Grain size variations along cross-shore profile Katwijk of Holland coast

Leo C. van Rijn

Abstract

Cross-shore grain size variations have been observed along many coasts. Selective sediment transport and sorting processes, leading to grain size variations, occur when the cross-shore profile consists of graded sediment. Each grain size fraction within a mixture of sediment responds differently to the same hydrodynamic regime; the basic rule is that finer grains are winnowed from the bed in the most energetic areas by turbulent processes and are carried away to less energetic areas, resulting in coarsening of the bed in the more energetic areas. Terwindt (1962) studied cross-shore grain size variations for the location Katwijk along the Holland coast before and after a (minor) storm event. The field results are discussed and compared to computational results of a cross-shore mathematical model for graded sediments. The cross-shore model represents the hydrodynamics, the sand transport rates per size fraction and the bed evolution. The effect of a minor storm on the bed material composition (coarsening effect) along the barred cross-shore profile of Katwijk can be reasonably well simulated by the model.

1 Introduction

Analysis of cross-shore bed surface samples shows the presence of systematic grain size variations along cross-shore profiles of many coasts (see Van Rijn 1998 for overview of literature). Pioneering work on this subject was done by Terwindt in 1962, who studied the grain size distribution along a cross-shore profile near Katwijk, The Netherlands (meso-tidal conditions).

Basically, the cross-shore grain size distribution depends on the composition of various sediment sources (dunes, cliffs, deltas, shoreface) and the energy level of the wind and wave forces at work in a particular environment. Generally, the results of cross-shore grain size studies show that the mean grain size is greatest (coarsest) near the wave plunge point at the base of the beach face (slopes between 1 to 10 and 1 to 30); the mean grain size decreases up the foreshore beach as well as down the offshore bottom. A slight coarsening of the sediments has been observed over the bar crests in the surf zone where the waves break. The summer berms on the beach generally consist of somewhat coarser materials brought there by the relatively strong uprush of the swash motion, but the fines may also be winnowed by wind action.

Generally, a seaward-fining and -thinning blanket of sand extends from the outer breakpoint bar to the 15/20 m depth contours, where it thins over layers of sometimes coarser sand. The fines originate from the dune, beach and surf zone or from nearby deltas and are carried offshore by breaking-induced bottom currents, rip currents and wind-induced currents.

Coarsening effects have been observed at the lower shoreface, where the alongshore tidal and geostrophic currents increase in strength which may result in the winnowing (removal) of local relatively fine sediments. Coarse sediments in deeper water may also have a relict origin. These sediments may consist primarily of fluvial and beach/cliff materials laid down during periods of relative lowering of the sea level. Sometimes, there is a transition zone in cross-shore direction consisting of a laminated structure (thin layers of alternating fine and coarse sediment).

The basic objective of the present paper is the cross-shore modelling of graded sediments based on a process-based mathematical model (hydrodynamics, sand transport rates and morphology in a loop system). The model results will be compared to the grain size data of the Katwijk profile (Holland coast) measured by Terwindt (1962). The data set is described in Section 2. The model and model results are described in Section 3.

2 Data of Katwijk profile, The Netherlands

The results of Terwindt (1962) for the location Katwijk are based on the analysis of samples collected in a summer period under different hydraulic conditions (fair-weather and minor storm event). The maximum significant wave heights outside the surf zone were estimated to be about 2 to 3 m (lightship Texel) during summer storm conditions. The cross-shore grain size variations, presented in Figure 1, show the following features:

- relatively coarse material (median grainsize d_{50} of about 300 micron) in the shallow swash zone near the water line;
- systematic fining of sediment material in the seaward direction over the width of the surf zone; seaward of the outer breaker bar, the d_{50} has reduced to a value of about 140 micron during periods with calm weather;
- fining of sediment from the swash zone (300 micron) to the dune top (220 micron);
- the sediments in the outer surf zone are found to be somewhat coarser (10% to 20%) after a storm period; the fraction 105-150 micron was affected mostly; during calm periods the fraction 105-150 micron is

dominant (50% to 70%) in the bed material; after a storm period the contribution of the 105-150 fraction is reduced to about 20%; thus the finer material is washed out during conditions with higher waves and is most probably transported in suspension to deeper water where it is deposited; during calm weather fine material may be transported back to the surf zone as bed load.

The results of Terwindt (1962) are in good agreement with those of Stauble and Cialone (1996) for the bar zone at the Duck site (USA).

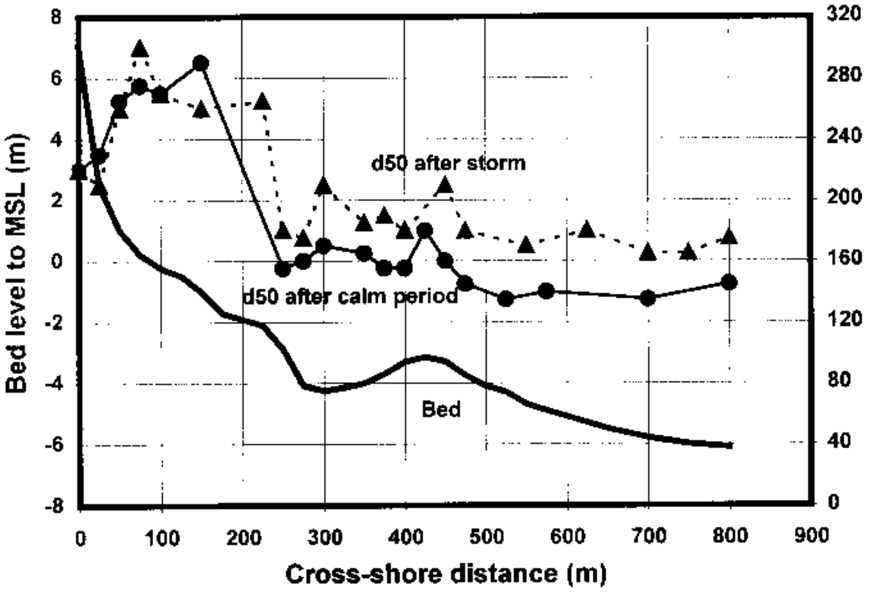


Figure 1 Cross-shore variation of sediment size along the Katwijk profile of Holland coast (after Terwindt, 1962), The Netherlands

3 Cross-shore modelling of graded sediments

Introduction

Cross-shore sorting of sediment mixtures was studied by Van Rijn (1997a,b) using a process-based model (CROSMOR) for computation of hydrodynamics (wave propagation and wave-induced currents), sand transport rates, bed composition and bed evolution. The model is based on a multi-wave and a multi-sediment fraction approach in the cross-shore direction. The sand transport method (Van Rijn, 1993) is implemented as a submodule in the cross-shore model. The bed composition is determined by using the one-layer concept introduced by Hirano (1971) for river flow.

Sorting processes

Cross-shore sorting is related to selective movement of sediment particles in a mixture near incipient motion at low bed-shear stresses and during generalised transport at higher shear stresses. A basic question is whether the initial movement of a particular size fraction within the total distribution of sizes is affected by the presence of the other size fractions, or in other words: is the initial movement of a particular fraction equal to that of uniform material of the same size as the fraction? Another question is the behaviour of the fractions, when all particles of the bed surface are fully mobilised.
Two effects are important:

- the degree of exposure of sediment particles of unequal size within a mixture (hiding of smaller particles resting or moving between the larger particles);
- the non-linear dependence of transport on particle diameter, for example: suspended load transport is inversely proportional to grain size; $q_s \approx d^m$ with m between -0.5 and -2; bed-load transport may increase with grain size in the fine particle range (between 0.1 and 0.5 mm) and decrease with grain size for coarse particles (> 0.5 mm).

Fenton and Abbott (1977) studied the effect of relative protrusion (p/d) on the initial movement of grains in the transitional and fully turbulent regime; p= protrusion of a particle above others and d= diameter. Test grains were placed on top of a rod between similar grains glued to the flume bottom. The rod was then screwed upwards, pushing the grain into the flow until it was swept away. This was repeated twenty times. Two types of grains were used: 2.5 mm diameter angular polystyrene grains and 5 to 10 mm well-rounded pea gravel. Relative protrusion was varied in the range between -0.2 and 0.8. A negative relative protrusion is a configuration with the top of the grain below that of the adjacent grains. The maximum relative protrusion of 0.8 is that of a grain sitting above one of the interstices formed by the other grains. The critical bed-shear stress for incipient motion (compared to that for zero protrusion p=0) was found to decrease for increasing positive relative protrusion and to increase for negative relative protrusion values. Comparing the data of Fenton and Abbott to the data of Shields, shows that the Shields curve represents conditions with relative protrusions in the range of 0.1 for larger particles to 0.3 for smaller particles.

For steady flow in gravel-bed rivers some researchers (Parker et al., 1982) have found that all sizes in a mixture begin moving at nearly the same bed-shear stress (equal mobility concept). Others (Komar, 1996) have shown that the bed-load material is becoming coarser for increasing bed-shear stresses to approach the composition of the bed material at high bed-shear stresses in the upper transport regime.

The critical bed-shear stress of individual fractions in a mixture is difficult to both define and measure. Different approaches to the problem have been presented.

Komar (1996) associates the critical condition for entrainment of gravel-type sediment with the maximum particle size (d_{max}) in the bed-load sample. Wilcock (1993) and others analysed measured transport rates of individual fractions for conditions just beyond initiation of motion. The fractional bed-load transport rates ($q_{b,i}$) are normalised to their availability (p_i) in the bed material and plotted as a function of the bed-shear stress ($q_{b,i}/p_i$ against τ_b). A small threshold transport (say 0.0001 kg/s/m) is generally introduced as a threshold criterion to find the threshold bed-shear stress for initiation of motion ($\tau_{b,cr,i}$) of each particular fraction. Petit (1994) studied the motion of marked individual gravel particles (d_{50} between 12 and 39 mm) in a flume. The bed-shear stresses were evaluated from measured near-bed velocity gradients, when initial movement of marked particles was observed to occur.

Figure 2 shows the critical bed-shear stress as a function of particle diameter based on the results of Wilcock (1993), Wilcock et al. (1988) and Petit (1994) for unimodal sediment mixtures. The Shields curve for uniform sediment is also shown.

Most of the data in Figure 2 are valid for relatively coarse sediment material (d>1 mm). The data sets show a slight increase of the critical bed-shear stress for the coarser fraction sizes within the mixture. The finest fractions (d_i<1 mm) of the Wilcock 1993 data set seem to have a somewhat higher critical shear stress. The data set of Wilcock et al. (1988) shows constant critical bed-shear stresses (horizontal line) for sand in the range of 0.5 to 1 mm. A horizontal line in Figure 2 implies equal mobility of all size fractions; all grain sizes of the mixture are set into motion at the same bed-shear stress. In that case the composition of the transported bed-load particles is the same as that of the original bed material under all conditions. Based on the data of Figure 2, the concept of equal mobility may be reasonably correct for gravel-type sediments between 2 and 10 mm. The curves cross the Shields curve (uniform sediment) at approximately the median diameter, except for the data set of Wilcock et al. (1988). As regards the data crossing the Shields curve, the larger sizes are set into motion at bed-shear stresses that are smaller than required for uniform

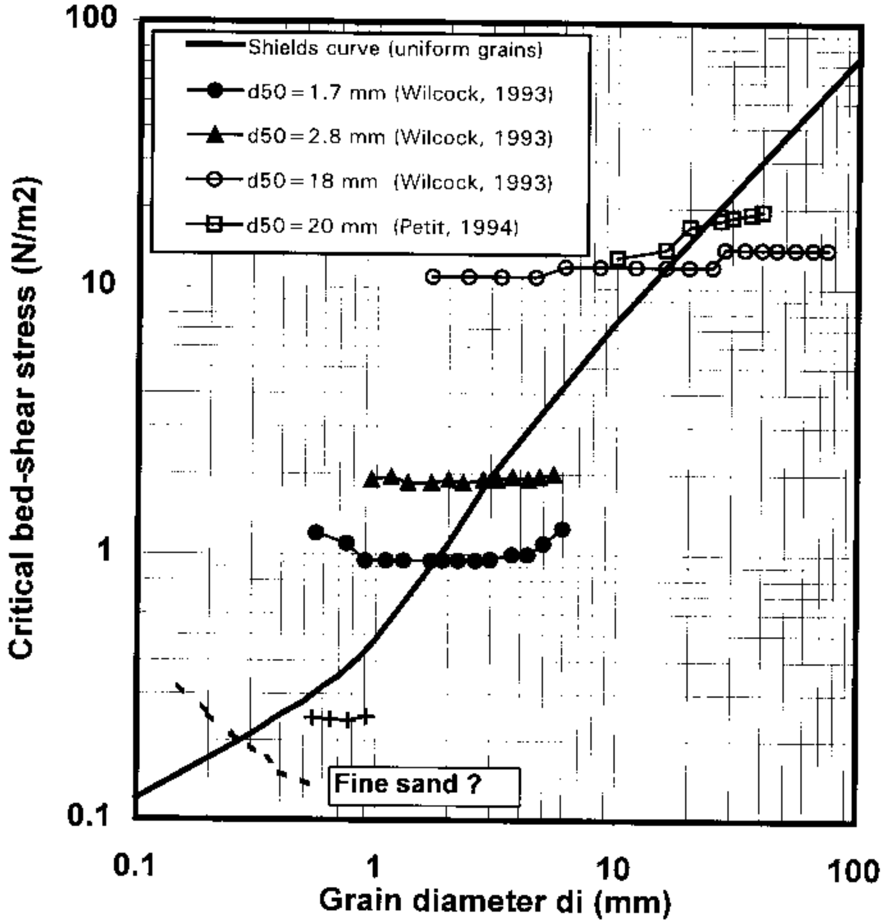


Figure 2 *Critical bed-shear stress of individual size fractions in a mixture as a function of grain diameter (modified after Wilcock, 1993)*

sizes, while the smaller size fractions require higher bed-shear stresses than for uniform material. The reason for this is that the largest sizes within a mixture are more exposed to the flow, while the smaller sizes tend to be sheltered from the flow by the larger particles. Thus, the larger particles in a mixture are substantially more mobile than in the uniform-bed case.

According to Komar (1996), the selective mobility pattern in finer materials (sand) is opposite to that found in coarser materials (gravel). In sandy bed material the entrainment of the finest fractions may be caused by relatively large bed-shear stresses (curve sloping downward to the right, see Figure 2). Thus, in the sand-size range the larger grains may be selectively removed, leaving behind the finer grains. The data set (MIT-funi, d_{50}=0.67 mm) of Wilcock et al. (1988), see Figure 2, does not confirm with the findings of Komar. More experimental data in the fine sand range are needed to determine the critical bed-shear stress of mixtures of sand.

The available data of Figure 2 can be used to derive the exposure or hiding factor for particles in a mixture, as follows:

$$\zeta_i = \frac{\tau_{b,cr,i}}{\tau_{b,cr,i,shields}} = F(d_i / d_{50}) \tag{1}$$

in which:

$\tau_{b,cr,i}$ = critical bed-shear stress of fraction d_i within a mixture

$\tau_{b,cr,i,shields}$ = critical bed-shear stress of fraction d_i based on Shields curve

F = function of.

The computed values of the exposure or hiding factor are shown in Figure 3. The hiding factor or exposure factor of Egiazaroff (1965), defined as a multiplication factor to the critical shear stress, is given by (see Figure 3):

$$\zeta_i = \left[\frac{\log(19)}{\log(19 d_i / d_{50})}\right]^2 \tag{2}$$

in which

d_i = mean particle diameter of size class i

d_{50} = median diameter of bed material mixture

According to Komar (1996), the initiation of motion of a grain by the flowing fluid is related to the pivoting angle of the grain about its contact point with an underlying grain, see Figure 3. Experiments have been performed to determine how the pivoting angle depends on grain shape, grain size, grain orientation and imbrication.

An exposure factor can also be derived from the work of Komar (1996), yielding

$$\varsigma_i = \frac{\tan\left[\theta_o (d_i / d_{50})^{-0.3}\right]}{\tan\theta_o} \tag{3}$$

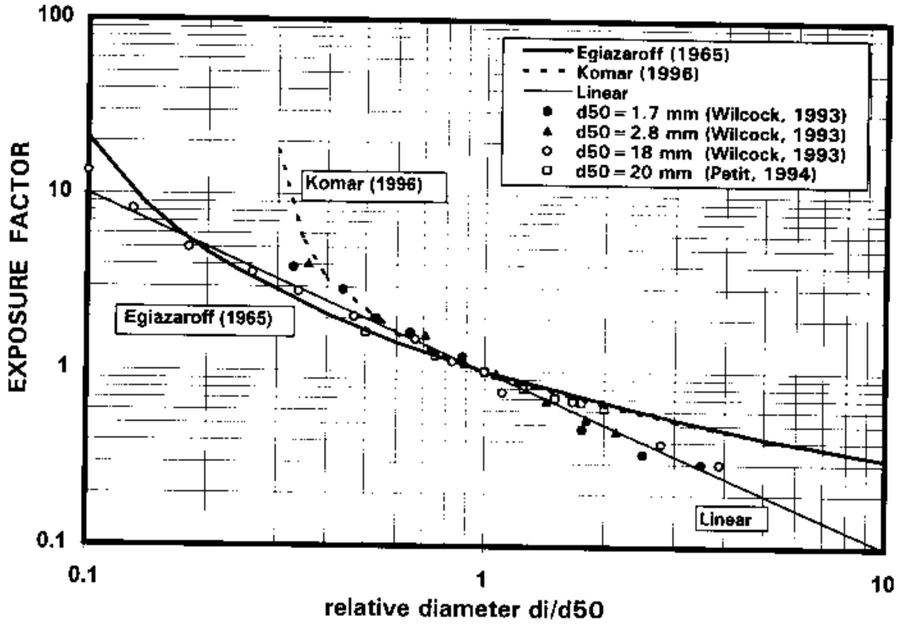
in which:

d_i = mean particle diameter of size class i

d_{50} = median diameter of bed material mixture

θ_o = 61.5° = angle of repose (or pivoting angle = angle between vertical line and a line through the contact points of grains, see Figure 3) for uniform grains; the ζ_i-factor goes to infinity for d_i/d_{50} approaching about 0.283.

Equation (3) is shown in Figure 3. For $d_i/d_{50}<1$, the angle of repose increases resulting in an increase of the hiding factor.



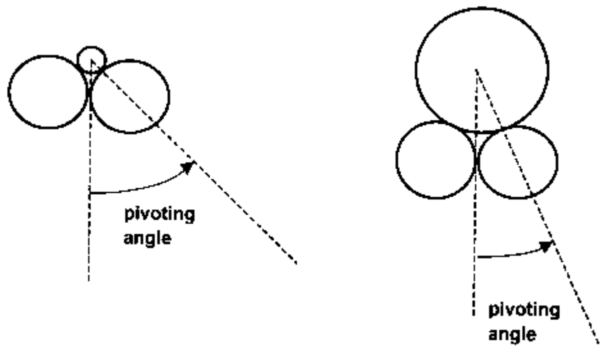


Figure 3 *Hiding factor according to Egiazaroff (1965), Komar (1996) and measured data*

Top: *Hiding factors*

Bottom: *Pivoting angles*

The hiding factor of Egiazaroff yields considerably smaller values than that of Komar for $d_i/d_{50}<1$, but both factors yield almost the same results for $d_i/d_{50}>1$. The data in Figure 3 can also be represented by a linear expression, namely $\zeta_i= (d_i/d_{50})^{-1}$.
The approaches of Egiazaroff and Komar do not account for vortex-induced pick-up of smaller grains hiding between larger grains.
The total sand transport rate for all size fractions of a mixture can be obtained by summation of the transport rates per fraction taking the probability of occurrence of each size fraction into account. This method is herein referred to as the Multi-Fraction method (MF method). The term Single Fraction method (SF method) will be used for a representation based on one single representative sediment diameter, namely d_{50}.
The influence of the particle diameter on the transport rate when suspended load is dominant, can be evaluated by using a simple transport formula of the type $q_s \approx v^3/d^2$ (transport decreases with increasing diameter), neglecting the effect of initiation of motion (v = velocity, d = diameter). In case of a symmetrical size distribution (N = 7 fractions) the MF transport can be expressed in terms of the SF transport, giving: $q_{s,N=7}>q_{s,N=1}$. Furthermore, the wider the size distribution, the larger is the effect. When the transport rate is proportional to d^2 in stead of d^{-2}, a similar result is obtained. Thus, the transport rates are the same, but in the former case ($q_s \approx d^{-2}$) the finer particles are dominant in the transport process, whereas in the latter case ($q_s \approx d^2$) the coarser particles are dominant.
Comparative computations (Van Rijn, 1997a,b) using both the SF and MF-methods for sand of 0.2, 0.4 and 0.8 mm (symmetrical size distribution) showed that the bed-load transport rates based on the MF-method are slightly to significantly larger (depending on conditions) than those of the SF-method. The suspended load transport rates based on the MF-method are significantly smaller than those of the SF-method at small current velocities. The hiding factor acting as a multiplier to the critical bed-shear stress has a substantial effect on the transport rate. For asymmetric size distributions the transport rate based on the MF-fraction method (without hiding effect) may become smaller or larger than that based on the SF-method depending on size asymmetry (more fine or more coarse material) and on the transport-diameter relationship.
The influence of the exposure or hiding factor is a reduction of the transport rate in the case of dominant suspended load transport because the critical bed-shear stress of the finer particles (hiding between the coarser particles) is enlarged.

Description of model (CROSMOR)

The propagation and transformation of individual waves (wave by wave approach) is described by a probabilistic model (Van Rijn and Wijnberg, 1994, 1996). 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 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 orbital peak velocity and generally onshore-directed in deeper water (symmetric waves). In shoaling waves in shallow water, the streaming in the boundary layer may be offshore-directed.

The sand transport rate for each wave (or wave class) is derived from 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 the 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 net current-related and the wave-related transport components (see, 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). This latter transport component involves a calibration coefficient (γ) in the range between 0.35 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. 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. Details are given by Van Rijn (1993).

The Single- and Multi-Fraction methods are both implemented to compute the sand transport rates. The Single Fraction method is based on one representative particle size, which is taken as the median particle diameter (d_{50}).

The Multi-Fraction method is based on a bed material schematisation into size fractions. The sand transport rate is computed for each size fraction using an existing Single Fraction method (replacing the median diameter of the bed material by the mean diameter of each fraction) with a correction factor (ζ_i) to account for the non-uniformity effects. Herein, the correction (hiding) factor of Egiazaroff (1965) is used. 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.
The influence of the hiding factor is a reduction of the transport rate in the case of dominant suspended load transport because the critical bed-shear stress of the finer particles (hiding between the coarser particles) is enlarged.
The Multi-Fraction method, as used in the CROSMOR-model, results in a transport rate larger or smaller than that based on the Single-Fraction method, depending on the hydrodynamic regime and bed material size.

Bed level changes per fraction i are described by

$$\frac{\rho_s(1-e)\Delta z_{b,i}}{\Delta t} + \frac{\Delta(p_i q_{t,i})}{\Delta x} = 0 \qquad (4)$$

in which:

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 the fractional bed level changes over all N-fractions: $\Delta z_{b,x,t} = \sum \Delta z_{b,i,x,t}$.
The bed material composition is computed in a thin (order of 0.1 m) surface mixing layer applying a one-layer approach. This approach was introduced by Hirano (1971) and later extended by Ribberink (1987). The thickness of the

surface layer is herein 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 of the bed. The mixing of sediment within the surface layer is assumed to be effectuated within each time step (instantaneous mixing) by small-scale bed form migration processes in the lower regime or by wave-induced vortices in the sheet flow regime.

At present stage of research 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 ($p_{0,i,x}$).

The bed material composition is computed according to the following procedure:

- the sediment mass M of the surface layer at t= 0 is subdivided in masses $M_{x,i}$ based on the initial fraction values $p_{o,x,i}$, as follows: $M_{x,i}= p_{o,x,i}\, M$;
- the sediment mass $M_{x,i}$ of fraction i changes due to sediment deposition or erosion at the surface of the bed; in case of deposition the mixing layer will move upward at a rate equal to the deposition rate, while an equal amount of sediment with the composition of the mixing layer will be lost at the bottom (exchange at base) of the mixing layer; in case of erosion the opposite process will take place and the mixing layer will move downward eroding itself into the subsoil, hence sediment with the composition of the subsoil will be absorbed by the mixing layer;
- the new composition of the bed material of the mixing layer is given by: $p_{x,i,t+\Delta t} = M_{x,i,t+\text{-}\Delta t}/M$.

Hereafter, computational results for the Katwijk profile are given.

Model results for Katwijk profile, storm event 1962

The basic input data are: $H_{s,0}$= 3 m (3 wave classes), deep-water wave incidence angle (= 20°), longshore tidal velocity v_0 = 0.6 and -0.5 m/s, tide levels h= 0.8 and -0.8 m, wave peak period T_p = 8 s, bottom friction $k_{s,w}$ = 0.05 m, oscillating suspended transport γ= 0.35, Multi-Fraction method (N=5), d_{50}= 0.14 to 0.28 mm (d_i = 0.1; 0.15; 0.2; 0.3; 0.5 mm).

Computed results after 1 day for a variable hiding factor and for h.f.=1 are given in Figure 4. The initial particle size is represented by a variation between d_{50}= 0.14 and 0.28 mm (see Figure 4). At this stage only the observed trend before the storm event is modelled; the fluctuations around the trend are not taken into account.

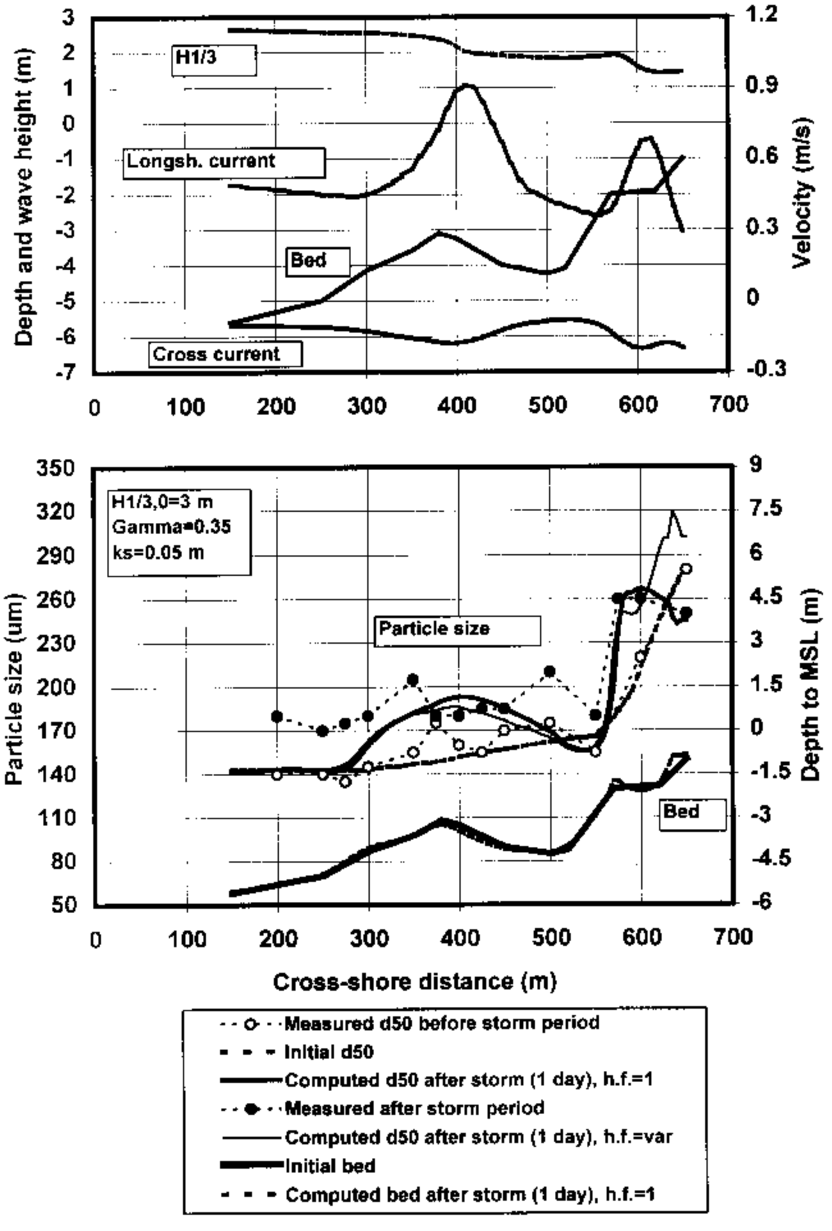


Figure 4 *Effect of storm event on cross-shore sand composition, Katwijk site, The Netherlands*

Top: *Wave heights and currents*

Bottom: *Particle size and bed profile*

The results for Katwijk profile can be summarised as:

- during a storm event the computed suspended transport is dominant and offshore-directed in the nearshore zone, where the longshore current is relatively large; the finer particles are eroded and carried seaward in larger quantities than the coarser particles resulting in coarsening of the bed surface in the shallow water zone between x= 560 m and 620 m; landward of x= 620 m the bed material is fining slightly for h.f.=1; the observed d_{50}-values are amazingly well simulated for h.f=1;
- the bed-load transport is dominant and onshore-directed in a narrow zone (bar trough zone) between 520 and 560 m, where the longshore current is relatively small; the coarser particles are eroded and carried landward in relatively large quantities leading to a slight fining of the bed material;
- seaward of x= 500 m the offshore-directed suspended transport is dominant and finer sediments are more easily transported resulting in coarsening of the bed surface in reasonably good agreement with the observed data both for h.f= variable and h.f.=1; the coarsening effects seaward of x=300 m are not predicted;
- similar results were obtained for an offshore wave height of H_s= 2.2 m; coarsening effects up to x= 325 m were predicted by the model.

4 Conclusions

Sorting processes occur when the cross-shore profile consists of graded sediments. Each grain size fraction within a mixture will respond differently to the same hydrodynamic regime; the basic rule is that finer grains are winnowed from the bed in the most energetic areas by turbulent processes and are carried away to less energetic areas, resulting in coarsening of the bed in the more energetic areas.

The following conclusions are given:

- the bed-load transport increases with increasing particle diameter for sediments between approximately 0.1 and 0.6 mm and decreases with particle diameter for sediments larger than 0.6 mm; the suspended transport decreases with particle diameter;
- during low wave-energy conditions the median particle size d_{50} decreases in erosion zones of the cross-shore profile, because the coarser particles are transported at relatively large rates; similarly the d_{50} increases in deposition zones; the hiding factor has a substantial effect on the bed evolution of graded sediments;

- during high wave-energy conditions the median particle size increases (coarsening effect) in the shallow surf zone with breaking waves because the finer sediments (suspension is dominant) are carried seaward;
- the effect of a minor storm on the bed material composition (coarsening effect) along a barred cross-shore profile can be reasonably well simulated (Katwijk profile).

References

Egiazaroff, I.V., 1965. Calculation of non-uniform sediment concentrations, Journal of the Hydraulics Division, ASCE, Vol. 91, HY 4.

Fenton, J.D. and J.E. Abbott, 1977. Initial movement of grains on a stream bed: the effect of relative protrusion. Proc. R. Soc. London, A. 352, 523-537.

Hirano, M., 1971. River bed degradation with armouring. Trans. JSCE, 3, part 2

Komar, P.D., 1996. Entrainment of sediments from deposits of mixed grain sizes and densities. Advances in fluvial dynamics and stratigraphy edited by P.A. Carling and M.R. Dawson, Wiley and sons, New York.

Parker, G. et al., 1982. Bed load and size distribution in paved gravel-bed streams. Journal of Hydraulics Division, ASCE New York, 108, 544-571.

Petit, F., 1994. Dimensionless critical shear stress evaluation from flume experiments using different gravel beds. Earth Surface Processes and Landforms, 19, 565-576.

Ribberink, J.S., 1987. Mathematical modelling of one-dimensional morphological changes in rivers with non-uniform sediment. Dissertation, Civil Eng. Dep., Delft Univ. of Technology, Delft, The Netherlands.

Stauble, D.K. and M.A. Cialone, 1996. Sediment dynamics and profile interactions: Duck94. Proc of 25th Int. Conf. on Coastal Eng., ASCE New York, 3921-3934.

Terwindt, J.H.J., 1962. Study of grain size variations at the coast of Katwijk (in Dutch), The Netherlands, Note K-324, Rijkswaterstaat, The Hague, The Netherlands.

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. Proc. Coastal Dynamics'97, ASCE New York, 88-98.

Van Rijn, L.C., 1998. Principles of Coastal Morphology. Aqua Publications. Amsterdam, The Netherlands.

Van Rijn, L.C. and K.M. Wijnberg, 1994. One dimensional modelling of individual waves and wave-induced longshore currents in the surf zone. Report R94-09, Dep. of Physiscal Geography, Utrecht University, The Netherlands.

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

Wilcock, P.R., 1993. Critical shear stress of natural sediments. Journal of Hydraulic Engineering, 119, 4, 491-505.

Wilcock, P.R. et al., 1988. Experimental study of incipient motion in mixed-size sediment.Water Resources Research, 24, 1137-1151.