BEACH AND DUNE EROSION DUE TO STORMS

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This paper presents results of experimental and mathematical modelling of beach and dune erosion under storm events. 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 mathematical model results have been used to develop a new simplified dune erosion rule.

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.

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 (Vellinga, 1986; Steetzel, 1993; 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, 2) the production of large-scale turbulence due to the impact (wave collision) of incoming breaking waves and reflected broken waves, 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 and 4) the regular sliding of the dune face when its has become too steep.

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.

Experimental results of dune erosion by extreme storms

The Dutch 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 (Vellinga, 1986, Van Gent et al., 2008). The median sediment diameter along the Dutch coast is assumed to be 225 μm (0.225 mm). The high storm surge level 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. The offshore significant wave height is $H_{s,o}$= 7.6 m and the peak wave period is T_p=12 s. The cross-shore profile is: 1) dune height at +15 m NAP, 2) dune face with slope of 1 to 3 down to a level of +3 m NAP,

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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

New experiments have been carried out in the Deltaflume of Delft Hydraulics in the period October 2005 to March 2006.

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 still water level (SWL) representing the storm surge level is set at 4.5 m above the original flume bottom. Irregular (single-topped) waves have been used. A double-topped wave spectrum has been used in Test T16. The eroded profiles of three tests after 6 hours are shown in Figure 1. 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 1. The erosion area decreases slightly by about 10% in the case of a double-topped spectrum (based on T03 and T16; not shown).

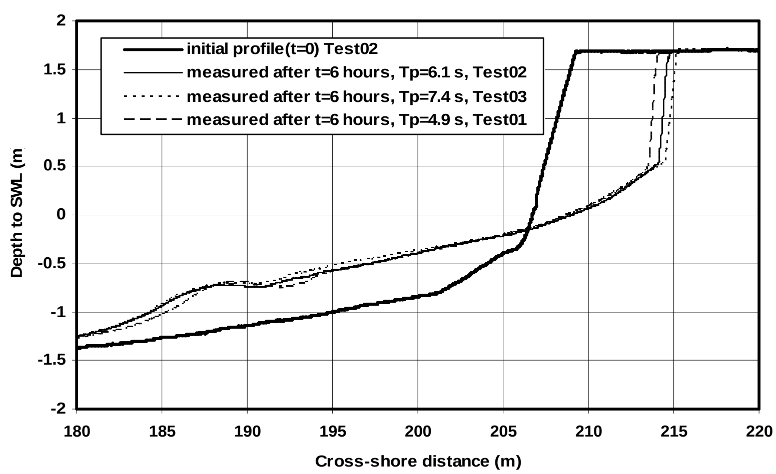

Figure 1. Measured bed profiles after 6 hours for Tests T01, T02 and T03

CROSS-SHORE MODELLING OF DUNE EROSION

Hydrodynamics and sediment transport

The CROSMOR2007-model is an updated version of the CROSMOR2004-model. 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 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. 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 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. By definition the swash zone is the zone where the bed is partly wet and dry. In the CROSMOR-model the numerical computation of the hydrodynamics (H) and sediment transport (S) is applied up to a point (last HS-grid point) just seaward of the downrush point, where the mean water depth is of the order of 0.1 to 0.2 m. Seaward of this last HS-grid point the bed is always submerged (always wet), landward of this point the bed is partly wet and dry (defined as the swash zone). The complicated wave mechanics in the swash zone is not explicitly modelled, but taken into account in a schematized way. The initial cross-shore profile is specified (input) from deep water to the dune crest and updated each time step depending on horizontal transport gradients. The transport gradients in the wet and dry swash zone are represented in a schematized way.
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). The total velocity variance (total wave energy) consists of high-frequency and low-frequency contributions ($U^2_{rms}=U^2_{hf,rms}+U^2_{lf,rms}$). The low-frequency significant wave height is related to the high-frequency significant wave height, as follows:

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

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 simply computed from long wave theory (Equation 1b). 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 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). 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 2.5 is found (based on Deltaflume experiments 2005; see later) to be valid for the shallow surf zone in front of the dune face. More details are given by Van Rijn (2009).

Erosion in swash zone

The swash zone (or dune erosion zone) in front of the relatively steep dune face is defined as the zone from the last HS-grid point up to the run-up level which is dominated by breaking bores (swash motions). Herein, the length of this 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 ($h_L \cong 0.1L_d$);

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. 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). Usually, the runup level is related the offshore wave height, also in in field conditions (Stockdon et al., 2006). To model dune erosion correctly, a run-up formula is required which is valid for steep slopes (up to 70^o).

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= $(H_{s,o}/L_{s,o})^{-0.5} \tan\beta$, $L_{s,o}$= wave length at deep water, $\tan\beta$=beach slope.

The total erosion area (A_E) over the length of the swash or dune erosion zone (L_s) defined as the zone between the last HS-grid point and the runup point is given by:

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

with: q_L=cross-shore transport computed at last HS-grid point at seaward end of the dune erosion zone, Δt=time step, p=porosity factor of bed material, ρ_s=sediment density. Equation (3) relates the total erosion (or deposition) between the last HS-grid point and the runup point to the total cross-shore transport computed in the last HS-grid point. The cross-shore transport at this location (last HS-grid point) generally is offshore directed during high energy (storm) conditions and onshore directed during low energy conditions. The erosion (or deposition) between the last HS-grid point and the runup point (=swash or dune erosion zone with length L_s) is assumed to have a triangular shape, yielding $A_E=0.5eL_s$, with e=maximum erosion (or deposition) depth. Thus, the maximum erosion (or deposition) depth in the swash zone can be computed as:

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

Bed level changes

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

$$\rho_s(1-p)\partial z_b/\partial t + \partial(q_t)/\partial x = 0 \tag{5}$$

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.

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 slided material is placed as a small bar (with a length of the order of 5 times the local water depth) at the toe of the dune. This bar stabilizes the lower dune slope. 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 :

$$\tan(\alpha_x) > \tan(\beta) \tag{6}$$

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.

MODELLING OF LARGE-SCALE LABORATORY DATA

The mathematical model simulations of the laboratory data are focussed 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, as shown in Figure 1. The incoming (offshore) significant wave height is 1.5 m. The limiting water depth is set to 0.1 m (water depth in last grid point). The maximum dune face slope is set to 50 degrees (failure and sliding for slope angles larger than 50 degrees).
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.

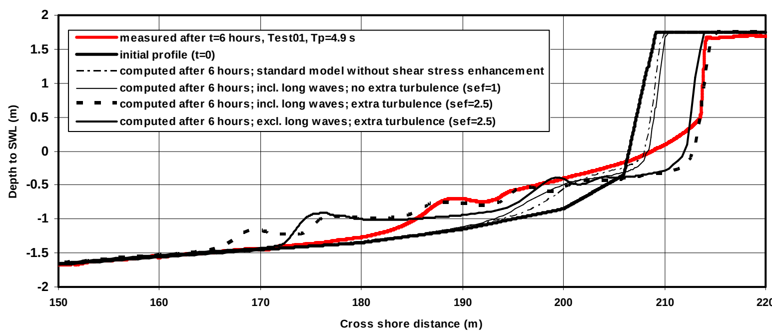

Figure 2 **Computed bed profiles after 6 hours for Test T01**

Figure 2 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. 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 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 main reason for this latter behaviour is the assumption of a constant sef-parameter in time (input value), whereas it should be an inherent property of model gradually reducing to sef=1 in time.

Figure 3 shows measured and computed concentrations near the bed for Test T01 (T_p=4.9 s). The measured concentration is the average value of the concentrations in the lowest three measurement points (between 4 and 8 cm above the bed). Just after the start of the experiment the concentrations show a strong increase from about 0.5 kg/m^3 at 175 m to about 30 kg/m^3 at 205 m. The concentrations in the swash zone (205 m) decrease in time to about 3 kg/m^3 after 375 minutes. The computed reference concentrations (defined at 1 cm above the bed) at initial time (t=0) including the effects of long waves and the extra turbulence (sef=2.5) are of the right order of magnitude in the swash zone. The computed concentrations outside the surf zone (<175 m) are much too large, because these concentrations are defined at 1 cm above the bed whereas the measured concentrations are the average values of the concentrations in the layer between 4 and 8 cm above the bed.

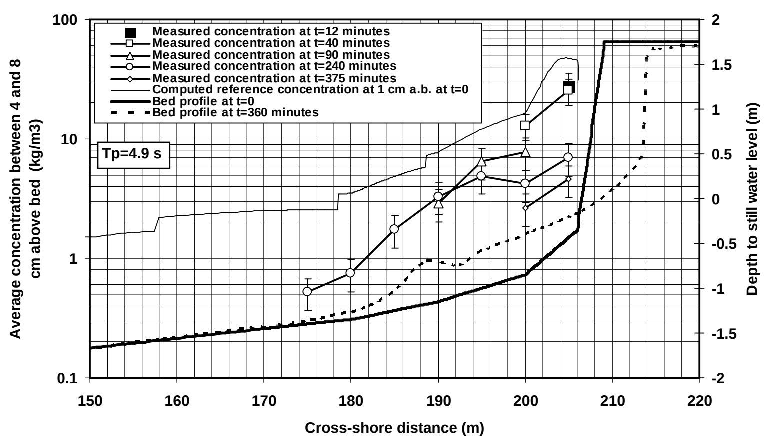

Figure 3 **Measured and computed reference concentration for Test T01**

The suspended sediment transport (seaward-directed) shows a similar pattern with increasing values if the long wave effects and the extra turbulence effects are included, see Figure 4

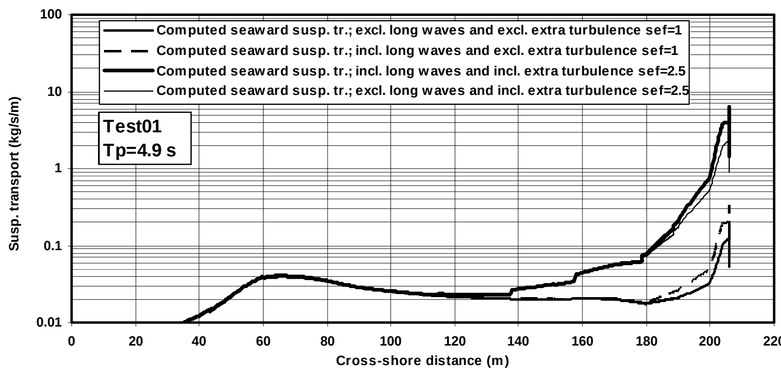

Figure 4 **Computed seaward suspended sand transport for test T01 (at t=0 hrs)**

SENSITIVITY STUDY AND 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 Dutch Reference Case. 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. The results of the sensitivity study have been used to develop a simplified dune erosion rule (DUNERULE), as follows (Fig. 5):

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

with:

$A_{d,t=5}$ = dune erosion area above storm surge level after 5 hours (m^3/m),
$A_{d,ref}$ = erosion area above storm level after 5 hours in Ref. 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,

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.

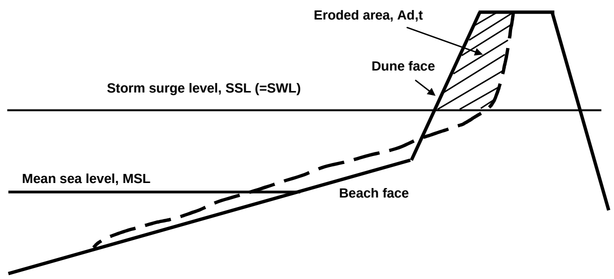

Figure 5 Sketch of dune erosion

The time development over 100 hours can be estimated from: $A_{d,t}=A_{d,t=5}\ (t/t_{ref})^{\alpha 6}$ with: t= time in hours (t_{ref}= 5 hours), α_6= exponent= 0.5 for $t<t_{ref}$ and 0.2 for $t>t_{ref}$. The average horizontal dune recession (R_d) can be estimated from: $R_d=A_d/(h_d\text{-}S)$. The maximum horizontal dune recession ($R_{d,max}$) at storm surge level can be estimated from: $R_{d,max}\cong 1.5\ R_d$ 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).
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, θ_o=20^o, 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 m 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.

Figure 6 shows 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 Equation (7) for the case of waves normal to the coast. 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. Dune erosion after 5 hours is largest for relatively fine sediments (0.15 mm) and reduces rapidly for coarser sediments. Dune erosion of very coarse sand (1 mm) is only 10% to 5% of that of fine sand (0.15 mm). The shoreline recession (R) due to dune erosion can be estimated from R=A/h with A= dune erosion area above storm surge level and h= dune height above the storm surge level. Figure 5 shows dune recession values (axis on right side of plot) based on a dune height of 10 m. Dune recession values are twice as large for dune height of 5 m.

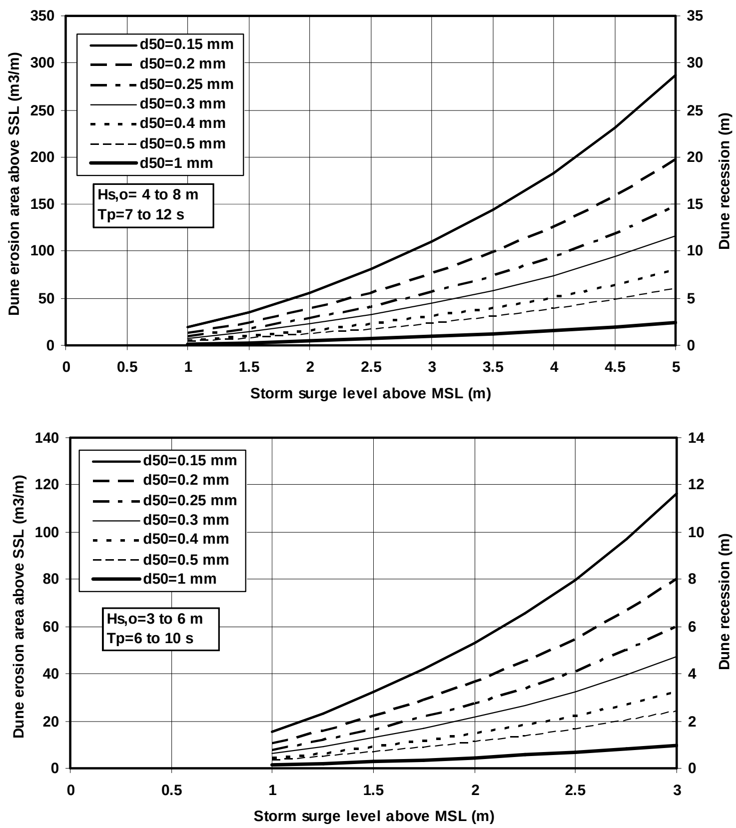

Figure 6 Dune erosion after 5 hours as function of sediment size and storm surge level for two wave climates: North Sea (upper) and Mediterranean (lower); dune recession based on dune height of 10 m above SSL

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 also Larson et al., 2004). The data have been clustered into 10 cases. 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 $\tan\beta$=0.0222.

Equation (7) has 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.

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. These results indicate some generality to Equation (7) which may be expected from a process-based model approach.

By definition the surge level (S) consists of tidal elevation (S_{tide}), wave set-up (S_{wave}) and wind-setup (S_{wind}). Wave set-up values at the beach values typically are in the range of S_w=0.1 to 0.15 $H_{s,o}$ (King et al., 1990, Thornton and Guza, 1981), yielding S-values ot about 0.2 to 0.5 m for minor storm events in non-tidal conditions (and no wind setup) and erosion volumes (sand of 0.2 mm) of about 3 to 5 m^3/m after 5 hours. Erosion volumes for minor storm events in tidal conditions (without wind setup) can be estimated by including the tidal elevation. Typical values for minor storm events with surge levels below 1 m (including tide) are in the range of 5 to 10 m^3/m (see Van Rijn, 1998, pages 4.180-4.181). The values of Equation (7) are in good agreement with these values.

The simplified method is very suitable for design purposes using a probabilistic approach requiring probability distributions for the parameters involved. This approach takes to a certain extent the erosion variability in nature due to local variations of particle size, beach slope, etc. into account. To account for model deficiencies (processes not or not accurately enough represented), the $A_{d,ref}$ parameter can be used as a stochastic variable with a mean of 250 m^3/m and a standard deviation of about 50 m^3/m or alternatively just using a safety factor (order of 1.2 to 1.5 depending on the value of $A_{d,ref}$ used). The detailed model should be used for special cases such as the occurrence of a series of successive storms and/or a very deviating cross-shore profile (with relatively high breaker bars, artifical reefs or deep channels).

CONCLUSIONS

This paper presents results of experimental and mathematical modelling of beach and dune erosion under storm events. 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. 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 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 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. This verification puts some generality to the applied modelling approach.

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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

King, B.A., Blackley, M.W.L., Carr, A.P. and Hardcastle, P.J., 1990. Observations of wave-induced set-up on a natural beach. Journal of Geophysical Research, Vol. 95, No. C12, p 22289-22297

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

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

Thornton, E.B. and Guza, R.T., 1981. Longshore currents and bed-shear stress. Proc. Directional Wave Spectra Applications, ASCE, New York, p.147-166

Van Gent, M. R. A., J. S. M. Van Thiel de Vries, E. M. Coeveld, J. H. De Vroeg, and J. Van de Graaff , 2008. Large scale dune erosion tests to study the influence of the wave periods, Coastal Engineering (in press)

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., 1998. Principles of coastal morphology. Aqua Publications, The Netherlands (www.aquapublications.nl)

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. et al., 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., 2009. Prediction of dune erosion due to storms. Coastal Engineering (accepted paper)

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., M. R. A. Van Gent, A. J. H. M. Reniers, and D. J. R. Walstra, 2008. Analysis of dune erosion processes in large scale flume experiments, Coastal Engineering (in press).

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

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BEACH AND DUNE EROSION DUE TO STORMS
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Abstract 271

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