THE EFFECT OF SEDIMENT COMPOSITION ON CROSS-SHORE BED PROFILES

Leo C. van Rijn[1]

Abstract

This paper provides information on the effect of sediment (sand) composition on cross-shore sand transport and cross-shore bed profile evolution, based on computational results of a mathematical cross-shore profile model (CROSMOR) and data from flume and field experiments (Egmond beach, The Netherlands and Duck beach, USA). The model has also been applied to study longshore sand transport along a sand-gravel beach. Finally, the effect of sediment size on shoreface nourishment is discussed.

Introduction

The sediment bed of the coastal zone may exhibit a large variation of sediment sizes. Generally, cross-shore sorting due to selective transport processes will occur in nature, yielding coarser sediment just beyond the waterline (wave plunging zone) and fining of sediment size in seaward direction. These effects can only represented by taking into account the full size composition of the bed material, which may vary across the profile. At present stage of research, mathematical modeling of sand transport and morphology generally is based on a single representative sediment fraction ($d=d_{50}$ and fraction size= 100%). A method is presented to compute the sand transport rate based on a multi-sediment fraction approach in cross-shore direction. The method is implemented as a submodule in a cross-shore model for wave propagation and wave-induced currents using a multi-wave (wave by wave) approach. The computational results of hydrodynamics and morphodynamics are compared to flume and field data. Model applications for sand-gravel beach and shoreface nourishment are given.

Model description

The details of the model (CROSMOR) are described by Van Rijn (1997b, 1998). Herein, a short summary is given.

[1]Delft Hydraulics and Dep. of Phys. Geography, Univ. of Utrecht
Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands
Email: Leo.vanRijn@wldelft.nl

The propagation, transformation (shoaling) and breaking of individual waves are described by a probabilistic model. The individual waves shoal until an empirical criterion for breaking is satisfied. Wave height decay due to bottom friction and breaking is modelled by using an energy dissipation method. Wave-induced set-up and set-down and breaking-associated longshore and cross-shore currents are also modelled (Van Rijn and Wijnberg, 1996). The near-bed orbital velocities of the high-frequency waves (low-frequency effects are neglected) are described by second order Stokes theory and by linear wave theory in combination with an empirical correction factor. 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. Streaming in the wave boundary layer due to viscous and turbulent diffusion of fluid momentum is taken into account. The streaming (u_b) in the wave boundary layer is of the order of 5% of the peak orbital velocity and generally onshore-directed in deeper water (symmetric waves).

To show the performance of the probabilistic model with respect to the computation of wave height and longshore velocity, a recent laboratory experiment (Reniers and Battjes, 1997) was simulated. Measurements of wave height and longshore velocity across a barred beach profile in a laboratory basin were performed. Herein, the test (S0-014) with random waves is considered. The deep-water boundary conditions are: depth=0.55 m, H_{rms}=0.07 m, T_p=1.3 s and wave incidence angle= 30°. The bed roughness of the cement floor was k_s=0.0005 m. Figure 1 shows computed and measured wave heights and longshore velocities. The breaking coefficient was taken to be 0.6. The horizontal mixing coefficient E was used as a fit parameter for the longshore current. Good results were obtained for E=0.05 m²/s in the surf zone (depth<0.1 m).

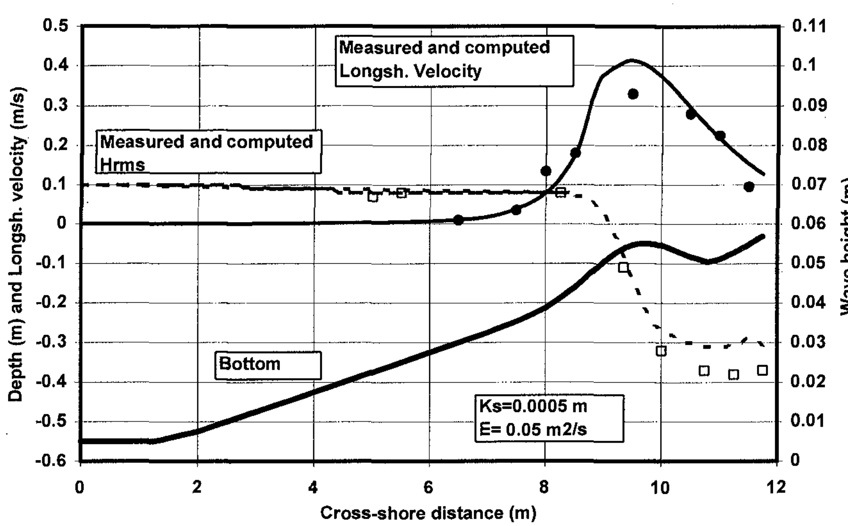


Figure 1. Measured and computed wave height and longshore velocity for basin experiment

The sand transport rate of the model 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 transport components (Van Rijn, 1993). 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 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 (1997a). The modelling of the $q_{s,w}$-component includes a calibration coefficient γ in the range between 0.3 and 0.7. 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 current velocity profile is represented as a two-layer system to account for the wave effects in the near-bed layer (Van Rijn, 1993). The convection-diffusion equation is applied to compute the equilibrium time-averaged sediment concentration profile for current-related and wave-related mixing. The effect of the local cross-shore bed slope on the transport rate is taken into account (Van Rijn, 1993, 1997a).
In the multi-fraction mode the bed material is divided in a number of size fractions and the sand transport rate of each size fraction is computed using an existing single fraction method (replacing the mean diameter of the bed material by the mean diameter of each fraction) with a correction factor to account for the non-uniformity effects (Van Rijn, 1993, 1997). This corrrection is necessary because the coarser particles are more exposed to the near-bed current and wave motion than the finer particles which are somewhat sheltered by the coarser particles (hiding effect). The interaction of the size fractions can be represented by increasing the critical shear stress of the finer particles and decreasing the critical shear stress of the coarser particles.
The total sand transport rate for all size fractions can be obtained by summation of the transport rates per fraction taking the probability of occurrence of each size fraction into account, as follows: $q_b = \Sigma p_i \, q_{b,i}$ and $q_s = \Sigma p_i \, q_{s,i}$ in which: p_i = probability of occurrence of size fraction i, N= number of size fractions
Bed level changes per fraction i are described by: $\rho_s(1\text{-}e)\partial z_{b,i} / \partial t + \partial(p_i q_{t,i})/\partial x = 0$ with: z_b= bed level to datum, $q_{t,i} = q_{b,i} + q_{s,i}$= volumetric total load (bed load plus suspended load) transport per fraction i, p_i= value of fraction i, ρ_s= sediment density, e= porosity factor. The total bed level change is obtained by summation of fractional bed level changes over all fractions. The bed material composition is computed in a thin surface mixing layer of thickness δ (order of 0.1 m) applying a one-layer approach. The thickness of the surfaee layer is assumed to be constant in space and time and is moving in vertical direction with the bed surface in response to bed level changes (deposition upwards and erosion downwards). Thus, the surface layer is always at the top layer of the bed. The mixing of sediment within the surface layer is assumed to be effectuated within each time step (instantaneous mixing) through small-scale bed form migration processes

in the lower regime or by wave-induced vortices in the sheet flow regime. The bed material composition of the subsoil below the surface layer is assumed to be uniform (no layered structure) and equal to the initially specified fraction values.

Model results of bar behaviour for Egmond, The Netherlands and Duck , USA

Computations using the single and multi-sediment fraction methods have been made for a sloping coastal profile with multiple bars along microtidal (Duck beach, USA) and mesotidal coasts (Egmond beach, The Netherlands).

Egmond beach, The Netherlands

The model has been applied to simulate nearshore bar behaviour at Egmond in The Netherlands (Wolf, 1997). The case considered is an onshore, accretive event (15 October to 26 October 1992) during which accretive hydrodynamic conditions are present, resulting in significant bar growth and onshore bar migration. As no cross-shore distributions of the hydrodynamic and transport parameters are available, the model is mainly evaluated based on measured profile developments.

The field site is a coastal area of about 1 kilometre alongshore and about 1 kilometre offshore. It is situated south of the village of Egmond aan Zee along the Holland coast. Longshore differences in the offshore wave climate are small due to the relatively uniform orientation of this section of the Dutch coast. The wave climate is dominated by wind waves related to low pressure areas moving from west (Atlantic) to east (European Continent). The tidal range near Egmond varies between 1.2 m (neap tide) and 2.1 m (spring tide). At the site, the flood tide has a duration of 4 hours and the ebb tide of 8 hours. The horizontal tide runs ahead of the vertical tide by about 45 minutes. The semi-diurnal tide induces asymmetrical surface currents which may reach values of 0.6 to 1.0 m/s.

Because of the absence of man-made structures in the area, the coast can be characterised as a natural coast. The sequence of (usually) three bars in the cross-shore profile is representative for a large part of the central Dutch coastal region.

Wave data were collected at Pole 3 (Profile No. 39500), located 545 m offshore at a water depth of about 4 m. The available data comprises time series of water level, wave height, wave period and direction. A sea-sledge (Sub-Aquatic Profiler, SAP) was used to monitor the inner bar. The SAP is pulled back and forth through the surf zone by a capstan (attached to a tractor) and a cable in a closed loop between the capstan and two pulleys, one of which is attached to a beach pole and the other to a pole in the surfzone.

The boundary conditions (over 11 days) of the accretive event are: wave heights (H_{rms}) between 0.5 and 2.5 m, wave period between 4.5 and 10 s, wave angle between 50° and -50° to coast normal, water levels between 1.25 m and -1 m (to MSL).

As the wave model is based on a probabilistic approach, the number of wave classes has to be prescribed. Generally, three to five wave classes are sufficient to give accurate results. One base run was made using ten wave classes. The computed bed profiles were almost identical to those of the run with four wave classes.

The initial bed profile, the measured and computed bed profiles after 11 days for the base run (no oscillatory suspended transport or gamma= 0, median sand size d_{50}= 0.3 mm, bed roughness= 0.016 m) are given in Figure 2.

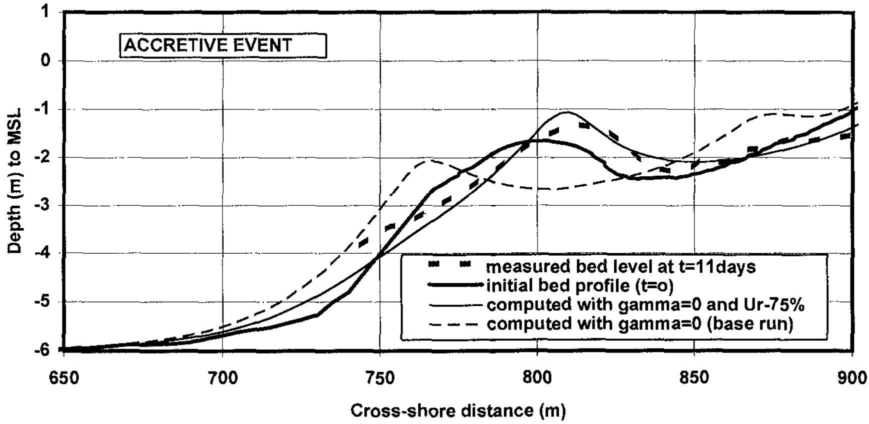


Figure 2. Base run and effect of undertow velocity on bar behaviour, Egmond

The computed profile shows offshore migration of the nearshore bar, whereas the measured profile shows weak onshore migration of the bar. The model produces minor bars in the swash zone near the beach, probably as a result of tide level variations modifying the location of the breaker zone.

The results of a series of sensitivity runs showed that the most sensitive parameters are: undertow velocity, bed roughness, oscillatory suspended transport (gamma-factor) and bed material composition.

The bed roughness was increased from 0.016 m to 0.05 m to better simulate the presence of vortex ripples on the bed, which may be present during accretive conditions. Increase of the bed roughness leads to reduced wave heights and reduced near-bed cross-shore velocities and hence to a relatively large decrease of offshore transport components.

Several gamma factors have been used to increase the onshore-directed suspended transport. Onshore bar migration was obtained for gamma values larger than about 0.3.

The undertow velocity (Ur) was by trial and error reduced to obtain reasonable agrreement between computed and observed bar behaviour. The reduction factor was found to be 75%. Results are given in Fig. 2. The measured bed profile is reasonably well represented for x>775 m. The erosion is overpredicted for x between 740 and 775 m.

The effect of sand fractions was studied by a run using the multi-fraction method with 4 fractions; the d_{50}-value of 0.29 mm was kept the same. The bed roughness was k_s=0.016 m in both runs.

The results are presented in Figure 3. The bed profile after 11 days shows a lower crest level without significant offshore migration of the crest. The undulations landward of the bar crest are somewhat larger. The cross-shore distribution of the d_{50} is changed after 11 days (constant value of d_{50}=0.29 mm at t=0). The nearshore sediment becomes coarser, because the fines are eroded in larger quantities and are carried in seaward direction.

The best agreement between measured and computed bed evolution (with onshore bar migration) was obtained by using four sand fractions, gamma= 0.3, k_s= 0.05 m, and a 20%-reduction of the undertow velocities. Results are shown in Figure 4.

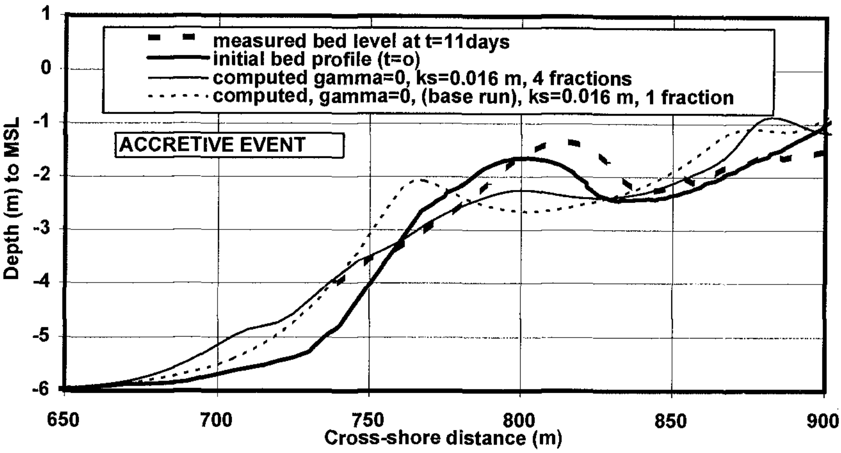


Figure 3. Effect of bed material distribution on bar behaviour, Egmond beach

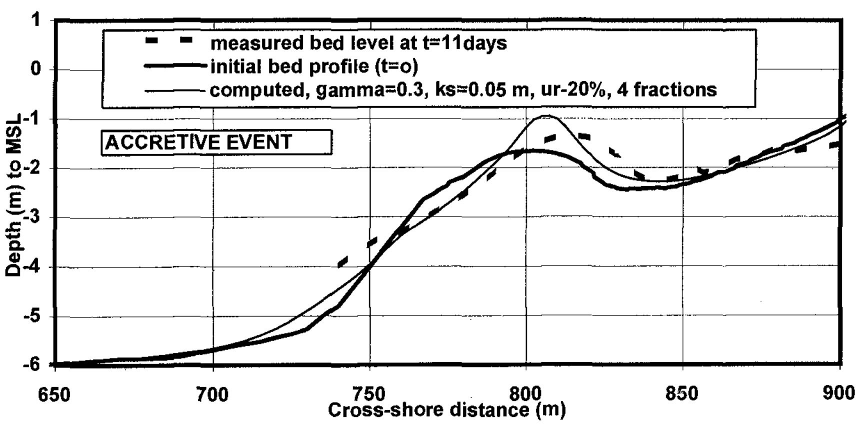


Figure 4. Optimum parameter setting for accretive event, Egmond beach

Duck beach, USA

The CROSMOR profile model has been applied to the cross-shore profile data measured at the Duck beach (USA) during the year 1982 (Mason et al., 1984). The Duck site is exposed to waves coming from the Atlantic Ocean. The tidal range is about 1 m; the tidal currents are weak. The winter period is dominated by storm waves; offshore wave heights can be as high as 6 m. The summer period is dominated by long-period swell. The bed profile generally shows a single bar in the surf zone; sometimes a low outer bar is present. The swash zone near the shoreline consists of relatively coarse material (1 to 2 mm); the sediment is fining down in landward direction to about 0.5 mm on the upper beach and in seaward direction to about 0.2 mm in the outer surf zone (Richmond and Sallenger, 1984). Two cases are considered: storm event 9-12 Oct. 1982 (inner bar moved offshore) and calm event 24 Feb.-24 Aug. 1982 (outer bar moved onshore; beach profile accreted and gained about 50 m^3/m due to 3D effects).

Basic input data of *Storm event, 9-12 Oct. 1982* : $H_{s,0}$= 2.4 m (3 wave classes), T= 11 s, wave angle= 20°, time step= 300 s. The gamma-factor of the wave-related suspended transport was set to 0.35. The thickness of the mixing layer was set to 0.1 m. The bed roughness was set to 0.01 m.

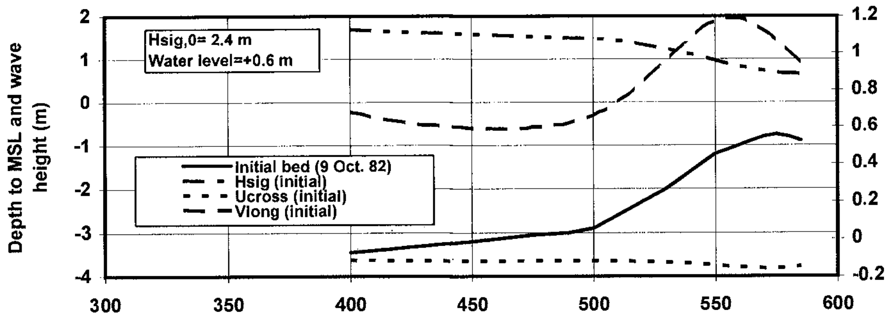


Figure 5. Computed significant wave height, depth-averaged cross-shore undertow velocity (below wave trough), and depth-averaged longshore velocity for storm event 9-12 Oct. 1982, Duck beach, USA

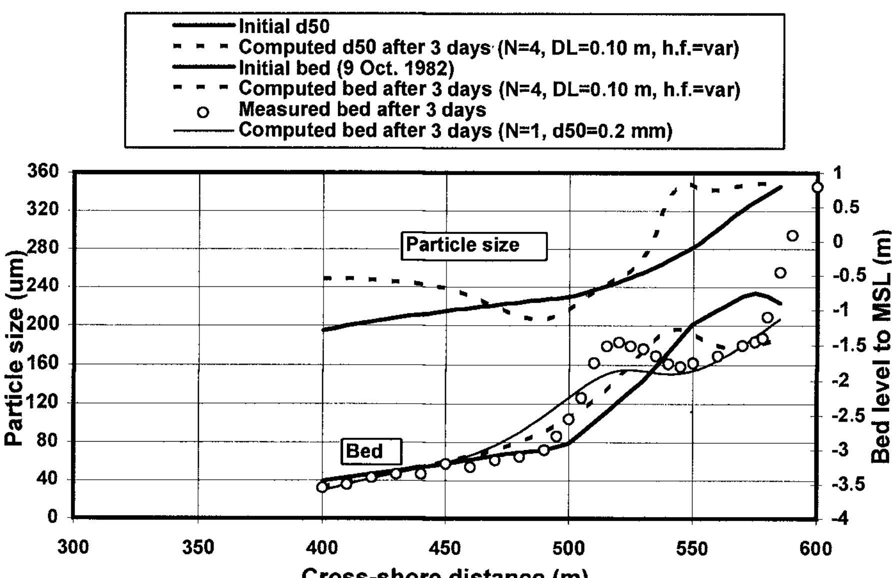


Figure 6. Effect of particle size distribution on bed profile evolution for storm event 9-12 Oct, 1982, Duck beach, USA

The computed hydrodynamic parameters (wave heights and currents) along the profile are shown in Figure 5. The wave height at the bar crest is reduced to about 0.8 m. The longshore current is maximum (about 1.2 m/s) near the bar crest. The maximum cross-shore return current is about 0.15 m/s near the bar crest.
The effect of particle size distribution on bed profile evolution using the multi-fraction method (N=4) instead of the single-fraction method (N=1) is shown in Figure 6.
The initial median particle size is assumed to vary between 0.2 mm at x=400 m and 0.35 mm at x=585 m for the run with N=4 fractions; the initial sediment size is taken constant along the profile for N= 1 fraction. Using N=1 fraction instead of N=4 fractions results in a more seaward position of the bar after 3 days; thus the bar position is significantly affected taking selective transport processes into account.

Basic input data of *Calm event, 24 Feb.- 24 Aug. 1982* are: $H_{s,0}$= 0.9 m (3 wave classes), T= 9 s, wave angle= 10°, time step= 21600 s. The gamma-factor of the wave-related suspended transport was set to 0.7. The thickness of the mixing layer was set to 0.1 m. The bed roughness was set to 0.01 m. The computed hydrodynamic parameters (wave heights and currents) along the profile are shown in Figure 7. The wave height in deep water is 0.9 m, which increases to about 0.95 m at the bar crest due to shoaling. The depth-averaged longshore current is zero up to the bar crest, after which it increases to about 0.15 m/s near the shoreline due to oblique wave breaking. The maximum depth-averaged (below wave trough) cross-shore return current is about 0.05 m/s near the shoreline. The effect of particle size on bed profile evolution using the multi-fracttion method (N=4 fractions) instead of the single-fraction method (N=1) is shown in Figure 8. The initial median particle size is assumed to vary between d_{50}=0.14 mm at x= 200 m and 0.35 mm at x= 635 m for N= 4 fractions; the median sediment size is constant (d_{50}= 0.2 mm) for N= 1. The computed sand transport rates and bed profile evolutions for N= 1 and N= 4 fractions are shown in Figure 8. Using N=1 fraction instead of N=4 fractions, results in a significant decrease of the onshore migration distance of the bar after 6 months (Figure 8); thus the bar position is significantly affected taking selective transport processes into account. Using N=1 fraction instead of N=4 fractions, results in a significant increase of the suspended transport close to the shore (x>600 m); this is an initial effect which hardly influences the bed level close to the shore after 6 months.

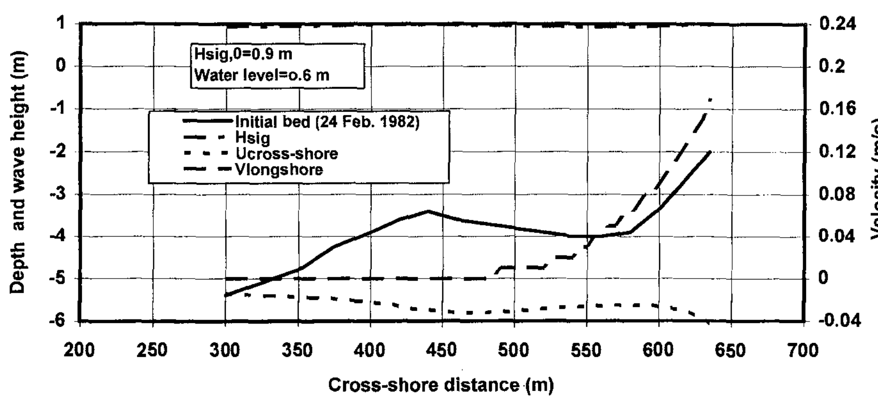


Figure 7. Computed significant wave height, cross-shore undertow velocity, and longshore velocity for calm event 24 Feb.-24 Aug. 1982, Duck, USA

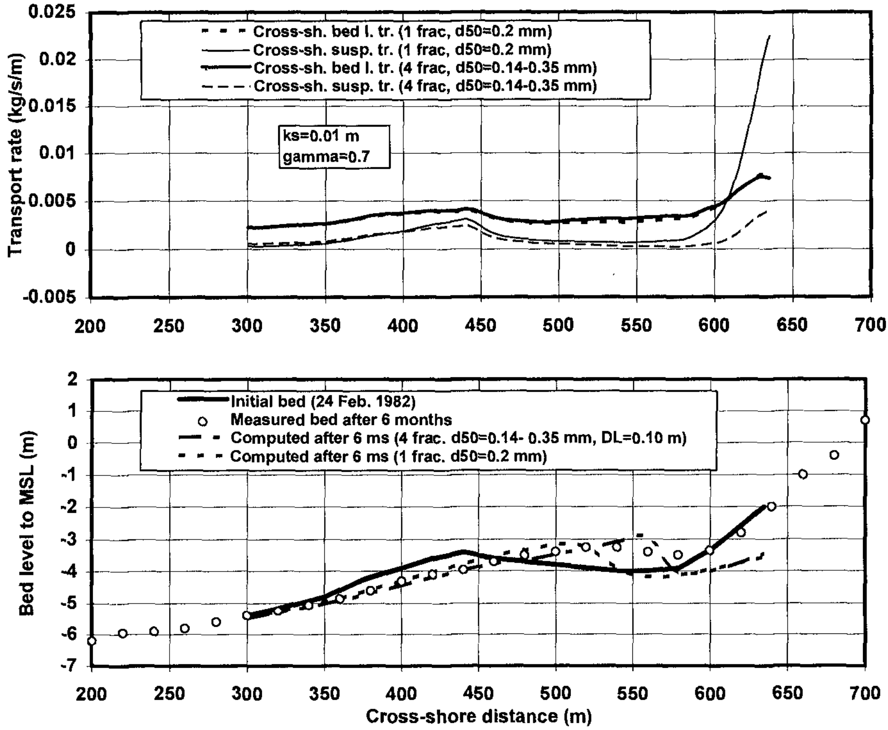


Figure 8. Effect of particle size distribution on computed sand transport distribution and bed profile evolution for calm event 24 Feb.-24 Aug. 1982, Duck beach, USA

Model results for sand-gravel beach

The model has been used to compute the cross-shore distribution of the longshore transport rate for a sand-gravel beach. The (hypothetical) beach profile consists of: slope of 1 to 20 between -10 and -3 m, slope of 1 to 10 between -3 and -2 m and slope of 1 to 5 landward of -2 m (Fig. 9). The model has been calibrated for gravel (taking sizes of 5 and 20 mm), using the available data of Chadwick (1989) and Nicholls and Wright (1991). The cross-shore distributions of significant wave height, wave-induced longshore current and sediment transport (bed load and suspended load) for sand-gravel in the range between 0.2 and 5 mm due to storm waves ($H_{s,0}$= 2.8 m) are given in Figure 9. The profile consists of uniform sand (d_{50}= 0.2 mm) seaward of x= 180 m, uniform gravel (d_{50}= 5 mm) landward of x= 190 m and a bimodal sand-gravel mixture between 180 and 190 m, see Figure 9. Results for a pure gravel beach (no sand) are also shown. Suspended sand transport is dominant, if the bed seaward of the -3 m line consists of fine sand (0.2 mm). The width of the active littoral zone is about 100 m for a sand-gravel beach and about 50 m for a pure gravel beach.

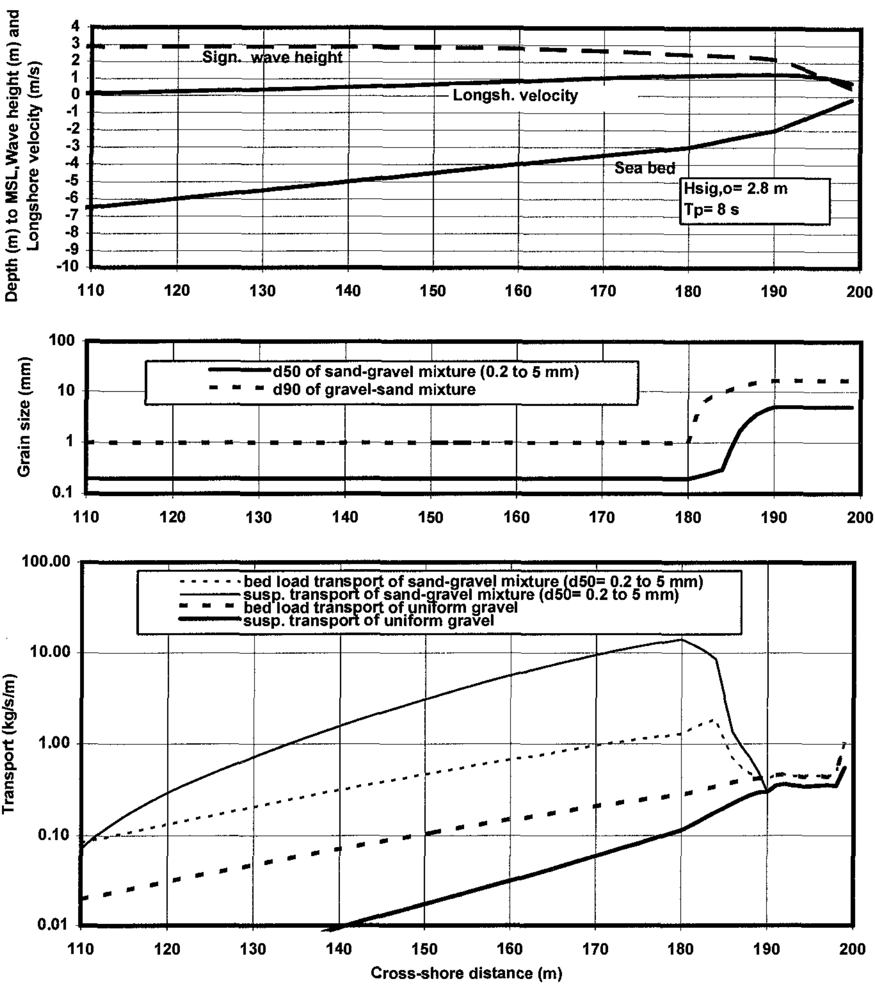


Figure 9. Cross-shore distribution of wave, current and transport parameters
$H_{s,0}$= 2.8 m, T_p= 8 s, wave angle= 30°
Top: Bed profile, wave height and longshore velocity
Middle: Grain size values (d_{50} and d_{90}) of sand-gravel mixture
Bottom: Longshore bed load and suspended load transport for uniform gravel (5 mm) and sand-gravel mixture (0.2-5 mm)

Results for a minor storm with $H_{s,0}$= 1.4 m are given in Fig. 10. The bed load transport is dominant in the gravel zone; the suspended load transport is dominant in the fine sand zone seaward of the -3 m line. The active sand zone has a width of about 30 m. The active gravel zone extends over about 10 m. Details are given by Van Rijn (1998).

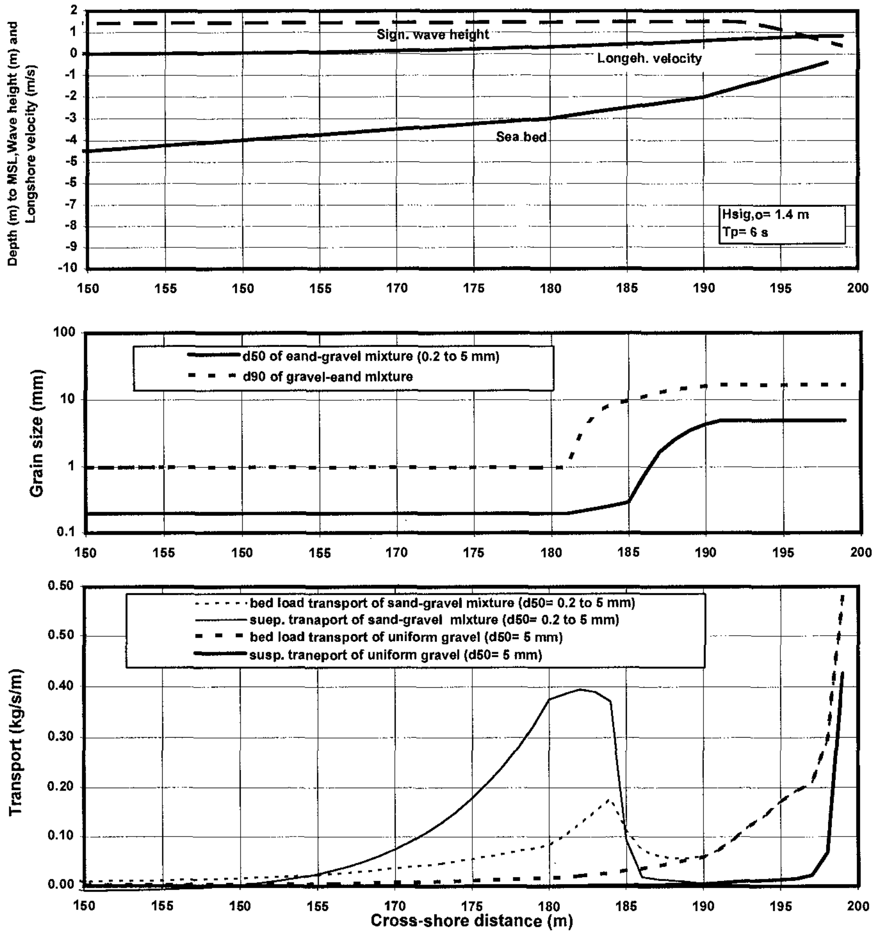


Figure 10. Cross-shore distribution of wave, current and transport parameters
$H_{s,0}$= 1.4 m, T_p= 6 s, wave angle= 30°
Top: Bed profile, wave height and longshore velocity
Middle: Grain size values (d_{50} and d_{90}) of sand-gravel mixture
Bottom: Longshore bed load and suspended load transport for uniform gravel (5 mm) and sand-gravel mixture (0.2-5 mm).

Model results for shoreface nourishment

The model was applied to a hypothetical case consisting of shoreface nourishment on a sloping cross-shore profile. The cross-shore profile is assumed to be plane, consisting of four sections: slope of 1:200 up to -6 m, slope of 1:70 between -6 and -3 m, slope of 1:50 between -3 and 0 m and slope of 1:30 on the beach (see Figure 11). The bed material consists of uniform sand with d_{50}= 0.3 mm. Two types of sand (d_{50}= 0.2 mm and d_{50}= 0.4 mm) are assumed to be available for shoreface nourishment.

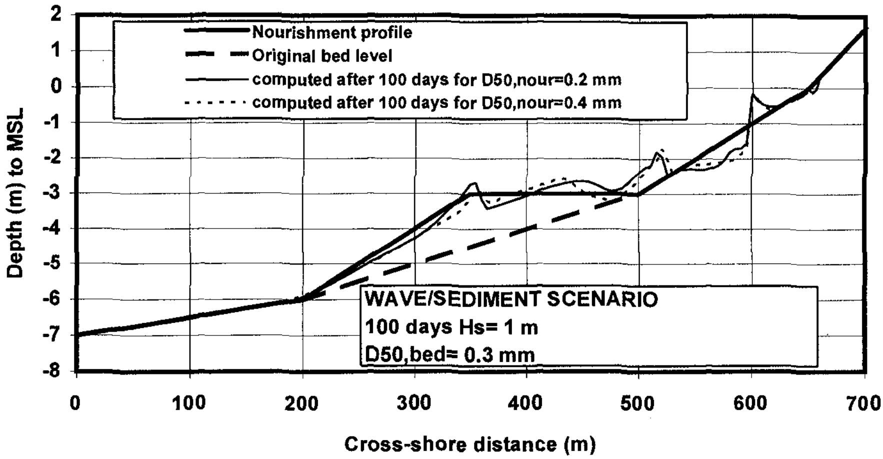
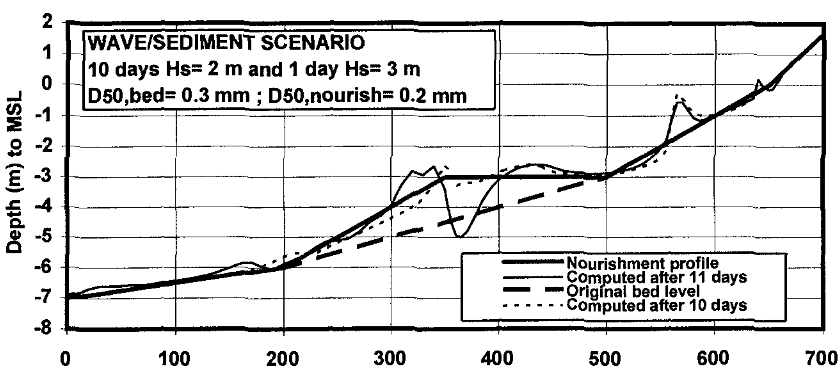


Figure 11. Effect of sediment size on shoreface nourishment for period of 100 days with low waves ($H_{s,0}$= 1 m)



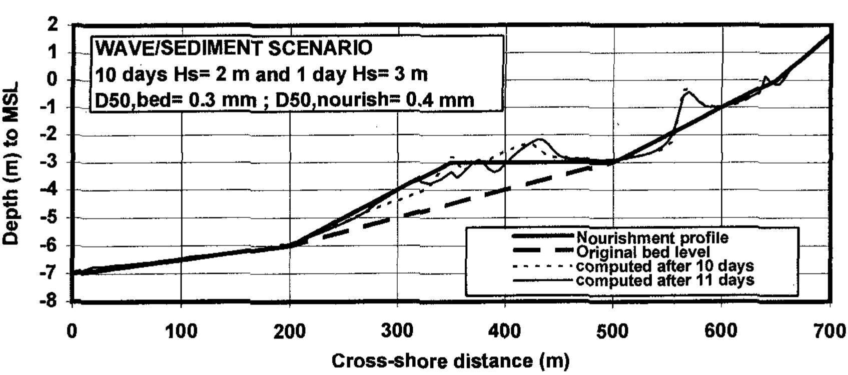


Figure 12. Effect of sediment size on shoreface nourishment for period of 11days with high waves ($H_{s,0}$= 2 and 3 m)

After nourishment the profile is assumed to be triangular with a slope of 1:50 over its seaward section of 150 m and a horizontal profile over its landward section of 150 m (see Figure 11). The water level is constant (no tide). Two wave scenarios are considered: calm period with H_s= 1 m during 100 days (T=7 s α= 30°); storm period with H_s= 2 m during 10 days (T=7 s, α= 30°) and H_s= 3 m during 1 day (T=7 s, α= 30°).
The computed evolutions of the nourishment profiles with 0.2 and 0.4 mm sediment for the calm period (100 days) are shown in Figure 11. The bed profiles after 100 days are almost similar, showing no clear effect of particle size for low waves.
The computed evolutions of the nourishment profiles with 0.2 and 0.4 mm sediment for the storm period (10 days with $H_{s,0}$= 2 m and 1 day with $H_{s,0}$= 3 m) are shown in Figure 12. The nourishment profile of 0.2 mm sediment is moulded into a relatively large sand bar with a deep trough during conditions with $H_{s,0}$= 3 m (1 day). Furthermore, minor offshore sand transport can be observed for the case with 0.2 mm sediment; about 5% of the nourishment volume is carried offshore after 11 days of storm waves. The nourishment profile of 0.4 mm sediment shows considerably less variability and no offshore transport. The profile development landward of the nourishment is not much affected by the sediment size on the short term time scale of storms.

Conclusions

The most sensitive model parameters are: undertow velocity, bed roughness, wave-related suspended transport (velocity asymmetry) and sand composition. The presence of graded sand leads to flatter and wider bars; uniform sand leads to more peaked bars. The wave-related suspended transport due to velocity asymmetry can not be neglected; it is essential for onshore bar migration/growth.
The modelling of selective transport depends on hiding factor and effect of particle size on bed and suspended load transport. The model results show that: (1) coarser sediment is carried shorewards as bed load during calm periods, (2) finer sediment is carried seawards as suspended load and is deposited in bar trough zones and in offshore zone during periods with storm waves and (3) coarser sediment is eroded from outer bar and is carried landwards as bed load to swash/beach zone during periods with storm waves.
Longshore suspended sand transport is dominant along sand-gravel beach under storm waves. The width of active littoral zone may be as large as 100 m for storm wave conditions.
Sand size between 0.2 and 0.4 mm has almost no effect on shoreface nourishment during periods with low waves (calm period). The use of fine sand of 0.2 mm for shoreface nourishment results in offshore loss (about 5% of nourishment volume) during storm conditions and more variability of the profile due to the generation of relatively large sand bars during storm waves.

References

Chadwick, A.J., 1989. *Field measurements and numerical model verification of coastal shingle transport, p. 381-402. BHRA, Fluid Engineering Centre, Bedford, England*
Houwman, K.T. and Ruessink, B.G., 1996. *Sediment transport in the vicinity of the shoreface nourishment of Terschelling. Dep. of Physical Geography. Univ. of Utrecht*

Mason, C. et al., 1984. *Duck82-a coastal storm processes experiment, p. 1913-1927, 19th ICCE, Houston, USA*

Nicholls, R.J. and Wright, P., 1991. *Longshore transport of pebbles: experimental estimates of K-factor, p. 920-933. Coastal Sediments, Seattle, USA*

Reniers, A.J. and Battjes, J.A., 1997. *Laboratory study of longshore currents over barred and non-barred beaches. Coastal Engineering, Vol. 30, p. 1-22*

Richmond, B.M. and Sallenger, A.H., 1984. *Cross-shore transport of bimodal sands. 19th ICCE, Houston, USA, p. 1997-2007.*

Van Rijn, L.C., 1993. *Principles of sediment transport in rivers, estuaries and coastal seas. Aqua Publications, Amsterdam, The Netherlands.*

Van Rijn, L.C., 1997a. *Cross-shore modelling of graded sediments. Delft Hydraulics, Report Z2174. Delft, The Netherlands*

Van Rijn, L.C., 1997b. *Sand transport and bed composition along cross-shore profile. Coastal Dynamics, Plymouth, England*

Van Rijn, L.C., 1998. *Principles of coastal morphology. Aqua Publications, Amsterdam, The Netherlands.*

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

Wolf, F.C.J., 1997. *Hydrodynamics, sediment transport and daily morphological development of a bar-beach system. Doc. Thesis, Dep. of Phys. Geography, Univ. of Utrecht, The Netherlands*