PREDICTION OF DUNE EROSION DUE TO STORMS

by Leo C. van Rijn, Delft Hydraulics and University of Utrecht (leo.vanrijn@wldelft.nl)

(published in Coastal Engineering Vol. 156, 2009, 441-457)

Abstract

This paper presents results of experimental and mathematical modelling of beach and dune erosion under storm events. Re-analysis of the experimental results on dune erosion in small-scale and large-scale flumes show that the dune erosion for extreme conditions is somewhat smaller than that based on earlier analysis results.

Dune erosion caused by wave impact has been modelled by a cross-shore profile model (CROSMOR-model), which is based on a 'wave by wave' modelling approach solving the wave energy equation for each individual wave. The model has been applied to the recent Deltaflume experiments on dune erosion. The three main processes affecting dune erosion have been taken into account: the generation of low-frequency effects, the production of extra turbulence due to wave breaking and wave collision and the sliding of the dune face due to wave impact. The calibrated model can very well simulate the observed dune erosion above the storm surge level during storm events in small-scale facilities, large-scale facilities and in the protoype (1953 storm in The Netherlands) using the same model settings. The mathematical model results have been used to develop a new dune erosion rule.

1. Introduction

Beach and dune erosion and associated mitigation measures are the most classical coastal engineering problems that are existing and have been studied extensively by many researchers (Dean 1973, Vellinga 1986, Kriebel et al. 1991, Dette and Uliczka 1987, Kraus et al. 1991, Steetzel, 1993, Larson et al., 2004).

Field experience over a long period of time in the coastal zone has led to the notion that storm waves cause sediment to move offshore while fair-weather waves and swell return the sediment shoreward. During high-energy conditions with breaking waves (storm cycles), the mean water level rises due to tide-induced forces, wind- and wave-induced setup and the beach and dune zones of the coast are heavily attacked by the incoming waves, usually resulting in erosion processes. When storm waves arrive at the beach, the crests break frequently, resulting in large volumes of water running up the beach face (see Figure 1A). 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, which may feed locally generated rip 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. These processes proceed relatively fast, as indicated by relatively large short-term variations (on the scale of events) of shoreline recession, formation of breaker bars and rip channels. During conditions with low non-breaking waves, onshore-directed transport processes related to wave-asymmetry and wave-induced streaming are dominant, usually resulting in accretion processes in the beach zone. A characteristic feature in the swash zone during low-energy conditions is the zig-zag movement of the sediment particles which is also known as beach drifting. In case of oblique wave incidence, the swash will run up the beach in the direction of wave propagation, but the backwash will move down the steepest slope under the influence of gravity. This latter movement usually is at a right angle to the shore. Sediment particles being moved by the swash and backwash will follow a zig-zag pattern along the shore parallel to the front of the breaking waves. The water carried in the uprush percolates partly through the sediment surface down to the water table at about mean sea level. This percolation reduces the volume of downwash, so causing the sand carried up to be deposited partly on the beach face. This build-up of the beach continues during low-energy conditions.

Herein, the attention is focussed on dune erosion processes during major storm events with relatively high surge levels. Detailed observations during recent dune erosion experiments in the large-scale Deltaflume of Delft

Hydraulics (Delft Hydraulics, 2004, 2006a,b; Van Gent et al., 2008; Van Thiel de Vries et al., 2008) show the dominance of four processes:

1) the generation of strong wave impact forces at the steep dune face generating relatively high bed-shear stresses and hence erosion of sediment,

2) the production of large-scale turbulence due to the impact (wave collision) of incoming breaking waves and reflected broken waves generating fountains of water (see Figure 1B) and sediment resulting in a significant increase of the sediment carrying capacity of the offshore-directed return flows in the surf zone in front the dune,

3) the generation of low frequency waves in the surf zone (surf beat) due to spatial and temporal variation of the breaking point of the irregular high-frequency waves resulting in a spatial and temporal variation of the wave-induced set-up and

4) the regular sliding of the dune face when its has become too steep and the formation of a small bar at the toe of the dune face.

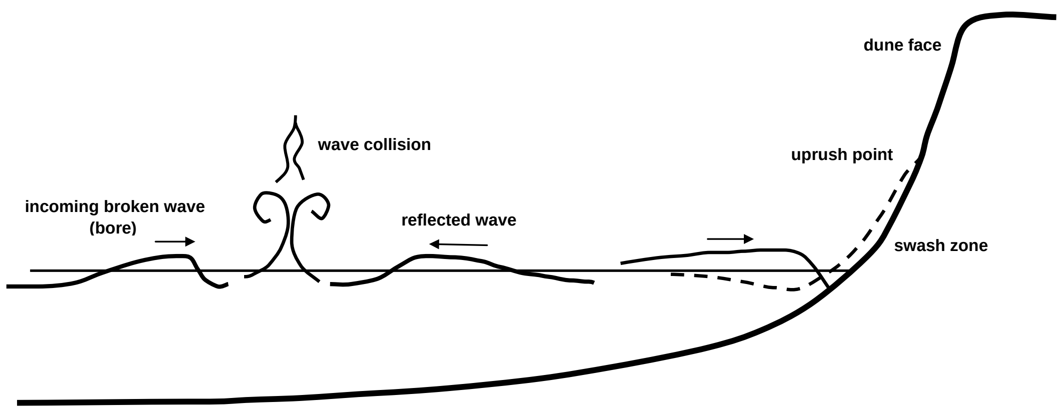

Figure 1A *Wave processes in the shallow surf zone in front of the dune*

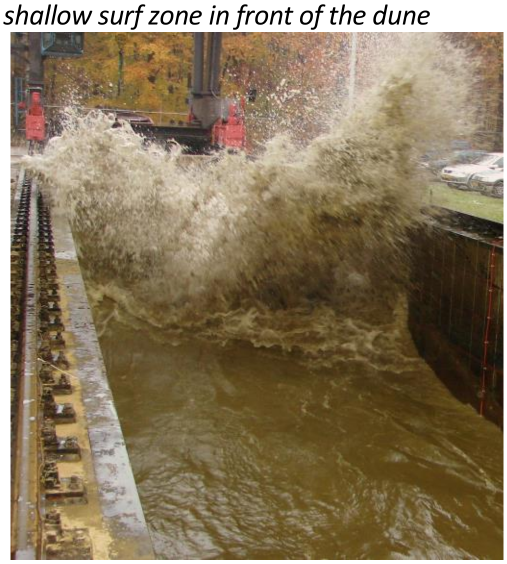

Figure 1B *Impact of incoming and outgoing (reflected) waves in Deltaflume*

An overview of existing empirical models to estimate dune erosion is given by Larson et al. (2004) and will not be repeated herein.

Vellinga (1986) developed the empirical DUROS-method, which was later improved (Deltares, 2007) into the DUROS+ method (ANNEX A).

A semi-empirical model (S-beach) has been proposed by Larson and Kraus (1989). This model is based on equilibrium theory with limited description of the physical processes. A beach profile is assumed to attain an equilibrium shape if exposed to constant wave conditions for a sufficiently long time. An equilibrium profile ($h=Ax^{2/3}$ with x=cross-shore coordinate and A=shape paramer depending on bed material diameter) dissipates

incident wave energy without significant net change in shape. The transport rate is related to the difference between the actual wave energy dissipation and the equilibrium wave energy dissipation along the equilibrium profile. The transport direction is determined from an empirical criterion.
Steetzel (1993) has proposed a process-based mathematical model based on cross-shore wave propagation, wave shoaling, wave refraction and wave breaking. The output of the wave model is used to compute the local cross-shore sand transport rate. Bed level changes are determined from cross-shore gradients of the transport rate in a numerical loop system. A crucial process in the model of Steetzel (1993) is the erosion of sand in the dune face zone, which is done empirically by the use of a function which relates the relative magnitude of the transport rate in this zone to its position and level with respect to the last grid point of the wave model. Low-frequency effects (surf beat), the production of extra turbulence due to collapsing and colliding waves as well as dune face sliding are not taken into account explicitly. The model of Steetzel (1993) has been calibrated using measured data from experiments in the large-scale Deltaflume of Delft Hydraulics. Varies field cases have been used to demonstrate the validity of the model for prototype conditions.
Van Thiel de Vries et al. (2008) worked on the implementation of the dominant dune erosion processes in the process-based DELFT3D-model including both low-frequency and high-frequency processes and the turbulent quantities. These modelling efforts show that the low-frequency effects (propagating bores) can be very well represented by a standard long wave model applied on the wave group time scale. The long waves, associated with the wave group varying short wave energy, can be solved with the surfbeat model (Reniers et al., 2004), which is implemented in DELFT3D-model. It is found that time series of the water surface elevations and the flow velocities in the inner surf and swash zone can be simulated accurately using a momentum conservative numerical scheme (Van Thiel de Vries et al., 2006). The model is being extended by including the wave breaking-induced turbulent quantities to represent the sediment suspension processes near the dune face. The interaction of simulated flows with the avalanching dune face is modeled in a relatively simple way, using seperate critical slopes for wet and dry sand (Van Thiel de Vries and Reniers, 2008).
In the present paper, the attention is focused on the cross-shore modelling of dune erosion using a process-based profile model (CROSMOR2007-model), which has been extended to include the afore-mentioned basic dune erosion processes (Sections 3, 4 and 5). Mathematical model results for a range of conditions have been parameterized to develop a simplified dune erosion rule (Section 5). Experimental results based on scale model tests, discussed in Section 2, are used to verify the mathematical model.

2. Experimental results of dune erosion by extreme storms

Experiments on dune erosion using scale models have been performed by Vellinga (1986) and Delft Hydraulics (2004, 2006a,b, 2007). The experimental data typically represent beach and dune erosion conditions along the Dutch North Sea coast during a very severe storm (design storm), which is herein defined as the Reference Case, see Table 1. The median sediment diameter along the Dutch coast is assumed to be 225 μm (0.225 mm). The high storm surge level (SSL) of 5 m above mean sea level (MSL) is assumed to be constant over a duration of 5 hours during the peak of the storm. This equivalent duration of 5 hours yields approximately the same overall dune erosion volume as a complete storm cycle with growing and waning phases (Vellinga, 1986). The offshore significant wave height is assumed to have a constant value of $H_{s,o}$= 7.6 m and the peak wave period is T_p=12 s.
The vertical scale of the model tests was varied in the range of n_h=84 to n_h=5. The median sediment diameter was varied in the range of 95 to 225 μm; thus: n_{d50}=2.4 to 1. Large-scale experiments using a depth scale of n_h=5 and an offshore wave height of 1.5 m have been done in the Deltaflume (length of 233 m, depth of 7m, width of 5 m), (Vellinga, 1986). Additional large scale tests with n_h=5 and 6 have been performed in the Deltaflume to study the effect of the wave period on the dune erosion volume (Delft Hydraulics, 2006a,b, 2007).

Parameter	Prototype conditions used by Vellinga (1986)
Offshore wave height (m)	7.6 (Pierson and Moskowitz spectrum)
Offshore wave period (s)	12
Offshore water depth (m)	21 m
Storm surge level above MSL (m)	+5 m NAP during 5 hours
Median sediment diameter (μm)	225
Median fall velocity (m/s)	0.0267
Water temperature (^{o}C)	10
Cross-shore profile	a) dune height at +15 m NAP, b) dune face with slope of 1 to 3 down to a level of +3 m NAP, c) slope of 1 to 20 between +3m and 0 m NAP, d) slope of 1 to 70 between 0 and -3 m NAP, e) slope of 1 to 180 seaward of -3 m NAP line

(Remark: Mean Sea Level (MSL) is about equal to NAP)

Table 1 *Parameters of Dutch coastal profile; Reference Case*

Figure 2 shows a plot of the scaled-up dune erosion area (data of Vellinga, 1986) as a function of time based on appropriates scaling laws (Van Rijn, 2008). Figure 3 shows the data of recent small-scale (Sflume) and large-scale flume tests (Dflume) performed at Delft Hydraulics (2004, 2006a,b, 2007) focussing on the effect of the wave period. The wave period was varied in the range of 12 to 18 s. Figure 3 shows that the dune erosion area above storm surge level after 5 hours increases with increasing wave period (about 18% for T increasing from 12 to 18 s). The dune erosion after 5 hours (in prototype values) is approximately 250 m^3/m for the Reference Case with a wave period of T=12 s (see Figures 2 and 3). Scale effects can be observed as the dune erosion area after 5 hours is much larger in the Deltaflume (about 25%) than that in the small-scale flume. The large-scale Deltaflume test of Vellinga (1986) shows (Figure 2) slightly larger erosion areas (about 5% to 10%) after 5 and 10 hours than that of Delft Hydraulics (2006a,b, 2007), shown in Figure 3.

To further evaluate the relative magnitude of scale errors, it is necessary to analyse prototype data of the Dutch coast related to a storm event. Storm erosion data (February 1953) is available for a coastal section between The Hague and Rotterdam (Delfland section; length of about 17 km). The data set comprises of cross-shore bed profiles measured a few days after the storm event (post-storm profiles) and bed profiles measured before the storm (pre-storm profiles measured about 3 to 6 months before the storm). The water level during the storm increased from +1.5 m to +3.9 m (above NAP; approx. mean sea level) over a period of about 30 hours. The maximum measured wave height is about $H_{s,o}$= 6.3 m at an offshore station. The local beach grain size is about 0.225 mm. The measured dune erosion area above the maximum storm surge level of +3.9 m varies in the range of 60 to 150 m^3/m with a mean value of about 90 m^3/m (Vellinga, 1986 and Steetzel, 1993).

Using empirical scaling laws (depth scale of 3.3 and a length scale of 4.6), the February 1953 storm including the time-varying storm surge level has been simulated by Vellinga (1986) in the Deltaflume of Delft Hydraulics. The measured dune erosion volume for this (distorted) laboratory test is about 120 m^3/m, which is about 30% larger than the mean observed value of 90 m^3/m for field conditions. These results indicate that the scaling laws based on (distorted) 2D laboratory tests produce values which are somewhat too large for 3D field conditions. Given the lack of data for extreme storm conditions, a firm conclusion on the scale errors cannot yet be given.

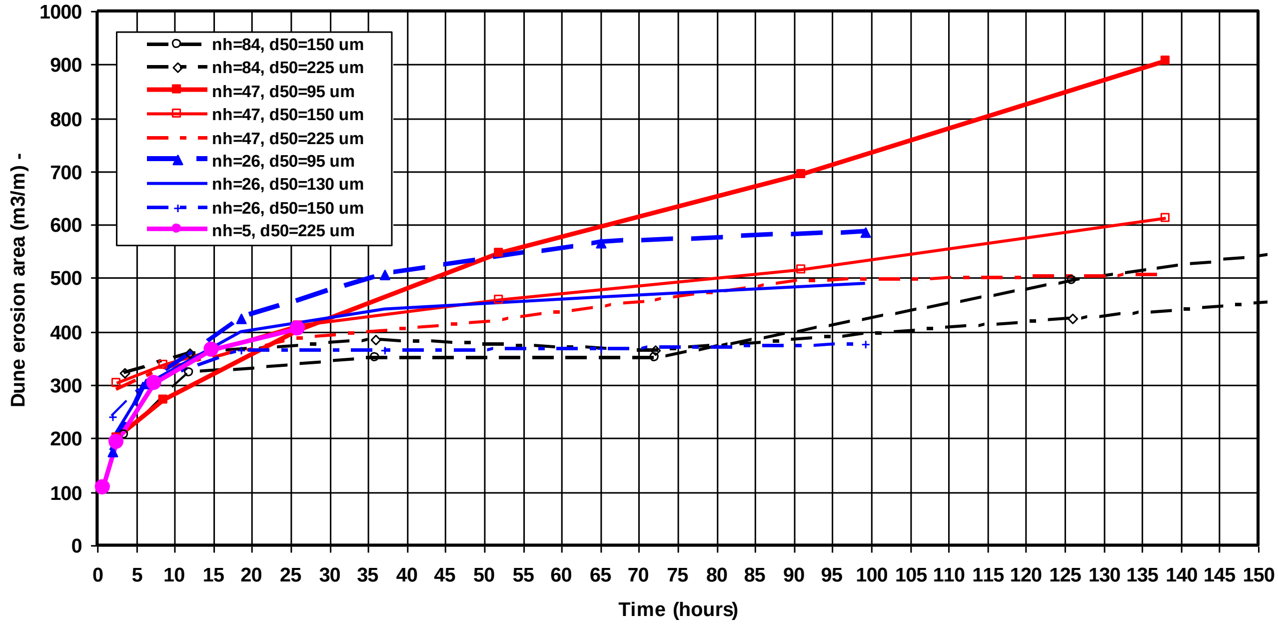

Figure 2 *Dune erosion area (above SSL) as function of time (prototype values) based on data of Vellinga (1986)*

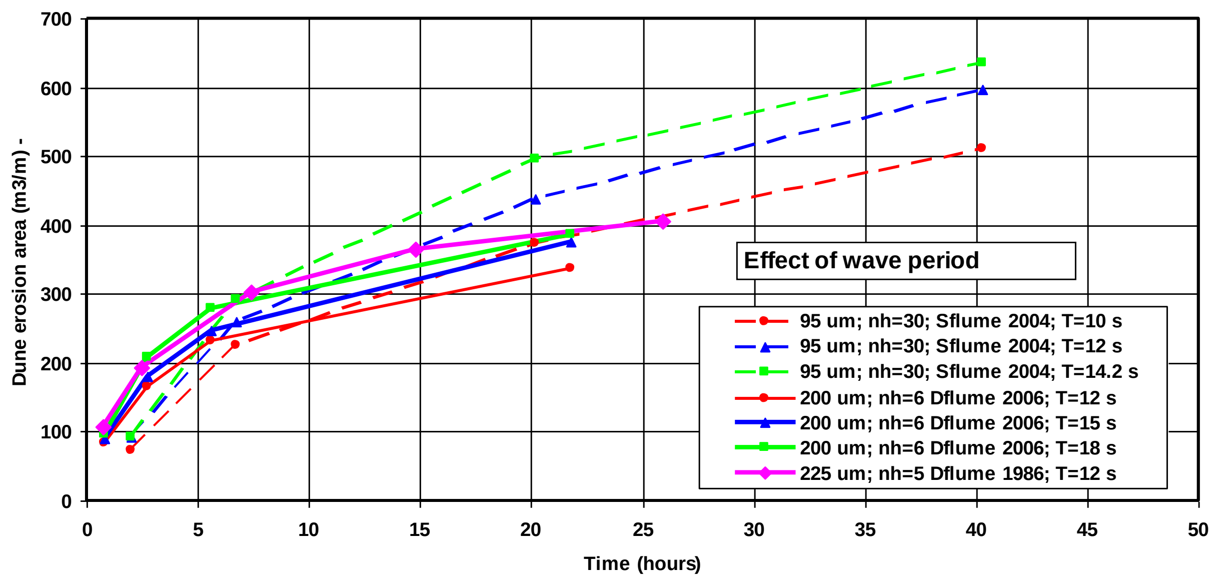

Figure 3 *Dune erosion area (above SSL) as a function of time based on recent laboratory tests (Delft Hydraulics, 2004, 2006a,b)*

3. Cross-shore modelling of dune erosion

Hydrodynamics and sand transport

The CROSMOR2007-model is an updated version of the CROSMOR2004-model (Van Rijn, 1997, 2006, 2007d). The model has been extensively validated by Van Rijn et al. (2003). The propagation and transformation of individual waves (wave by wave approach) along the cross-shore profile is described by a probabilistic model (Van Rijn and Wijnberg, 1994, 1996) solving the wave energy equation for each individual wave. The individual waves shoal until an empirical criterion for breaking is satisfied. The maximum wave height is given by $H_{max}=\gamma_{br}$ h with γ_{br}= breaking coefficient and h=local water depth. The default wave breaking coefficient is represented as a function of local wave steepness and bottom slope. The default breaking coefficient varies between 0.4 for a horizontal bottom and 0.8 for a very steep sloping bottom. The model can also be run a with a constant breaking coefficient (input value). Wave height decay after breaking is modelled by using an energy dissipation method. Wave-induced set-up and set-down and breaking-associated longshore currents are also modelled. Laboratory and field data have been used to calibrate and to verify the model. Generally, the measured $H_{1/3}$-wave heights are reasonably well represented by the model in all zones from deep water to the shallow surf zone. The fraction of breaking waves is reasonably well represented by the model in the upsloping zones of the bottom profile. Verification of the model results with respect to wave-induced longshore current velocities has shown reasonably good results for barred and non-barred profiles (Van Rijn et al., 2003; Van Rijn and Wijnberg, 1994, 1996).
The application of a numerical cross-shore profile model to compute the erosion of the beach and duneface poses a fundamental problem which is related to the continuous decrease of the water depth to zero at the runup point on the dune face. The numerical modelling of the (highly non-linear) wave-related processes in the swash zone with decreasing water depths is extremely complicated and is in an early stage of development. In the CROSMOR-model the numerical method is applied up to a point (last grid point) just seaward of the downrush point, where the mean water depth is of the order of 0.1 to 0.2 m. The complicated wave mechanics in the swash zone is not explicitly modelled, but taken into account in a schematized way. The limiting water depth of the last (process) grid point is set by the user of the model (input parameter; typical values of 0.1 to 0.2 m). Based on the input value, the model determines the last grid point by interpolation after each time step (variable number of grid points).
The cross-shore wave velocity asymmetry under shoaling and breaking waves is described by the semi-empirical method of Isobe and Horikawa (1982) with modified coefficients (Grasmeijer and Van Rijn, 1998; Grasmeijer ,2002). Near-bed streaming effects are modelled by semi-empirical expressions based on the work of Davies and Villaret (1997, 1998, 1999). The streaming velocities at the edge of wave boundary layer may become negative for decreasing relative roughness values (A_w/k_w with A_w=peak wave excursion near bed; k_w= wave-related bed roughness value).
The depth-averaged return current (u_r) under the wave trough of each individual wave (summation over wave classes) is derived from linear mass transport and the water depth (h_t) under the trough. The mass transport is given by 0.125 g H^2/C with C= $(g\ h)^{0.5}$ = phase velocity in shallow water. The contribution of the rollers of broken waves to the mass transport and to the generation of longshore currents (Svendsen, 1984; Dally and Osiecki, 1994) is taken into account. The vertical distribution of the undertow velocity is modelled by schematizing the water depth into three layers with a logarithmic distribution in the lower two layers and a third power distribution in the upper layer, yielding velocities which approach to zero at the water surface.
Low-frequency waves are generated in the surf zone due to spatial and temporal variation of the wave breaking point resulting in spatial and temporal variation of the wave-induced set-up creating low-frequency waves (surf beat). This involves a transfer of energy in the frequency domain: from the high frequency to the low frequency waves. The total velocity variance (total wave energy) consists of high-frequency and low-frequency contributions ($U^2_{rms}=U^2_{hf,rms}+U^2_{lf,rms}$). Basically, accurate modelling of low-frequency waves requires the application of a long-wave model on the wave group time scale (Van Thiel de Vries et al., 2006). Such an approach is beyond the present scope of work. Herein, a more pragmatic approach is introduced to crudely represent the

low-frequency effects. The low-frequency significant wave height is related to the high-frequency significant wave height, as follows:

$$H_{s,lf}=(\gamma-\gamma_{tr})^{\alpha}\ H_{s,hf} \quad (1a)$$
$$U_{lf}=0.5\ (H_{s,lf}/h)(gh)^{0.5} \quad (1b)$$

with: $H_{s,lf}$= low-frequency significant wave height, $\gamma=H_{s,hf}/h$=relative significant high-frequency wave height, γ_{tr}= threshold value (=0.5), h= water depth, $H_{s,hf}$= significant high-frequency wave height, α=0.3, U_{lf}= peak velocity of low-frequency waves. The α-exponent is found to be 0.3 based on the data of the Deltaflume experiment. The long wave velocity is computed from long wave theory. Using this approach, long wave motion (surf beat) is generated under strongly breaking waves (plunging waves) in the surf zone.
Figure 4 shows measured and computed values of the low-frequency waves (wave height and peak velocity).

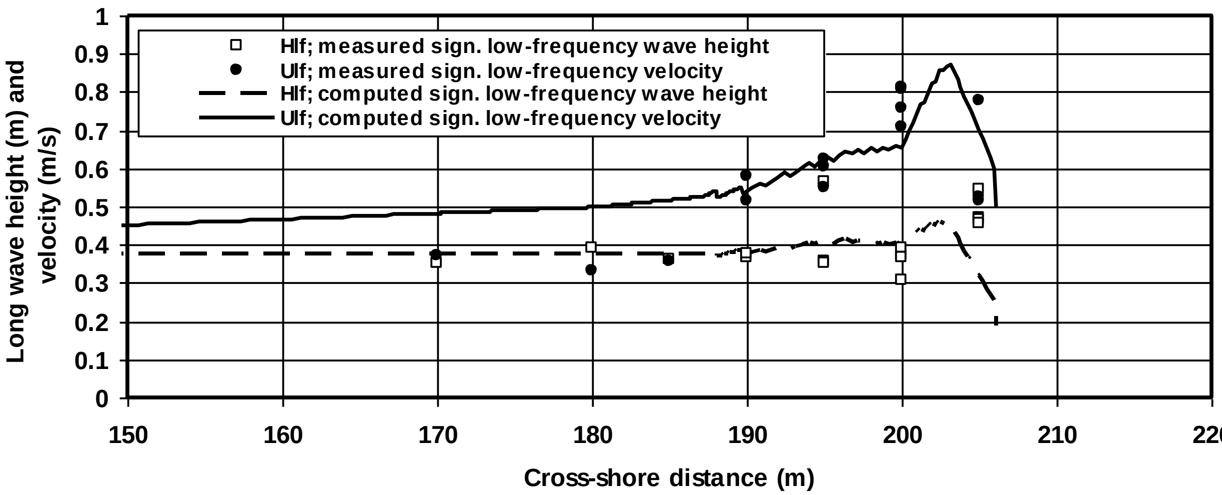

Figure 4 *Low-frequency wave height and velocity in surf zone of Deltaflume experiment on dune erosion (Test T01)*

The measured significant low-frequency velocity is related to the measured rms-value of the low-frequency velocity: $U_{lf}=1.4U_{lf,rms}$. Reasonable agreement between measured and computed values can be observed. The peak velocity of the low-frequency waves is added to the peak velocity of the high-frequency waves: $U^2_w=U^2_{hf}+U^2_{lf}$, with: U_{hf}= peak velocity of high-frequency waves near the bed and U_{lf}= peak-velocity of low frequency waves. The total velocity (U^2_w) is used to compute the bed-shear stress. The maximum amplitude of the low-frequency water level variations is of the order of 0.2 m at x=200 (see Figure 4).
The sand transport of the CROSMOR2007-model is based on the TRANSPOR2004 sand transport formulations (Van Rijn, 2006, 2007a,b,c,d). The effect of the local cross-shore bed slope on the transport rate is taken into account (see Van Rijn, 1993, 2006).
The sand transport rate is determined for each wave (or wave class), based on the computed wave height, depth-averaged cross-shore and longshore velocities, orbital velocities, friction factors and sediment parameters. The net (averaged over the wave period) total sediment transport is obtained as the sum of the net bed load (q_b) and net suspended load (q_s) transport rates. The net bed-load transport rate is obtained by time-averaging (over the wave period) of the instantaneous transport rate using a formula-type of approach.
The net suspended load transport is obtained as the sum ($q_s= q_{s,c} + q_{s,w}$) of the current-related and the wave-related suspended transport components (Van Rijn, 1993, 2006, 2007). The current-related suspended load transport ($q_{s,c}$) is defined as the transport of sediment particles by the time-averaged (mean) current velocities (longshore currents, rip currents, undertow currents). The wave-related suspended sediment transport ($q_{s,w}$) is

defined as the transport of suspended sediment particles by the oscillating fluid components (cross-shore orbital motion). The oscillatory or wave-related suspended load transport ($q_{s,w}$) has been implemented in the model, using the approach given by Houwman and Ruessink (1996). The method is described by Van Rijn (2006, 2007a,b,c,d). Computation of the wave-related and current-related suspended load transport components requires information of the time-averaged current velocity profile and sediment concentration profile. The convection-diffusion equation is applied to compute the time-averaged sediment concentration profile based on current-related and wave-related mixing. The bed-boundary condition is applied as a prescribed reference concentration based on the time-averaged bed-shear stress due to current and wave conditions. An additional calibration factor (sef-factor=suspension enhancement factor) acting on the time-averaged bed-shear stress and hence on the reference concentration in the shallow swash zone (dune erosion zone) in front of the dune face has been used to calibrate the model for dune erosion conditions; sef=1 yields the default model settings; a sef-value in the range of 2 to 3 is found (based on Deltaflume experiments 2005; see later) to be valid for the shallow surf zone in front of the dune face. The sef-factor is used to simulate the effects of wave collision and breaking in the shallow surf zone on the bed-shear stress and on the mixing capacity (increased turbulence) of the system resulting in a significant increase of the sand transport capacity. The shallow dune erosion zone is defined as the zone with a length scale of a few meters (of the order of the dune face length scale). To ensure a gradual transition from sef=1 outside the dune erosion zone, a linear transition is assumed to be present seaward of it.

Erosion in swash zone

The dune erosion zone in front of the relatively steep dune face is defined as the zone up to the run-up level which is dominated by breaking bores (swash motions). Herein, the length of the dune erosion zone (L_s) is determined as the maximum value of two length scales. Hence, $L_s=\max(L_{s1}, L_{s2})$ with:

1) $L_{s1}=6h_{L,m}$ with: $h_{L,m}$ =average water depth of last, five computational grid points. The last computational point is set by the model user by specifying a minimum water depth h_L (input value). This value should be approximately 0.1 times the dune face length ($h_L \cong 0.1 L_d$);

2) $L_{s2}=x_R-x_L$ with: x_R=horizontal coordinate of run-up point and x_L=horizontal coordinate of last computational point.

Both approaches produce similar results. The length of the dune erosion zone is in the range of 0.5 to 1 times the dune face length (L_d, see Figure 5) above the still water level (SWL). The dune face length is in the range of L_d=1 to 3 m for large-scale laboratory conditions (Deltaflume) and L_d=3 to 5 m for field conditions.

Many run-up formulae are available in the literature. Most of these formulae (Stockdon et al., 2006) are only valid for natural beaches with relatively flat slopes (dissipative beaches). To model dune erosion correctly, a run-up formula is required which is valid for steep slopes (up to 70°).

The runup level (above SWL plus set-up) associated with significant waves is estimated by (default approach):

$$R_s = 0.4\, H_{s,o} \tanh(3.4\zeta_o) \qquad (2)$$

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

Equation (2) yields a value of ζ_o=5 and R_s=3 m for the Reference Case with $H_{s,o}$=7.6 m, T_p=12 s, $L_{s,o}$=175 m (wave length at depth of 30 m), $\tan\beta$=1 (assuming a dune toe angle of about 45°).

Other formulae are available in the literature and have been used in a sensitivity analysis (Van Gent, 2001; Larson et al., 2004). Using these functions, the run-up level exceeded by 33% of the waves is roughly in the range of 3 to 6 m for a steep dune front of the Reference Case.

The total erosion area (A_E) over the length of the dune erosion zone is defined as:

$$A_E=q_L\, \Delta t/((1-p)\rho_s) \qquad (3)$$

with: q_L=cross-shore transport computed at last grid point at the toe of the dune erosion zone (Figure 5), Δt=time step, p=porosity factor of bed material, ρ_s=sediment density. The cross-shore transport generally is offshore directed during high energy (storm) conditions and onshore directed during low energy conditions. The erosion profile of the dune erosion zone with length L_s is assumed to have a triangular shape (see Figure 5), yielding A_E=0.5eL_s, with e=maximum erosion depth. The maximum erosion depth in the swash zone is:

$$e= 2q_L \Delta t/(L_s(1-p)\rho_s) \qquad (4)$$

In the case of onshore-directed transport (q_L) at the last grid point, the same procedure is followed resulting in accretion with a triangular shape (swash bar generation). This may occur during low-energy events (post storm conditions).

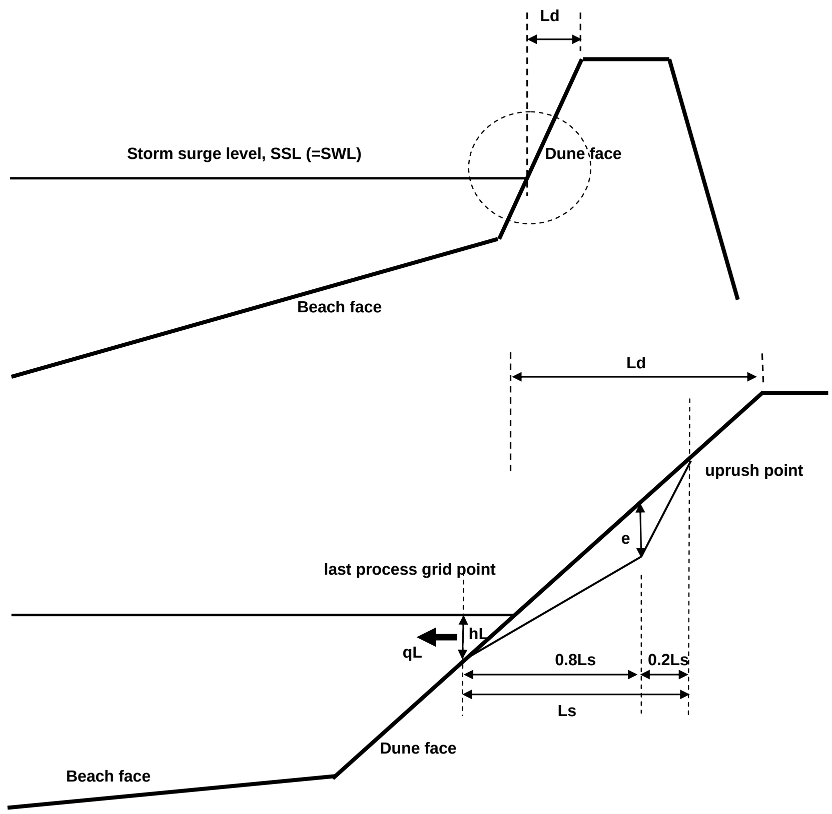

Figure 5 *Definition sketches of bed level changes in swash zone*
Top: Beach and dune face
Bottom: Erosion in swash zone at dune face

Bed level changes

Bed level changes seaward of the last grid point are described by:

$$\rho_s(1-p)\partial z_b/\partial t + \partial(q_t)/\partial x = 0 \qquad (5a)$$

with: z_b= bed level to datum, q_t= q_b + q_s= volumetric total load (bed load plus suspended load) transport, ρ_s= sediment density, p= porosity factor.

In discrete notation:

$$\Delta z_{b,x,t} = -[(q_{t,})_{x-\Delta x} - (q_t)_{x+\Delta x}] [\Delta t/(2 \Delta x(1-p)\rho_s] \qquad (5b)$$

with: Δt= time step, Δx= space step, $\Delta z_{b,i,x,t}$ = bed level change at time t (positive for decreasing transport in positive x-direction, yielding deposition). The new bed level at time t is obtained by applying an explicit Lax-Wendorf scheme.

Bed sliding at steep slopes

The bed level in the swash zone at the dune face may become so steep due to wave-induced erosion and other undermining processes that the local bed becomes unstable resulting in local bed failure. A wedge-shaped part of the dune face will slide downward to settle at the toe of the dune face, where it can be eroded again by wave-induced processes. The sliding procedure is a post-processing procedure after each time step, which is repeated until the bed is stable everywhere along the profile.

The local bed is assumed to slide out, if :

$$\tan(\beta)>\tan(\alpha_x) \qquad (6)$$

with: $\tan(\alpha_x)=(z_{bo,i+1}-z_{bo,i})/(x_{i+1}-x_i)$ and β=maximum bed slope angle (input parameter), $z_{bo,i+1}$=old bed level at point i+1, $z_{bo,i}$=old bed level at point i

4. Modelling results of large-scale laboratory and field data

Large-scale Deltaflume data

New experiments have been carried out in the Deltaflume of Delft Hydraulics in the period October 2005 to March 2006, focussing on the effect of the wave period and type of wave spectrum on the dune erosion volumes for the Reference Case (see Section 2).

The bed material used is marine sand with d_{10}=0.142 mm, d_{50}= 0.2 mm and d_{90}= 0.286 mm. The fall velocity of the bed material has been determined by tests in a settling tube resulting in: w_s=0.023 m/s at a temperature of 9 ^{o}C. The still water level (SWL) representing the storm surge level (SSL) is set at 4.5 m above the original flume bottom. Irregular waves with a single topped Pierson-Moskowitz spectrum (single-topped) have been generated during 6 hours at the entrance of the flume during most tests. A double-topped wave spectrum has been used in Test T16. Most tests have been repeated twice to perform detailed process measurements during the second test.

The eroded profiles of three tests after 6 hours are shown in Figure 6.

The profile shows erosion above a level of -0.2 m (to SWL); deposition can be observed offshore of the -0.2 m bed level over a length of about 30 m. The erosion area increases by about 15% (based on T01 and T03) in the case of a larger wave period (from 4.9 s to 7.4 s), see also Figure 6.

The erosion area decreases slightly by about 10% in the case of a double-topped spectrum (based on T03 and T16; not shown).

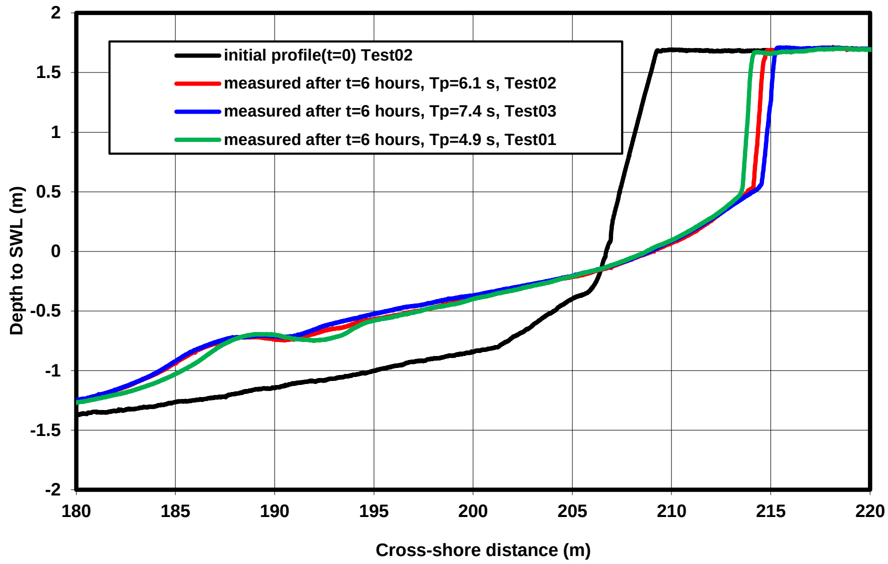

Figure 6 *Measured bed profiles after 6 hours for Tests T01, T02 and T03*

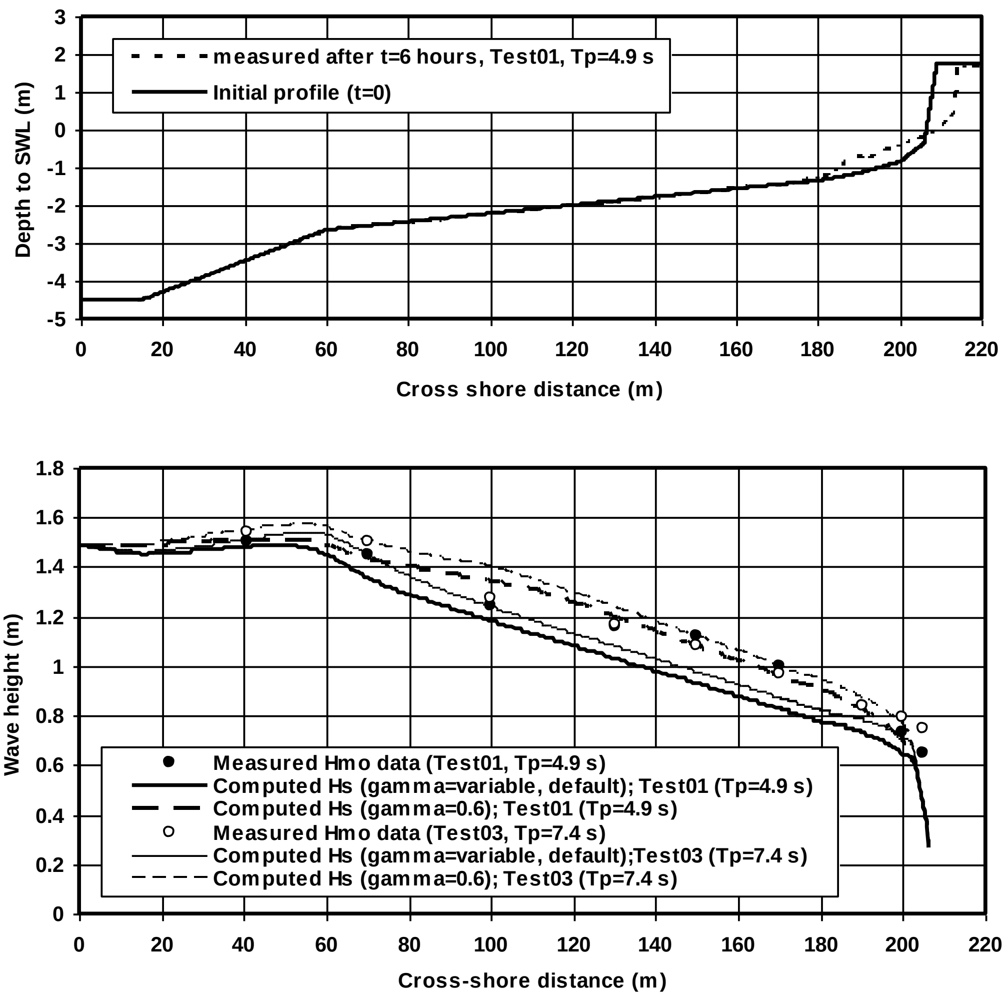

Figure 7 *Top:* *Measured bed profiles*
Bottom: *Computed and measured wave heights for Tests T01 and T03 (initial values)*

The mathematical model simulations are focused on Test T01 with the smallest wave period of T_p=4.9 s and on Test T03 with the largest wave period of T_p=7.4 s. The incoming (offshore) significant wave height is 1.5 m. Since the CROSMOR-model is a model for individual waves; the wave height distribution is assumed to be represented by a Rayleigh-type distribution schematized into 6 wave classes. Based on the computed parameters in each grid point for each wave class, the statistical parameters are computed in each grid point. The limiting water depth is set to 0.1 m (water depth in last grid point). Based on this value (including the computed wave-induced set-up), the model determines by interpolation the number of grid points (x=0 is offshore boundary, x=L is most landward computational grid point). The effective bed roughness in the violent dune erosion zone is set to a fixed value of 0.02 m; the bed roughness outside the dune erosion zone is predicted by the model.
Figure 7 shows the computed significant wave heights (initial values at t=0) along the cross-shore profile for two tests T01 (period of 4.9 s) and T03 (period of 7.4 s) based on a constant breaking coefficient γ=0.6 and a variable breaking coefficient (depending on bed slope and wave steepness). This latter approach is the default approach of the model. Measured H_{m0}-wave heights (based on spectral parameters) are also shown. Comparison of measured and computed data shows:

- computed wave heights along the bed profile are in close agreement with measured data for a breaking coefficient of γ=0.6; the computed wave heights are somewhat too small (10% to 15%) for a variable γ-factor (default approach);
- computed wave heights are somewhat too small in front of the dune face (x=205 m);
- measured wave heights show no marked influence of the wave period; the computed wave heights are slightly larger (5% to 10%) for a larger wave period.

The dune erosion profiles of Test T01 have been used to calibrate the sef-parameter of the model. The sef-parameter is the suspension enhancement factor (multiplication factor) acting on the time-averaged bed-shear stress and hence on the reference concentration and the sediment mixing coefficient in the shallow dune erosion zone; sef=1 refers to the default transport model.

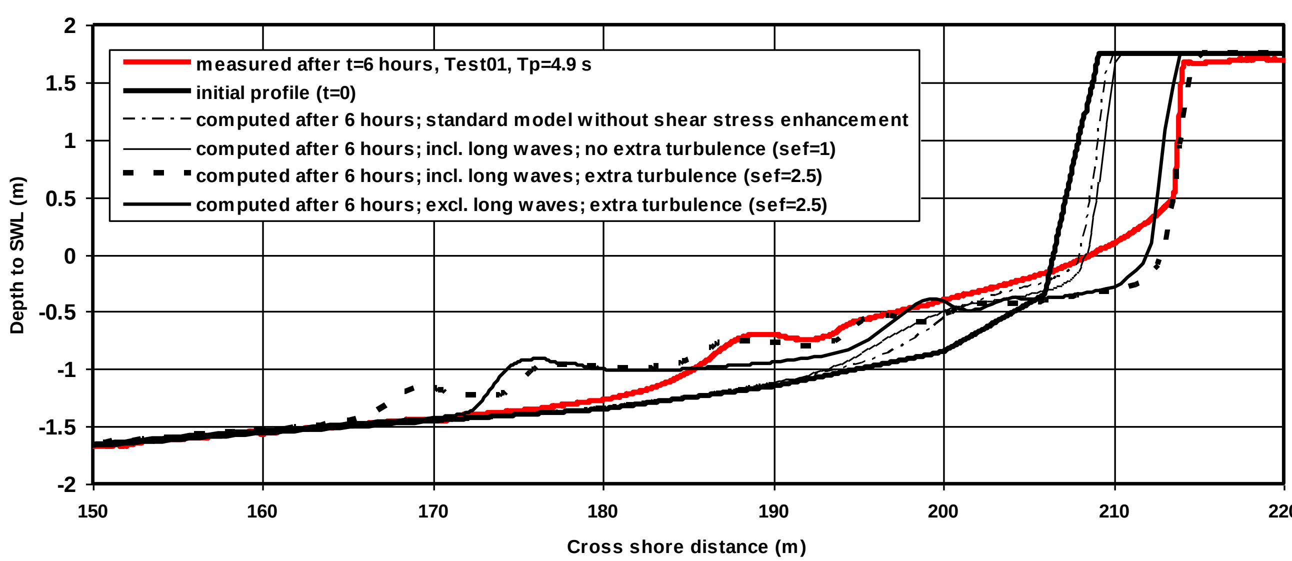

Figure 8 *Computed bed profiles after 6 hours for Test T01*

Figure 8 shows computed bed profiles for Test T01 based on sef=1 and sef=2.5 with and without the long wave effect. The long wave effect means that the contribution of the low-frequency waves to the near-bed velocities and hence to the bed-shear stresses are included; the low-frequency water level variations are not included. The maximum dune face slope is set to 50 degrees (failure and sliding for slope angles larger than 50 degrees). A sef-value of 1 (default sand transport model) yields insufficient erosion of the dune face (underestimation by a factor

of about 3). Inclusion of the long wave effect on the near-bed velocities increases the dune erosion by about 20%. When the low-frequency variations (amplitude of about 0.2 m) of the water level are included (not shown; see Van Rijn, 2008), the dune erosion is only marginally larger. Hence, it is not really necessary to include the low-frequency water level variations. Most important is to include the low-frequency velocity variations near the bed. The computed reference (near-bed) concentration in the swash zone in front of the dune shows an increase by a factor of about 2 (from 2 to 4 kg/m^3) when low-frequency velocity variations are included. Inclusion of the suspension enhancement factor (extra turbulence sef=2.5) yields an increase of the reference concentration in the swash zone by a factor of about 10 (from 4 to about 50 kg/m^3). When the long wave effect is neglected the maximum reference concentration is about 20 kg/m^3. Measured concentrations up to 50 kg/m^3 have been observed in the swash zone in front of the dune. It is concluded that the inclusion of extra turbulence effects (by the sef-factor) on the bed-shear stress in the dune erosion zone is essential to model the near-bed concentrations correctly. The inclusion of the low-frequency waves is of lesser importance.
The best overall agreement between computed and measured dune face recession (shoreline recession) after 6 hours is found for sef=2.5 with the long wave effect included. The erosion volume above SWL is slightly too large (5% to 10%); the erosion volume below SWL is much too large. The computed bed slope in the beach zone is too flat (tan β=0.02 with β=beach slope) compared with the obserbed bed slope in the beach zone (tan $\beta_{observed}$=0.04). The time development of the computed bed profiles (sef=2.5) is shown in Figure 9. It can be seen that the erosion process very gradually slows down. The computed bed level profiles show small-scale bars which are generated by small irregularities in the spatial distribution of the suspended sediment transport introduced by the sef-parameter. These irregularities disappear for a smaller time step.
Figure 10 shows the computed and measured dune erosion area above storm surge level (SSL) as a function of time. A significant difference between computed and measured results can be observed. The measured dune erosion area is much larger (about 50%) than the computed value in the initial phase (time<150 minutes) of the dune erosion process. This initial effect with relatively large erosion values cannot be represented by the model. Almost half of the total dune erosion is produced in the first 60 minutes of the total test duration of 360 minutes (6 hours). At the end of the test duration the measured and computed values are within 15% of each other; the computed values are somewhat larger than the measured values.

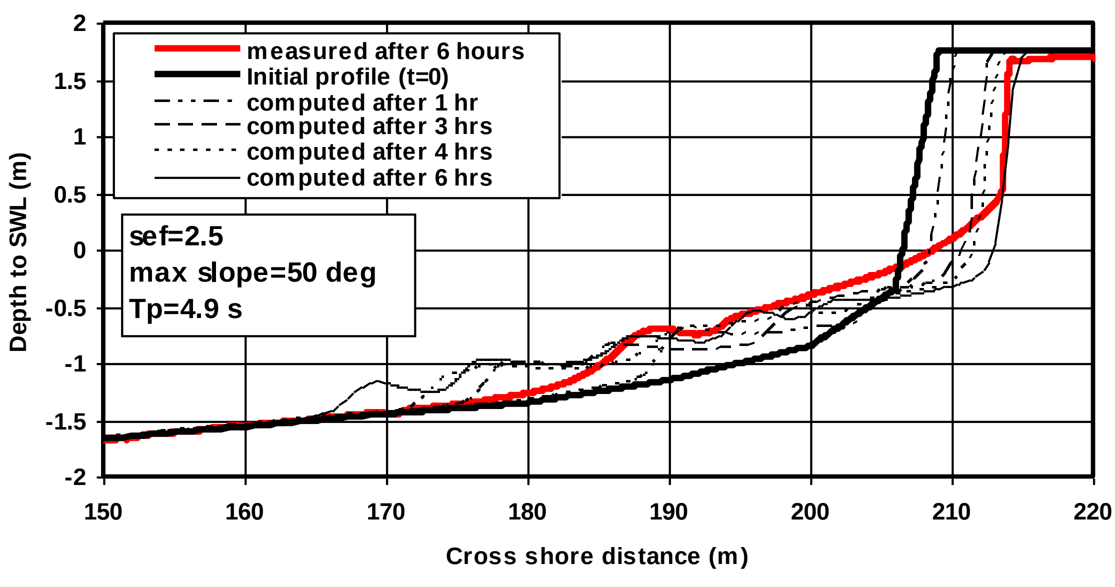

Figure 9 *Time development of computed bed profiles for Test T01*

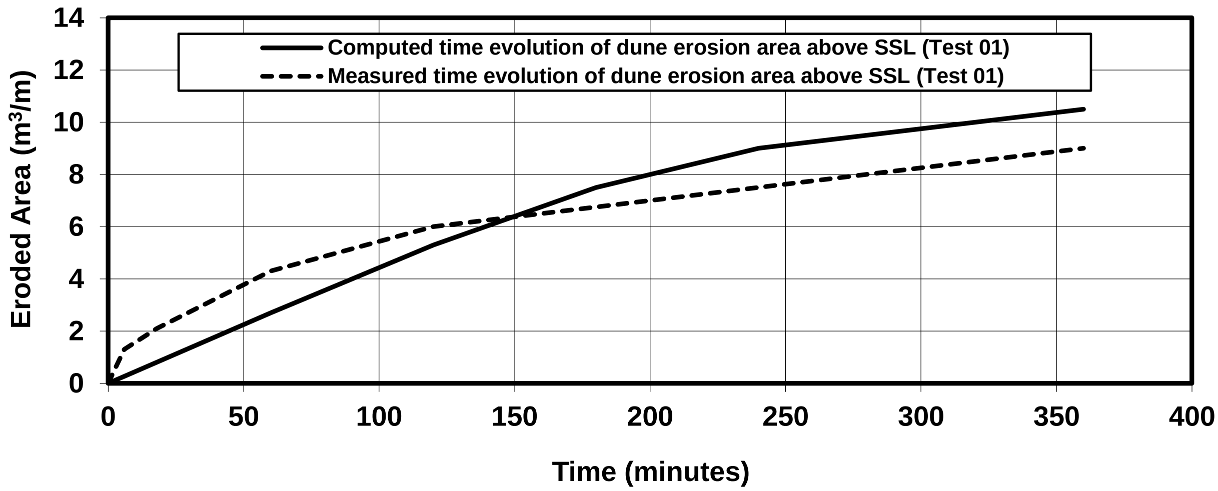

Figure 10 *Time development of computed and measured dune erosion area above SSL for Test T01*

Effect of maximum dune face slope

Figure 11 shows the effect of the maximum dune face slope on the computed bed profile. The maximum slope has been varied in the range of 30 to 70 degrees. The initial dune face slope is about 35 degrees (slope of 0.7 to 1). Horizontal dune erosion is largely suppressed when the dune face sliding procedure is not taken into account. In the latter case the erosion mainly proceeds in the vertical direction resulting in a large-scale scour hole. Neglecting dune face sliding, the model produces a deep scour hole at the dune face position.

Using the sliding procedure, the dune face slope steepens during the erosion process; the observed dune face slope after 6 hours is about 70 degrees (slope of 2.5 to 1). The model can simulate the slope steepening process to some extent. Using a maximum dune face slope of 50 degrees, the dune face slope after 6 hours is steepened from the initial value of 35 degrees to a value of about 45 degrees. A smaller value (30 degrees) of the maximum dune face slope yields a dune face slope of 30 degrees after 6 hours. A larger value (70 degrees) of the maximum dune face slope yields a lower dune face slope of about 60 degrees after 6 hours. This latter slope is somewhat smaller than the applied maximum slope of 70 degrees, which is caused by the applied dune toe smoothing procedure reducing the maximum dune face slope, particularly for relatively steep slopes. The upper dune face slope is affected by the smoothing procedure in the case of a slope of 70^o.

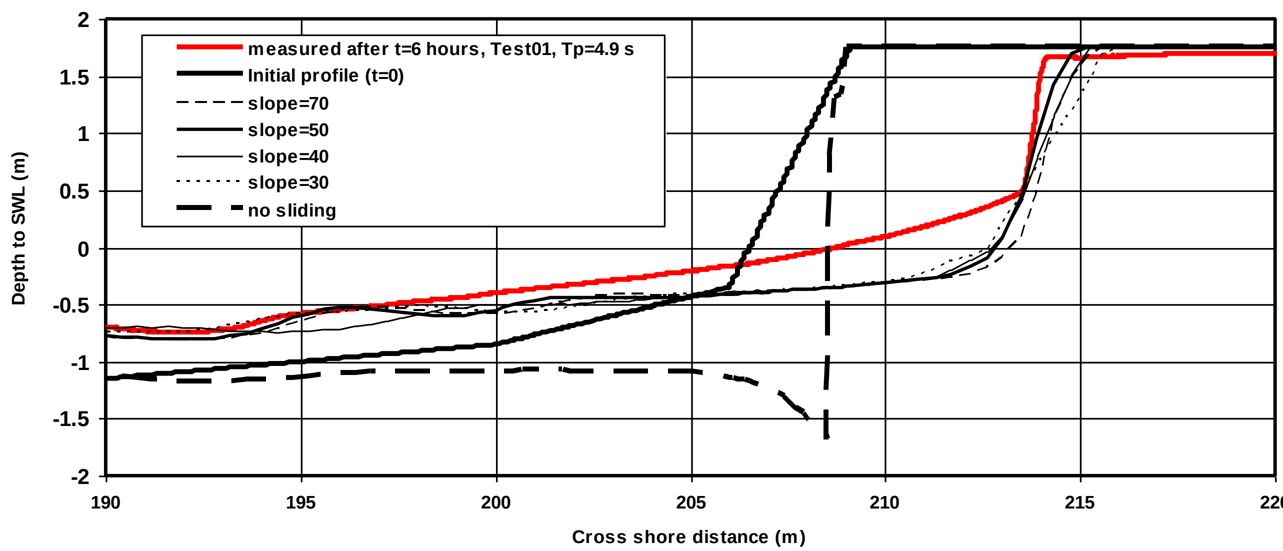

Figure 11 *Effect of dune face slope on computed bed profiles for Test T01*

Effect of length of dune erosion zone

Figure 12 shows the effect of the length of the dune erosion zone (L_s). This length scale is determined as the maximum value of 1) $L_s=6h_{L,m}$ with $h_{L,m}$= average water depth of last, five computational grid points or 2) $L_s=x_R-x_L$ with x_R=horizontal coordinate of run-up point and x_L=horizontal coordinate of last computational point. The water depth of the last computational point has been set to a value of h_L=0.1 m (input value) for the Deltaflume conditions. The water depth h_L is approximately equal to $0.05L_d$ for Test T01, with L_d=length of dune face (about 2.5 m). The length of the dune erosion zone is varied in the range of L_s=3 to 10 h_L or L_s=0.15 to $0.5L_d$.

As can be observed in Figure 12, the length of the dune erosion zone has not much effect on the computed bed profile after 6 hours. A length of L_s=3 h_L leads to somewhat more erosion in the dune toe zone. Using another run-up formula, similar results are obtained (not shown). Hence, the results are not noticeably affected by the type of run-up formula, provided that realistic run-up values based on observations are used.

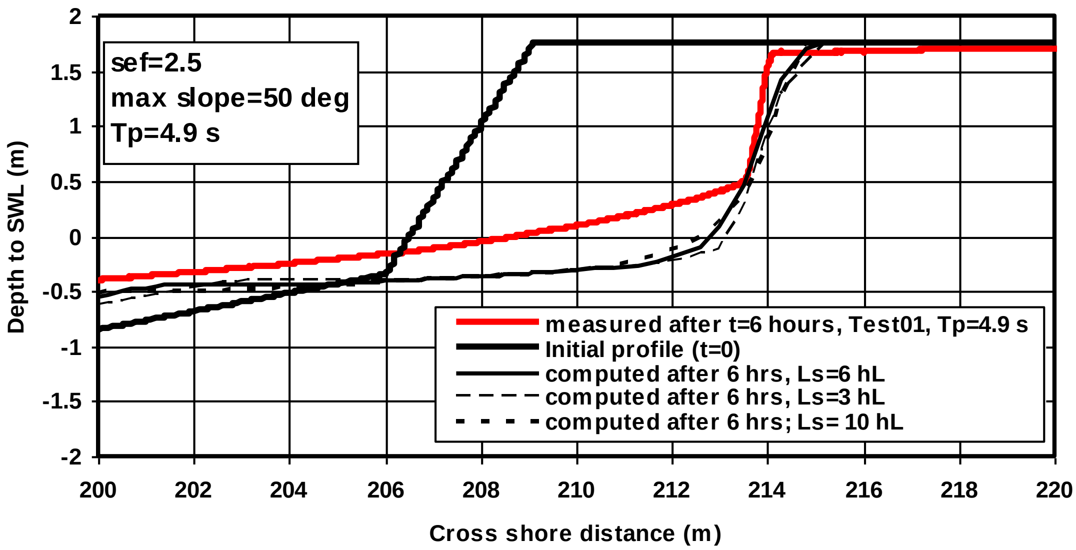

Figure 12 *Effect of length of dune erosion zone on computed bed profiles for Test T01*

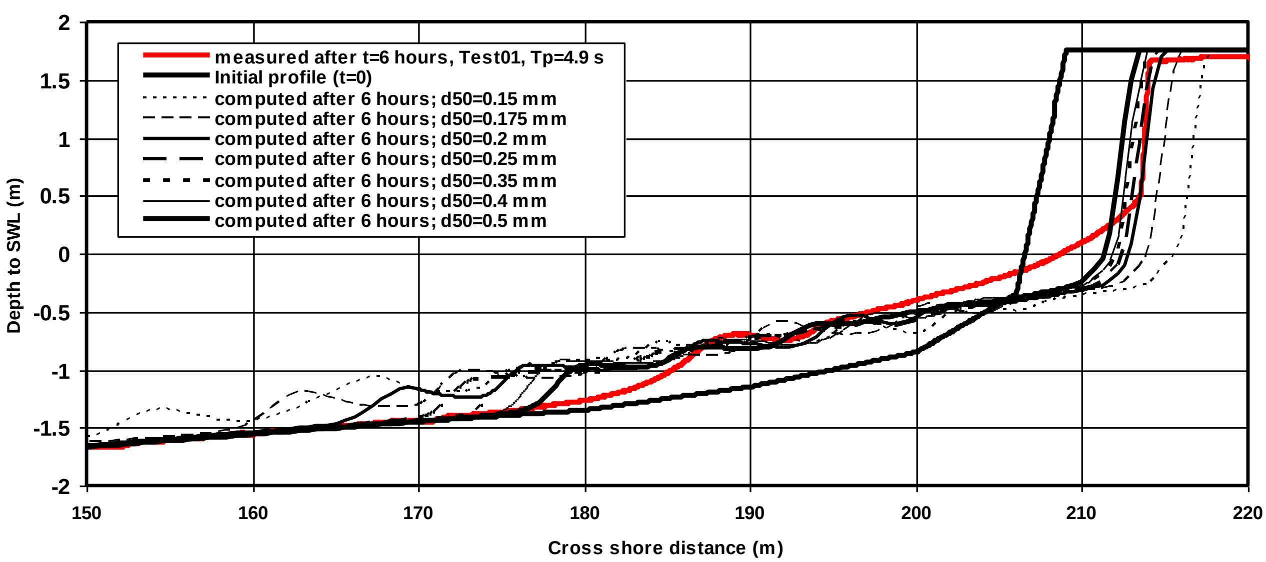

Figure 13 *Effect of bed material diameter on computed bed profiles for Test T01*

Effect of bed material diameter

Based on the analysis results of many bed material samples taken at various locations along the bed profile during all tests, the d_{50} of the bed material is found to vary between 0.175 and 0.225 mm for the Deltaflume experiments (Delft Hydraulics, 2006a,b). The mean value is d_{50}=0.2 mm.

Figure 13 shows the effect of the bed material diameter using d_{50}=0.15 to 0.5 mm for Test T01. A smaller bed material diameter of d_{50}=0.15 mm yields considerably larger (50%) dune erosion; a larger d_{50}-value in the range of 0.25 to 0.5 mm leads to slightly smaller (10% to 20%) dune erosion values.

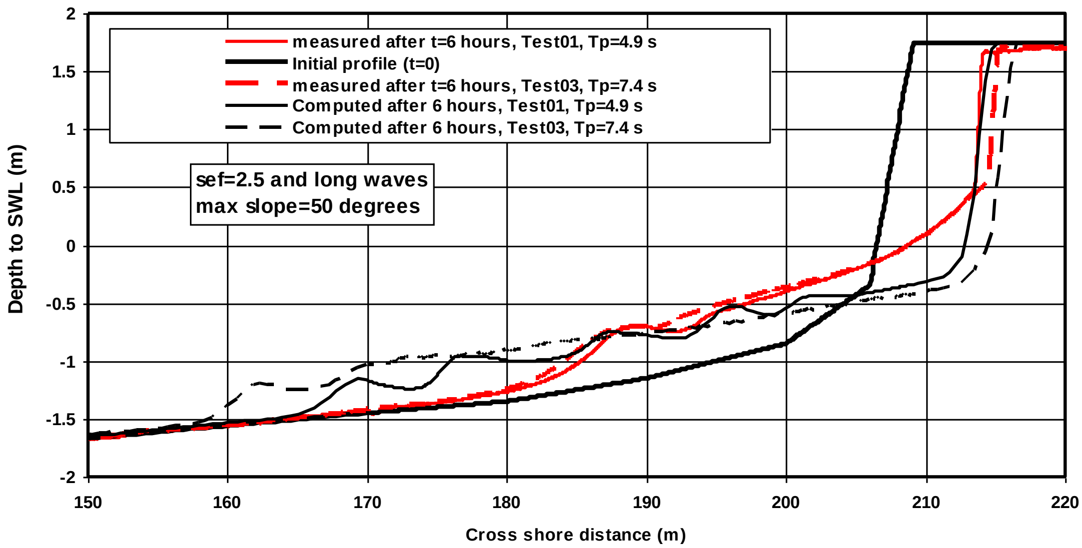

Figure 14 *Effect of wave period; Test T01 and T03*

Effect of wave period

Figure 14 shows the effect of a larger wave period (T_p=7.4 s in stead of T_p=4.9 s). The incoming wave height is the same $H_{s,o}$=1.5 m. A larger wave period of T_p=7.4 s yields a larger dune face recession in good agreement with the observed value of Test T03. The increase of the erosion is caused by the influence of the wave period on the peak onshore orbital velocity; a larger wave period results in a larger peak onshore orbital velocity near the bed and hence larger bed-shear stresses, reference concentrations and suspended transport rates.

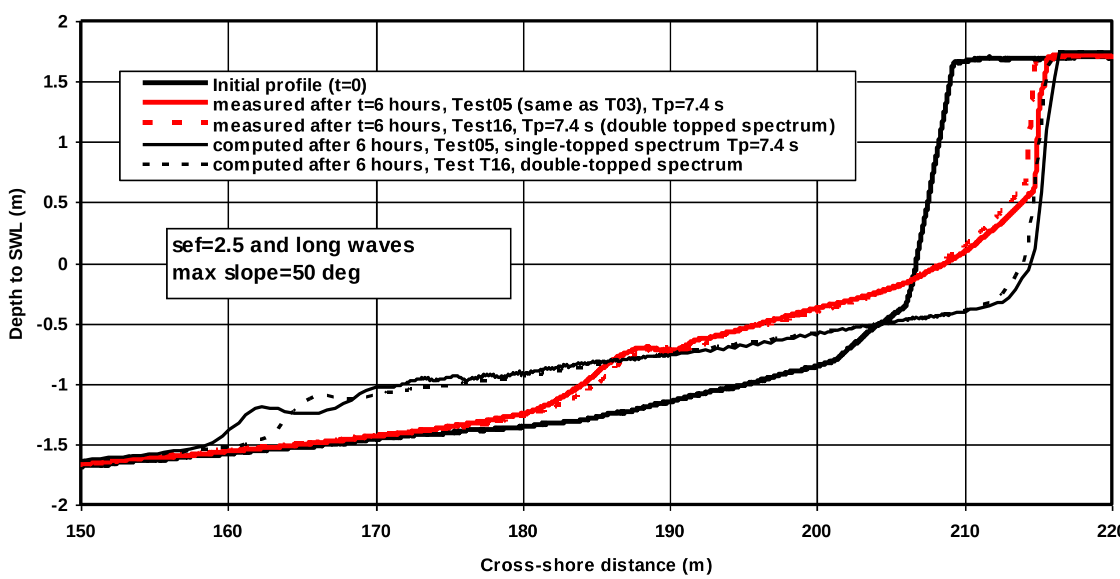

Figure 15 *Effect of wave spectrum on computed bed profiles; Test T05 and T16*

Effect of wave spectrum

The effect of the wave spectrum was studied by applying a double-topped spectrum in Test T16 with T_{p1}=7.6 s and T_{p2}=4.3 s (Delft Hydraulics, 2006a,b). Based on the available wave exceedance line, the wave spectrum is schematized into 8 wave classes. The largest wave period is assumed to be T=10 s; the smallest wave period is taken to be T=3 s. The computed significant wave height is $H_{s,o}$=1.47 m and T_s=7.4 s.

Figure 15 shows the computed bed profile after 6 hours for Test T16 and for Test T05. A double-topped spectrum leads to a smaller dune face recession than a single-topped spectrum due to a shift of wave energy from larger wave periods to smaller wave periods. The model prediction is in good agreement with the observed pattern. The computed horizontal dune face recession is slightly too large compared with the observed value of Test T16.

February 1953 storm, The Netherlands

The model has been used to simulate the February-1953 storm which attacked the Dutch coast and particularly the south-west part of The Netherlands. The initial bed profile consists of four line sections as shown in Figure 16. The beach slope is 1 to 20 and the dune slope is set to about 1 to 1 (angle of 45 degrees). The dune height is set to 12 m above MSL. The dune toe is at +3 m above MSL. The storm surge level (SSL) varies between +1.5 and +3.9 m above MSL over a period of 30 hours (storm duration). The maximum SSL occurs after 14 hours and remains constant for about 2 hours. The wave height at deep water varies between 4.9 and 6.3 m; the peak wave period varies between 8.8 and 10 s. Measured erosion volumes in the Delfland region (south-west part of the Holland coast) are in the range of 60 to 150 m^3/m with a mean value of 90 m^3/m, which is equivalent to a dune recession of about 10 m above the dune toe level.

Model runs have been made using a bed material diameter of 0.2 and 0.25 mm. The wave height distribution is represented by a Rayleigh-type distribution schematized into 6 wave classes for each wave condition. The computed dune erosion volume above the maximum SSL varies between 100 m^3/m for 0.25 mm and 120 m^3/m for 0.2 mm, which is somewhat larger than the observed values. The maximum horizontal dune recession is about 13 m for 0.2 mm. Computed bed profiles are shown in Figure 16.

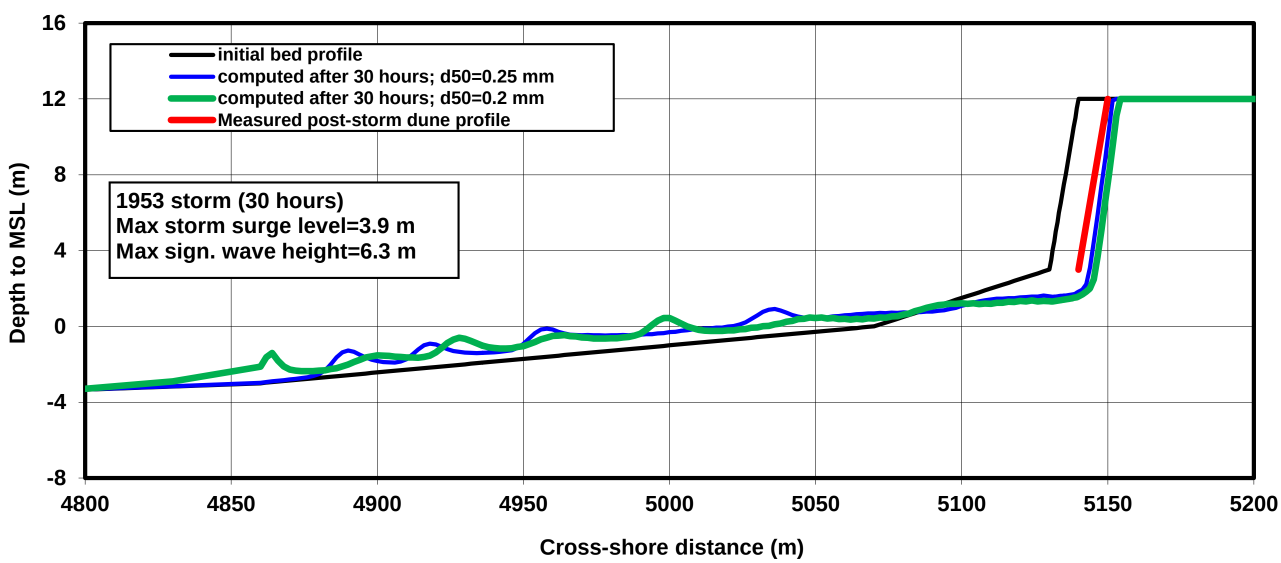

Figure 16 *Measured and computed bed profiles for February 1953 storm, The Netherlands*

5. Sensitivity study and development of simplified dune erosion rule

The CROSMOR-model has been used to study the effect of various key parameters on the computed dune erosion after 5 hours (duration of standard storm) for the Reference Case:

- effect of storm surge level in the range of 2 to 8 m;
- effect of offshore wave height in the range of 3.8 to 10 m;
- effect of peak wave period in the range of 9 to 18 s;
- effect of wave angle in the range of 0 to 30 degrees;
- effect of bed material size in the range of 0.15 to 0.3 mm;
- effect of steeper and milder beach profile.

The Reference Case is defined in Table 1 as proposed by Vellinga (1986).
The initial profile consists of four line sections as shown in Figure 17.
The beach slope is 1 to 20 and the dune slope is 1 to 3 (angle of about 20^o).
The dune height is set to 15 m above MSL. The dune toe is at +3 m above MSL.
The storm surge level is set to +5 m. The duration of a standard storm is set to 5 hours.
The wave height at deep water is set to 7.6 m. The peak wave period is 12 s.
The forcing parameters are constant in time; the growing and decaying phases of the storm have been neglected.
The wave height distribution of the CROSMOR-model is represented by a Rayleigh-type distribution schematized into 6 wave classes.
The computed dune erosion volumes above the storm surge level (+5 m to MSL) for the Reference Case is 170 m^3/m after 5 hours, which is considerably smaller than the value of 250 m^3/m based on scale model results (see Section 2). Upscaling of the laboratory results to field conditions may introduce scaling errors. Furthermore, scale errors may also be introduced by schematization of 3D field conditions to 2D flume conditions. The 2D laboratory simulation results of the 3D prototype dune erosion caused by the February 1953 storm show an over-estimation of the measured prototype dune erosion by about 30% (see Section 2).
As regards scaling errors, the mathematical model is more reliable. This model has been verified using field data. For example, the CROSMOR-model has been used to simulate the 1975 hurricane Eloise in the USA (Van Rijn, 2008) and the 1953 storm in The Netherlands (Section 4). In both cases the model over-estimates the observed erosion. Hence, the model seems to produce conservative rather than optimistic results.

Effect of storm surge level

Figure 17 shows the effect of the storm surge level (in the range of S=2 to 8 m above mean sea level) on the bed profile after 5 hours. The reference storm surge level is S_{ref}=5 m above mean sea level. The dune erosion strongly increases with increasing storm surge level. The computed dune erosion area (A_d) above storm surge level after 5 hours can roughly be represented by: $A_d/A_{d,ref}=(S/S_{ref})^{\alpha}$ with: $A_{d,ref}$=170 m^3/m, S_{ref}=5 m above mean sea level, α=1.3 for $S<S_{ref}$ and =0.5 for $S>S_{ref}$. yielding values of about $A_{d,}$=50 m^3/m for S=2 m and $A_{d,}$=215 m^3/m for S=8 m.

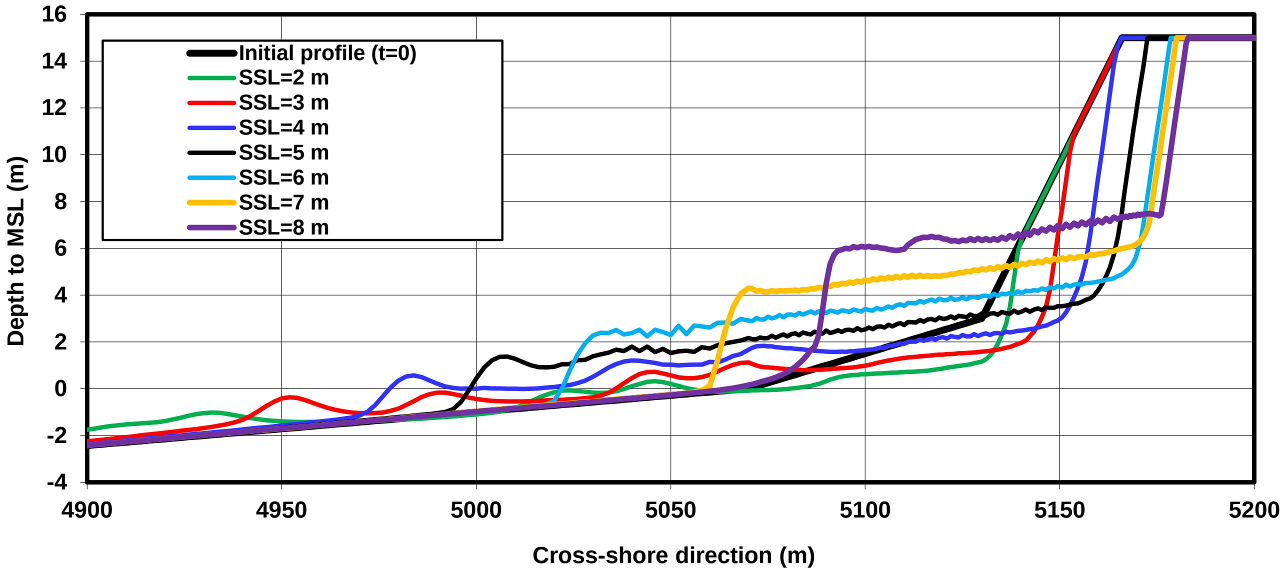

Figure 17 *Effect of storm surge level on computed bed profile after 5 hours for Reference Case*

Effect of offshore wave height

Figure 18 shows the effect of the offshore wave height (in the range of 3.8 to 10 m) on the bed profile after 5 hours. The reference offshore wave height is $H_{s,o}$= 7.6 m. The dune erosion increases with increasing wave height. The computed dune erosion area (A_d) above storm surge level after 5 hours can roughly be represented by: $A_d/A_{d,ref}=(H_{s,o}/H_{s,o,ref})^{0.5}$ with: $A_{d,ref}$=170 m^3/m and $H_{s,o,ref}$=7.6 m, yielding values of about $A_{d,}$=120 m^3/m for $H_{s,o}$=3.8 m and $A_{d,}$=195 m^3/m for $H_{s,o}$=10 m.

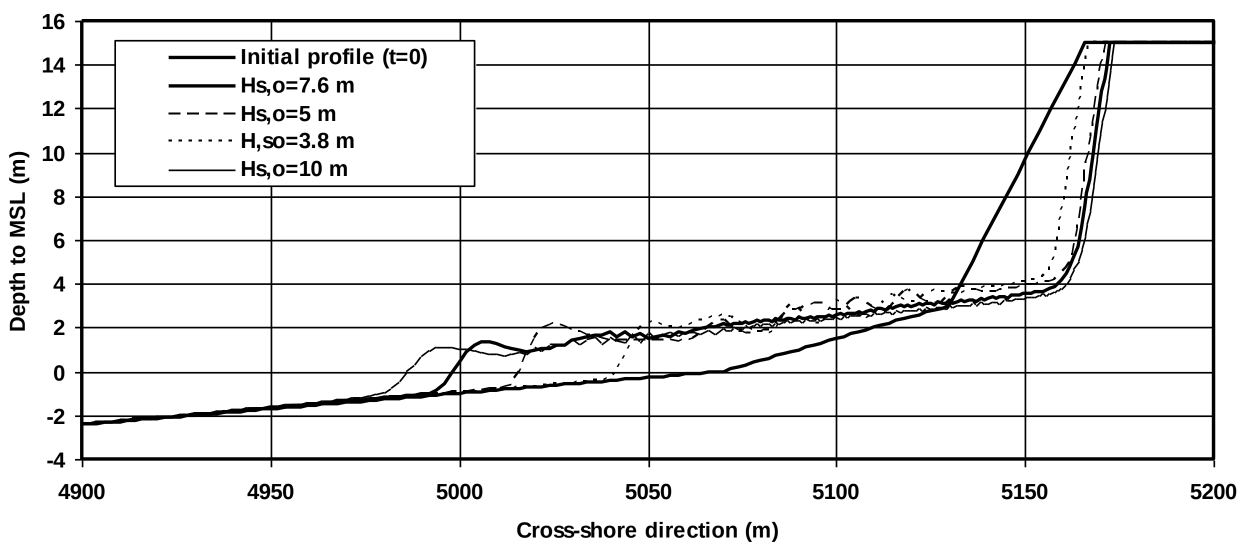

Figure 18 *Effect of offshore wave height on computed bed profile after 5 hours for Reference Case*

Effect of offshore peak wave period

Figure 19 shows the effect of the peak wave period (in the range of 9 to 18 s) on the bed profile after 5 hours. The reference offshore wave height is T_p=12 s. The dune erosion increases with increasing wave period. The computed dune erosion area (A_d) above storm surge level after 5 hours can roughly be represented by:

$A_d/A_{d,ref}=(T_p/T_{p,ref})^{0.5}$ with: $A_{d,ref}$=170 m^3/m and $T_{p,ref}$=12 m, yielding values of about $A_{d,}$=145 m^3/m for T_p= 9 s and $A_{d,}$=210 m^3/m for T_p=18 s.

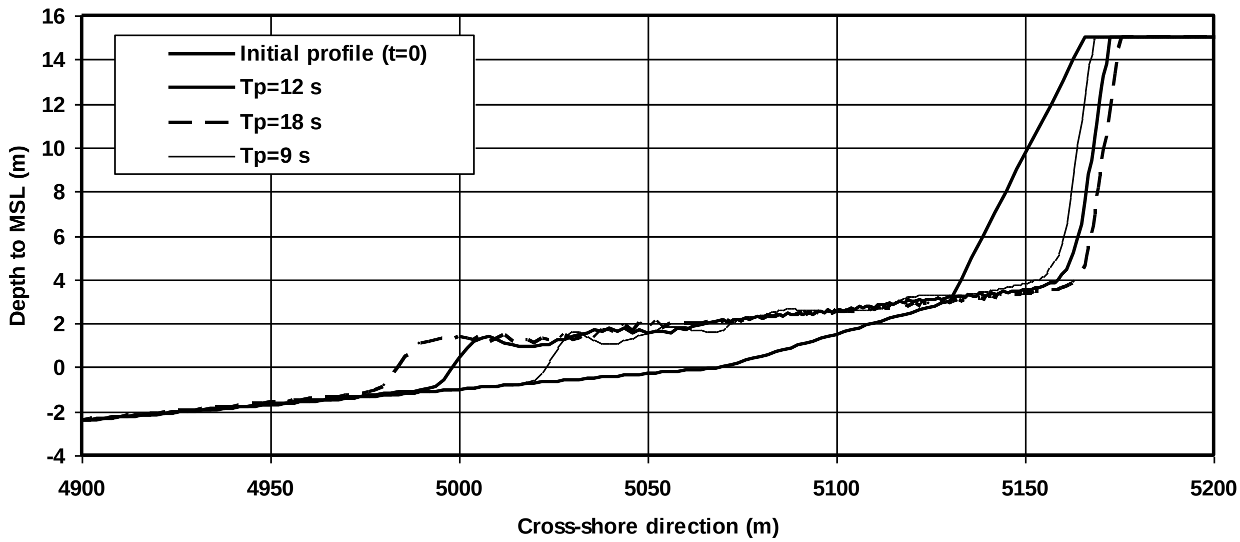

Figure 19 *Effect of peak wave period on computed bed profile after 5 hours for Reference Case*

Effect of offshore wave angle

Figure 20 shows the effect of the offshore wave angle (in the range of 0 to 30^o to coast normal) on the bed profile after 5 hours. The reference offshore wave angle is α_o=0^o (normal to coast). When the offshore wave incidence angle is non-zero, two adversary effects do occur: 1) oblique incident waves produce a longshore current in the shallow surf zone resulting in an increase of the transport capacity in the shallow surf zone and a larger erosion capacity and 2) oblique incident waves are refracted in the nearshore zone resulting in a decrease of the wave height and hence transport capacity in the surf zone. The longshore current scours a channel in the surf zone. The dune erosion increases for wave angles in the range of 0 to 10^o and remains about constant for larger values. The computed dune erosion area (A_d) above storm surge level after 5 hours can roughly be represented by: $A_d/A_{d,ref}=(1+\alpha_o/100)^{0.5}$ with: $A_{d,ref}$=170 m^3/m and α_o =offshore wave angle to coast normal (in degrees), yielding values of about $A_{d,}$=195 m^3/m for α_o =30^o.

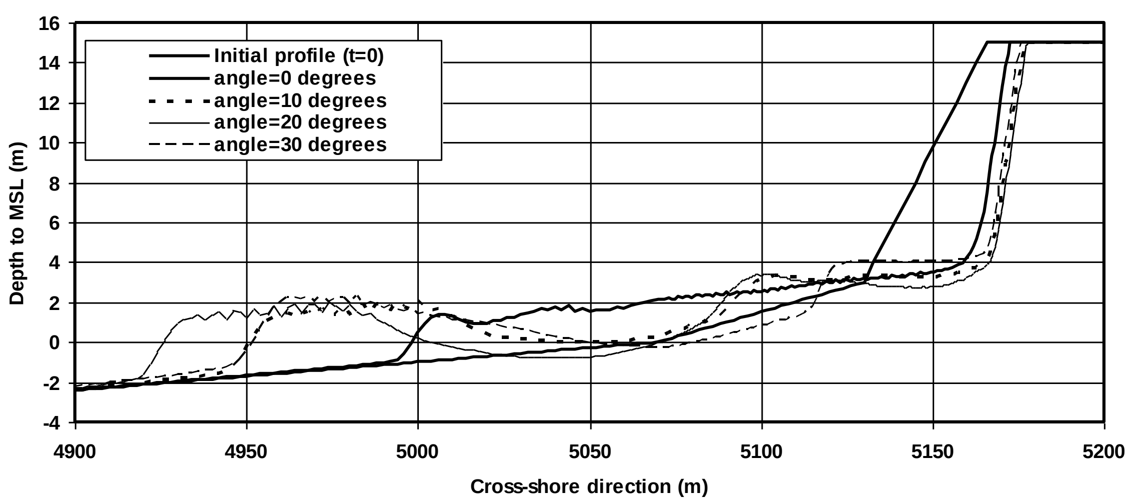

Figure 20 *Effect of incident wave angle (deep water) on computed bed profile after 5 hours for Reference Case*

Effect of bed material diameter

Figure 21 shows the effect of the bed material diameter (in the range of 0.15 to 0.3 mm) on the bed profile after 5 hours.

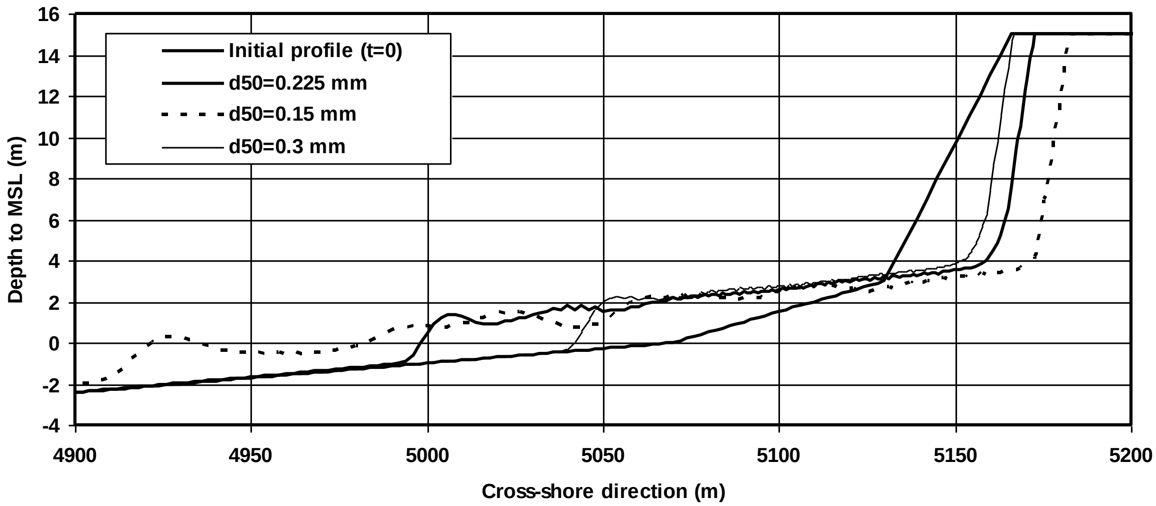

Figure 21 *Effect of bed material diameter on computed bed profile after 5 hours for Reference Case*

The reference bed material diameter is d_{50}=0.225 mm. The dune erosion decreases with increasing bed material diameter. The computed dune erosion area (A_d) above storm surge level after 5 hours can roughly be represented by: $A_d/A_{d,ref}=(d_{50,ref}/d_{50})^{1.4}$ with: $A_{d,ref}$=170 m^3/m and $d_{50,ref}$=0.225 mm, yielding values of about $A_{d,}$=100 m^3/m for d_{50}=0.3 mm and $A_{d,}$=250 m^3/m for d_{50}=0.15 mm.

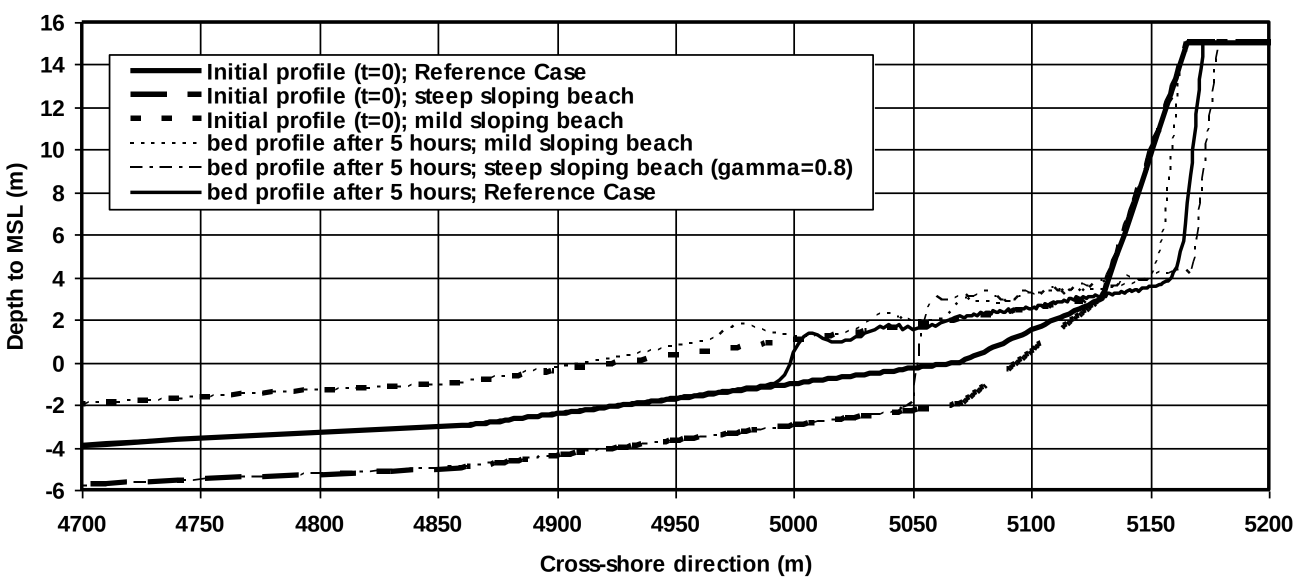

Figure 22 *Effect of beach profile steepness on computed bed profiles*

Effect of steeper and milder coastal profile

Figure 22 shows the effect of steep sloping and mild sloping coastal profiles. The coastal slope is defined as the slope between the +3 m and -3 m contours. The coastal slope of the Reference Case is 1 to 45 ($\tan\beta_{ref}$=0.0222). A steeper slope (1 to 22 or $\tan\beta$=0.046) yields a 20%-increase of the dune erosion volume. A milder slope (1 to 100 or $\tan\beta$=0.01) leads to a 30%-decrease of the dune erosion volume.

Simplified dune erosion rule (DUNERULE-model)

The results of the sensitivity study have been used to develop a simplified dune erosion rule (DUNERULE-model), as follows (see Figure 23):

$$A_{d,t=5}= A_{d,ref}\ (d_{50,ref}/d_{50})^{\alpha 1}\ (S/S_{ref})^{\alpha 2}\ (H_{s,o}/H_{s,o,ref})^{\alpha 3}\ (T_p/T_{p,ref})^{\alpha 4}\ (\tan\beta/\tan\beta_{ref})^{\alpha 5}\ (1+\theta_o/100)^{\alpha 6} \qquad (7)$$

with:

$A_{d,t=5}$ = dune erosion area above storm surge level after 5 hours (m^3/m),
$A_{d,ref}$ = dune erosion area 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),
θ_o = offshore wave incidence angle to coast normal (degrees),
α_1 = exponent=1.3,
α_2 = exponent=1.3 for $S<S_{ref}$ and α_2=0.5 for $S>S_{ref}$,
α_3 =α_4=α_6=0.5 (exponents),
α_5 = exponent=0.3.

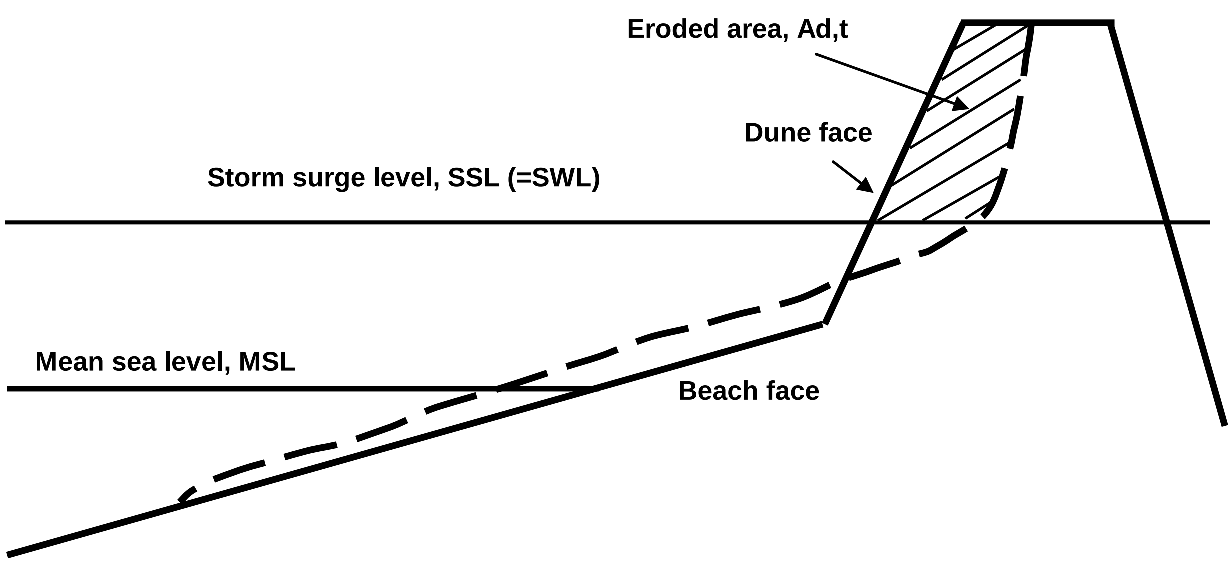

Figure 23 *Sketch of dune erosion*

Equation (7) yields zero erosion for S=0 (no storm surge set-up).

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

$$R_d=A_d/(h_d-S) \qquad (8)$$

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

$$R_{d,max} \cong 1.5\ R_d \qquad (9)$$

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:

$$A_{d,t}=A_{d,t=5}\ (t/t_{ref})^{\alpha 6} \qquad (10)$$

with:

t = time in hours (t_{ref}= 5 hours),
α_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 m^3/m. According to the experimental values (Vellinga, 1986), this value is in the range of 250 to 300 m^3/m. The storm surge level (S) above mean sea level and the bed material diameter (d_{50}) are the most influencial parameters. Equation (7) 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 m, $H_{s,o}$=5m, T_p=10 s, d_{50}=0.0002 m, α_o=20°, h_d=15, tanβ=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 m^3/m after 5 hours.
A_d= 82 m^3/m after 2.5 hours and 135 m^3/m after 10 hours.
R_d= 115/(15-4)=10.5 m after 5 hours; 7.5 after 2.5 hours and 12.5 m after 10 hours.
$R_{d,max}$= 16 m after 5 hours; 11 m after 2.5 hours and 19 m after 10 hours.

Equation (7) is most valid for dune erosion under major storms, but also yields realistic results for minor storm events. Data are taken from the storm erosion field database summarized by Birkemeier et al. (1988), (see Table 3 of Larson et al., 2004). The data have been clustered into 10 cases, shown in Table 2. The bed material diameter at these beaches varies in the range of d_{50}=0.3 to 0.5 mm. The coastal slope is taken as tanβ=0.0222.

Field site	Wave height (m)	Wave period (s)	Surge level (m)	Surge duration (hours)	Measured dune erosion volume (m^3/m)	Predicted dune erosion volume (m^3/m)
LBI	2.6	9	1.5	14	15±7	10
AC,LB	2.6	8	1.5	14	6±5	10
LB	3.4	8	1.4	24	8±4	11
LBI	1.9	8	1.5	36	27±7	10
LB	2.1	7	1.5	36	10±3	9
NB	2.4	8	2	10	25±3	15
NB	3.6	9.5	2.5	12	27±10	24
MB,WB,JB	3.8	10.5	2	11	10±5	18
AC,LB	3.0	8	1.8	10	5±3	12
LB	1.8	10	1.5	12	7±4	9

NB= Nauset Beach, MB=Misquamicut Beach, WB=Westhampton Beach, JB= Jones Beach, LBI=Long Beach Island, AC=Atlantic City, LB=Ludlam Beach

Table 2 *Dune erosion volumes during minor storm events along various USA-beaches*

Equations (7) and (10) have been used to predict the dune erosion volumes at these beaches. The wave incidence angle is assumed to be zero (normal to coast). The bed material diameter is set to 0.4 mm for all cases. As an example the dune erosion at Nauset Beach is computed by using Equation (7):

$A_{d,t=5} = 170\ (0.225/0.4)^{1.3}\ (2.5/5)^{1.3}\ (3.6/7.6)^{0.5}\ (1)^{0.3}\ (9.5/12)^{0.5} = 20\ m^3/m$ after 5 hours.

Equation (10) yields the dune erosion volume after 12 hours: $A_{d,t=12} = 20\ (12/5)^{0.2} = 24\ m^3/m$. The measured value is 27 m^3/m.

The predicted dune erosion is within the variation range for 6 cases; systematically too large for 2 cases and systematically too small for 2 cases.

Dune erosion graphs based on the simplified method are shown in ANNEX B.

6. Conclusions

This paper presents results of experimental and mathematical modelling of beach and dune erosion under storm events.

Re-analysis of the experimental results on dune erosion in flumes (work of Vellinga, 1986 and others) show that the dune erosion for the Reference Case is about 250 m^3/m, which is somewhat smaller than the value of 300 m^3/m given by Vellinga (1986). Laboratory simulation results of the dune erosion caused by the February 1953 storm (including the time-varying storm surge level) show that the dune erosion volume for the (distorted) laboratory test is about 30% larger than the mean (observed) value for field conditions. This result may indicate that the scaling laws based on (distorted) 2D laboratory tests produce values which are somewhat too large for 3D field conditions. Given the lack of data for extreme storm conditions, a firm conclusion on this cannot yet be given.

Dune erosion caused by wave impact has been modelled by a cross-shore profile model (CROSMOR-model), which is based on a 'wave by wave' modelling approach solving the wave energy equation for each individual wave. The individual waves shoal until an empirical criterion for breaking is satisfied. Wave height decay after breaking is modelled by using an energy dissipation method. Wave-induced set-up and set-down and breaking-associated longshore currents are also modelled. The model has been applied to the recent Deltaflume experiments on dune erosion. The three main processes affecting dune erosion have been taken into account: the generation

of low-frequency effects, the production of extra turbulence due to wave breaking and wave collision and the sliding of the dune face due to wave impact. The inclusion of low-frequency effects only marginally affects the dune erosion. The two most influencial model parameters are the suspension enhancement factor (sef) which represents the effect of extra turbulence in the dune erosion zone and the wave breaking coefficient, which determines the maximum wave height. The suspension enhancement factor (sef) is required to model the increase of the sand transport capacity in the shallow surf zone in front of the dune face, which is supposed to be primarily caused by large-scale turbulence generation due to wave collision effects. The Deltaflume test results can be reasonably well simulated by using sef=2.5 (sef=1 means no effect). The sef-parameter is assumed to be constant in time, but this assumption basically is not correct. The sef-parameter should decrease in time as the dune erosion process will gradually diminish due to the development of a new coastal profile representative for storm conditions. The gradual decay of the sef-parameter cannot be represented by the simplistic schematization used herein. This may be the cause for the overestimation of the erosion below the storm surge level. Basically, the sef-parameter should be related to the wave breaking and wave collision processes (future research).
The calibrated model (based on Deltaflume results) can very well simulate the observed dune erosion above the storm surge level during storm events in small-scale facilities, large-scale facilities and in the protoype (1953 storm in The Netherlands) using the same model settings. The dune erosion above storm surge level after 5 hours generally is slightly over-estimated. The erosion below the storm surge level is considerably over-estimated by the model.
Based on the results of a detailed sensitivity study, the two most influencial parameters are found to be the storm surge level (above mean sea level) and the bed material diameter. Dune erosion increases with increasing storm surge level (S) and with decreasing bed material diameter (d_{50}). The wave period also has a marked influence. Dune erosion increases with increasing wave period. The wave spectrum has no significant effect on dune erosion.
The relative changes of the erosion parameters (erosion area above storm surge level) caused by variation of physical parameters such as wave period, wave spectrum and bed material size are of the same order as those caused by variation of basic model parameters (wave breaking coefficient, roller model, swash zone parameters).

Application of the CROSMOR-model to the prototype Reference Case as defined by Vellinga (1986) yields a dune erosion volume of about 170 m^3/m, which is considerably smaller than the value of about 250 to 300 m^3/m based on scale model results**.** This discrepancy may be caused by upscaling errors (using available scaling laws) of laboratory test results to prototype conditions and by mathematical modelling errors. As regards scaling errors, the mathematical model is more reliable. The model has been verified using field data. For example, the CROSMOR-model has been used to simulate the 1975 hurricane Eloise in the USA and the 1953 storm in The Netherlands (Van Rijn, 2008). In both cases the model over-estimates the observed erosion. Hence, the model seems to produce conservative rather than optimistic results for field conditions.
A sensitivity study for the Reference Case shows that the most influencial parameters are the storm surge level and the sand diameter. The wave period and the offshore wave incidenc angle have a smaller effect. Dune erosion increases slightly with increasing wave period and increasing wave angle (oblique waves). The mathematical model results have been used to develop a new dune erosion rule (DUNERULE-model). This dune erosion rule estimates the dune erosion with respect to a base Reference Case, which represents a storm of 5 hours duration with a constant wave height of 7.6 m (period of 12 s; normal to coast), bed material diameter of 0.225 mm and storm surge level of +5 m (above mean sea level). The computed dune erosion (above storm surge level) of the base Reference Case is 170 m^3/m after 5 hours. The most influencial parameters are the storm surge level (S) and bed material diameter (d_{50}). Dune erosion decreases for smaller storm surge levels, smaller wave heights, smaller wave periods, shorter storm duration and coarser sand. The new dune erosion rule is most valid for dune erosion under major storms, but also yields realistic results for minor storm events based on a comparison with measured data from USA-beaches.

Acknowledgements
The Basic Research Program of Delft Hydraulics and the European Research Projects SANDS and CONSCIENCE sponsored by the European Community are gratefully acknowledged for their financial support.

References

Birkemeier, W.A., Savage, R.J., Leffler, M.W., 1998. *A collection of storm erosion field data. Miscellaneous Paper CERC-88-9, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, USA*

Dally, W.R. and Osiecki, D.A., 1994. *The role of rollers in surf zone currents. Proc. 24th ICCE, Kobe, Japan*

Davies, A.G. and Villaret, C., 1997. *Oscillatory flow over rippled beds. In: J.N. Hunt (ed.), Gravity waves in water of finite depth: Chapter 6, p. 215-254. Advances in fluid mechanics, Computational Mechanics Publications*

Davies, A.G. and Villaret, C., 1998. *Wave-induced currents above rippled beds, p. 187-199. In: Physics of estuaries and coastal seas, edited by J. Dronkers and M. Scheffers, Balkema, Brookfield*

Davies, A.G. and Villaret, C., 1999. *Eulerian drift induced by progressive waves above rippled and very rough bed, p. 1465-1488. Journal of Geophysical Research, Vol. 104, No. C1*

Dean, R.G., 1973. *Heuristic models of sand transport in the surf zone. Conf. on Eng. Dynamics in coastal zone, Sydney, Australia*

Delft Hydraulics, 2004. *Model study of dune erosion: experimental results of small-scale pilot tests (in Dutch), Report H4265. Delft, The Netherlands*

Delft Hydraulics, 2006a. *Dune erosion,large-scale model tests and dune erosion prediction method. H4357, Delft, The Netherlands*

Delft Hydraulics, 2006b. *Dune erosion, measurement report of large-scale model tests. H4357, Delft, The Netherlands*

Delft Hydraulics, 2007. *Technical Report Dune Erosion (in Dutch). Report H4357, Delft Hydraulics, Delft, The Netherlands*

Dette, H.H. and Uliczska, K., 1987. *Prototype investigation on the time-dependent dune recession and beach erosion. Coastal sediments, New Orleans, USA, p. 1430-1444*

Grasmeijer, B.T., 2002. *Process-based cross-shore modelling of barred beaches. Doctoral Thesis. Department of Physical Geography, University of Utrecht, Utrecht, The Netherlands*

Grasmeijer, B.T. and Van Rijn, L.C., 1998. *Breaker bar formation and migration. Proc.26th ICCE., Copenhagen, Denmark*

Houwman, K.T. and Ruessink, B.G., 1996. *Sediment transport in the vicinity of the shoreface nourishment of Terschelling. Dep. of Physical Geography. University of Utrecht, The Netherlands*

Isobe, M. and Horikawa, K., 1982. *Study on water particle velocities of shoaling and breaking waves. Coastal Engineering in Japan, Vol. 25.*

Kraus, N.C., et al., 1991. *Evaluation of beach erosion and accretion predictors. Coastal Sediments, Seattle, USA, p 572-587*

Kriebel, D.L. et al., 1991. *Engineering methods fore predicting beach profile response. Coastal Sediments, Seattle, USA*

Larson, M. and Kraus, N.C., 1989. *S-beach: numerical model simulating storm-induced beach change. Report 1: empirical foundation and model development. Technical Report CERC-89-9. US Army Engineer Waterways Experiment Station, Vicksburg, USA*

Larson, M., Erikson, L. and Hanson, H., 2004. *An analytical model to predict dune erosion due to wave impact. Coastal Engineering, Vol. 51, p. 675-696*

Reniers, A. J. H. M., J. A. Roelvink and Thornton, E.B., 2004. *Morphodynamic modeling of an embayed beach under wave group forcing. Journal of Geophysical Research 109, doi:10.1029/2002jc001586*

Steetzel, H., 1993. *Cross-shore transport during storm surges. Doctoral Thesis, Delft University of Technology, Delft, The Netherlands*

Stockdon, H.F., Holman, R.A., Howd, P.A. and Sallenger, A.H., 2006. *Empirical parameterization of setup, swash and runup. Coastal Engineering, Vol. 53, p. 73-588*

Svendsen, I.A., 1984. *Mass flux and undertow in the surf zone. Coastal Engineering, Vol. 8, p. 347-365*

Van Gent, M.R.A., 2001. *Wave runup on dikes with shallow foreshores. Journal of Waterways, Port, Coastal and Ocean Engineering, Vol. 127, No. 5, p. 254-262*

Van Gent, M. R. A., J. S. M. Van Thiel de Vries, et al., 2008. *Large scale dune erosion tests to study the influence of the wave periods. Submitted to Coastal Engineering.*

Van Rijn, L.C., 1993, 2006. *Principles of sediment transport in rivers, estuaries and coastal seas, including update of 2006. Aqua Publications, Amsterdam, The Netherlands (www.aquapublications.nl)*

Van Rijn, L.C., 1997. *Cross-shore sand transport and bed composition. Coastal Dynamics, Plymouth, England, p. 88-98*

Van Rijn, L.C., 2006. *Principles of sedimentation and erosion engineering in rivers, estuaries and coastal seas. Aqua Publications, The Netherlands (www.aquapublications.nl)*

Van Rijn, L.C., 2007a. *Unified view of sediment transport by currents and waves, I: Initiation of motion, bed roughness and bed-load transport. Journal of Hydraulic Engineering, ASCE, Vol. 133, No. 6, p. 649-667*

Van Rijn, L.C., 2007b. *Unified view of sediment transport by currents and waves, II: Suspended transport. Journal of Hydraulic Engineering, ASCE, Vol. 133, No. 6, p. 668-689*

Van Rijn, L.C., 2007c. *Unified view of sediment transport by currents and waves, III: Graded beds. Journal of Hydraulic Engineering, ASCE, Vol. 133, No. 7, p. 761-775*

Van Rijn, L.C., 2007d. *Unified view of sediment transport by currents and waves, IV: Application of morphodynamic model. Journal of Hydraulic Engineering, ASCE, Vol. 133, No. 7, p. 776-793*

Van Rijn, L.C., 2008. *Modelling of beach and dune erosion. Report Z4173/Z4230. Delft Hydraulics, Delft , The Netherlands*

Van Rijn, L.C. and Wijnberg, K.M., 1994. *One-dimensional modelling of individual waves and wave-induced longshore currents in the surf zone. Report R 94-09, Department of Physical Geography, University of Utrecht.*

Van Rijn, L.C. and Wijnberg, K.M., 1996. *One-dimensional modelling of individual waves and wave-induced longshore currents in the surf zone. Coastal Engineering, Vol. 28, p. 121-145*

Van Rijn, L.C., Walstra, D.J.R., Grasmeijer, B., Sutherland, J., Pan, S. and Sierra, J.P., 2003. *The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based profile models, p. 295-327. Coastal Engineering, 47*

Van Thiel de Vries, J.S.M., Van de Graaff, J., Raubenheimer, B., Reniers, A.J.H.M. and Stive, M.J.F., 2006. *Modeling inner surf hydrodynamics during storm surges. Proc. 30th ICCE, San Diego, USA, p. 896-908*

Van Thiel de Vries, J.S.M., Clarke, L.B., Aarninkhof, S.G.J., Coeveld, M., Holman, R.A., Palmsten, M.L., Reniers, A.J.H.M., Stive, M.J.F. and Uijttewaal, W.S.J., 2007. *Interaction of dune face and swash zone. Coastal sediments, New Orleans, USA*

Van Thiel de Vries, J. S. M. and A. J. H. M. Reniers, 2008. *Modeling sediment suspension in the inner surf during storm surges. Accepted to ICCE 2008. Hamburg.*

Van Thiel de Vries, J.S.M., Van Gent, M.R.A., Walstra. D.J.R. and Reniers, A.J.H.M., 2008. *Analysis of dune erosion processes in large-scale flume experiments. Submitted to Coastal Engineering.*

Vellinga, P., 1986. *Beach and dune erosion during storm surges. Doctoral Thesis, Delft University of Technology, Delft, The Netherlands (Publication 372, Delft Hydraulics)*

ANNEX A Empirical DUROS+ method

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 A1**):

$$Y= 0.4714 (H_{o,s}/7.6) [(H_{o,s}/7.6)^{1.28} (12/T_p)^{0.45} (w_s/0.0268)^{0.56} x + 18]^{0.5} – 2 \quad (1)$$

$$X_{max}=250 (H_{o,s}/7.6)^{1.28} (0.0268/w_s)^{0.56}$$

$$Y_{max}=[0.4714\{250(12/T_p)^{0.45} +18\}^{0.5} – 2] (H_{o,s}/7.6)$$

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

with:
y= depth below the storm surge level (m), x= distance from new dune foot origin (m),
$H_{o,s}$= significant wave height at deep water (m), T_p= peak wave period (s),
w_s= fall velocity of sand in seawater of 5° Celsius (m/s).

The origin (x=0, y=0) is defined as the intersection of Equation (1) 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 A1).
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 $A_1 + A_2 = A_3$ (continuity of erosion and accretion).
The total dune area (A_{total}) above the storm surge level required to have a safe coastal dune is $A_{total}= A_1+ A_u+A_s$ with: A_u= area related to uncertainties involved (about $0.25A_1$) and A_s= area of safety profile (about $0.25A_1$).

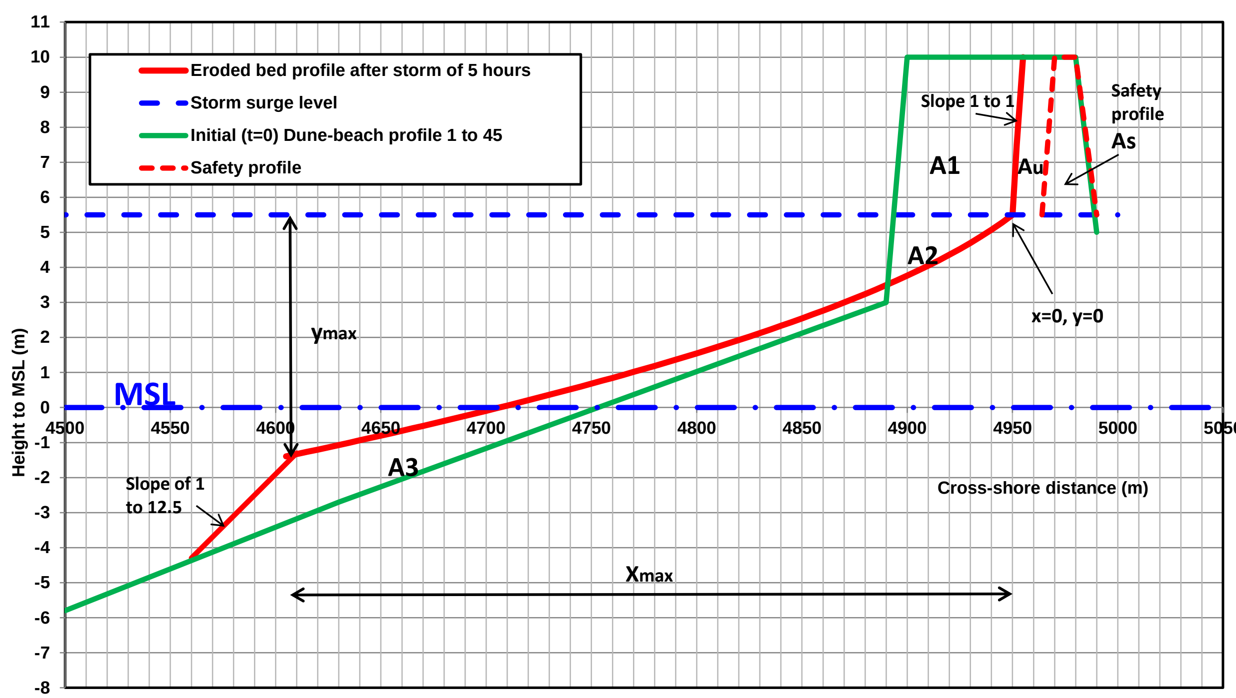

Figure A1 *Duros+ method;*
$H_{o,s}$= 10 m, T_p= 16.2 s, SSL=5.5 m, d_{50}=0.00025 m, w_s=0.0281 m/s, Dune erosion A1+A2≃300 m^3/m

ANNEX B Dune erosion graphs

Figure B1 shows plots of the dune erosion area (above the storm surge level) after 5 hours as a function of the sediment size and the storm surge level for two wave climates (North Sea and Mediterranean) based on the simplified model of Van Rijn for the case of waves normal to the coast.

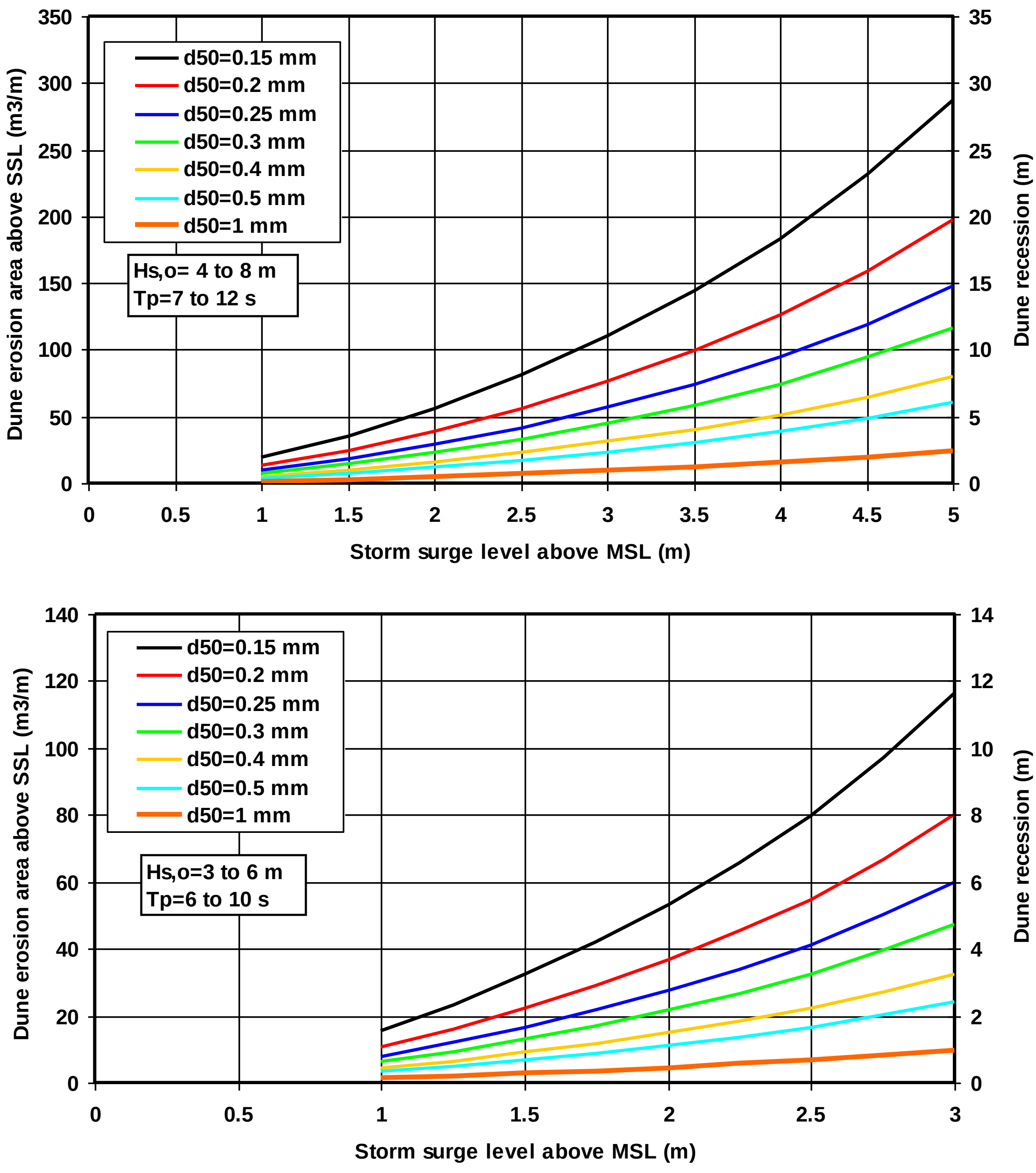

Figure B1 *Dune erosion after 5 hours during a storm event as function of sediment size and storm surge level for two wave climates: North Sea (upper) and Mediterranean (lower); dune recession based on dune height of 10 m above SSL*

The significant offshore wave height in the North Sea is assumed to vary between 4 and 8 m for surge levels between 1 and 5 m above mean sea level (MSL).
Dune erosion after 5 hours is largest for relatively fine sediments (0.15 mm) and reduces rapidly for coarser sediments.
Dune erosion of gravel (1 mm) is only 15% of that of fine sand (0.15 mm).

The shoreline recession (E) due to dune erosion can be estimated from E=A/h with A= dune erosion area above storm surge level SSL and h= dune height above the storm surge level.
Figure 10 shows dune recession values (axis on right side of plot) based on a dune height of 10 m above SSL. Dune recession values are twice as large for dune height of 5 m.

Dune erosion is very much related to extreme events with high surge levels including tidal effects. Extreme storms have a large return period. For example, a North Sea storm with a surge level of 5 m above mean sea level has, on average, a return period of about 10,000 years (so once in 10,000 years), but it can happen tomorrow. The return period of a surge level of only 2 m is 1 year; so, once every year. The computed dune erosion values after 5 hours are of the order of 20 m^3/m for a surge level of 1 m and up to 300 m^3/m (d_{50}=0.15 mm) for a large surge level of 5 m, see Figure 10.

To withstand an extreme event with a surge level of 5 m above mean sea level, the dune row fronting the sea should have a minimum width of the order of 50 m. In 'normal' conditions with two or three events per year with surge levels between 1 and 2 m per year, the total annual dune erosion may be as large as 50 m^3/m/year locally along the sandy North Sea coasts. Most of the eroded dune sand will be deposited on the beach from where it can be returned to the dune front by wind-induced forces or carried away by cross-shore and longshore currents. Dune accretion at the dune front due to wind effects is of the order of 10 to 20 m^3/m/year and is generally not sufficient to compensate dune erosion on the annual time scale by natural processes. Thus, dune erosion generally leads to a permanent loss of sand which can only be compensated by artificial nourishment (dune restoration).