.18 ^{10}\log(d_{50}) + 3.226 \quad (C2)$$

with:

y= depth below the storm surge level (m),

x= distance from new dune foot origin (m),

H<sub>o,s</sub>= significant wave height at deep water (m),

T<sub>p</sub>= peak wave period (s),

w<sub>s</sub>= fall velocity of sand in seawater of 5° Celsius (m/s).

The origin (x=0, y=0) is defined as the intersection of Equation (C1) and the storm surge level. The lower transition between the eroded bed profile and the original sea bed is assumed to have a slope of 1 to 12.5 (see **Figure C1**). The dune front through the origin (x=0, y=0) is assumed to have a slope of 1 to 1.

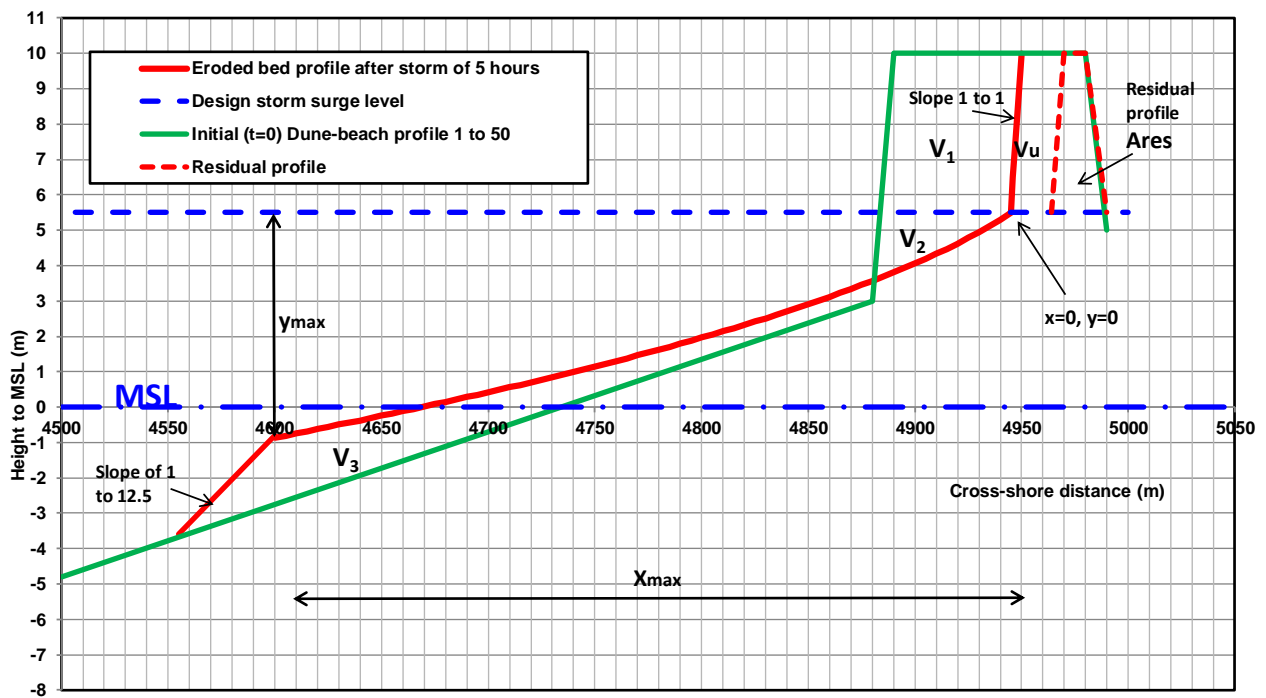
The origin should be shifted until V<sub>1</sub> + V<sub>2</sub> = V<sub>3</sub> (continuity of erosion and accretion).

The total dune volume per unit width (V<sub>total</sub>) above the storm surge level required to have a safe coastal dune is: V<sub>total</sub>= V<sub>1</sub> + V<sub>u</sub> + V<sub>Res</sub>

with:

V<sub>u</sub>= area related to uncertainties involved (about 0.25V<sub>1</sub>) and

V<sub>Res</sub>= area of residual dune (about 0.25V<sub>1</sub>).



**Figure 4** *DUROS+ method;*  
 $H_{0,s} = 10 \text{ m}$ ,  $T_p = 16.2 \text{ s}$ ,  $SSL = 5.5 \text{ m}$ ,  $d_{50} = 0.00025 \text{ m}$ ,  $w_s = 0.0281 \text{ m/s}$ ,  
Dune erosion  $V_1 + V_2 \cong 300 \text{ m}^3/\text{m}$



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