MORPHOLOGICAL MODELLING OF ARTIFICIAL SAND RIDGE NEAR HOEK VAN HOLLAND, THE NETHERLANDS

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Abstract: The study is focussed on the morphological modelling (based on DELFT3D model) of an artificial sand rige at the Dutch shoreface near Hoek van Holland close to the harbour of Rotterdam. The ridge is perpendicular to the coast and to the tidal flow. The sediment size is about 0.3 mm. The tidal range is about 2 m. The peak flood velocities (to north) and ebb velocities (to south) are about 0.6 and 0.55 m/s. Using a 1DH (depth-averaged) model approach, the growth and migration of a sand ridge can not be simulated properly as the modification of the velocity profiles can not be represented. This latter effect can only be simulated by using a 2DV (two-dimensional vertical) or a 3D model approach. Growth of the sand ridge can occur when bed-load transport is dominant. Decay (flattening) of the ridge occurs when suspended load transport is dominant, particularly when waves are important.

INTRODUCTION

From 1982 to 1986 dumpings of sand at the shoreface near Hoek van Holland (close to entrance of harbour of Rotterdam) created an artificial sand ridge, known as sand ridge Hoek van Holland, with a length of about 3600 m normal to the peak tidal current and the shore (location Hoek van Holland, see Figure 1A) in an area with depths between 15 m and 23 m on the northern side of the approach channel to harbour of Rotterdam. In all, 3.5 million m^3 sand was dumped over the period 1981 to 1986 (Van Woudenberg, 1996). The ridge dimensions just after creation of the ridge were: length of about 3600 m; toe width between 250 m and 370 m; height between 1.3 and 4 m; slopes between 1:50 and 1:100 on the south flank and between 1:20 and 1:50 on the north flank; d_{50} between 0.15 mm and 0.45 mm. The landward end of the ridge is about 6300 m from the shoreline. The sand ridge Hoek van Holland is located close to Loswal Noord, which is a dumping site for mud from the Rotterdam harbour basins. The ridge is perpendicular to the coast and to the tidal flow. Primary goals were to study the stability of this submerged ridge, normal to the tidal flow and to study the effect of the ridge on the sand transport at the shoreface.

Figure 1B shows a schematic plan view of the sounding area and sections; the sections are 400 m apart. The width of the sounding area is about 2100 m. Section 1 is about 6 km from the coast. In this study the attention is focussed on the modelling of Section 3 using the DELFT3D model in line and in area mode (1DH, 2DV, 2DH and 3D). Details of the modelling of other sections are given by Tonnon (2005).

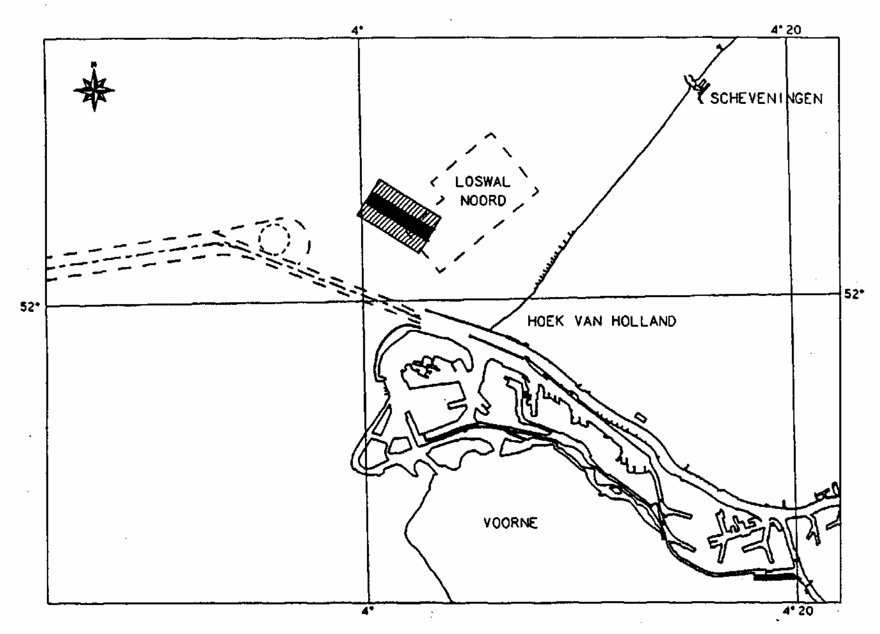

Figure 1A. Location sand ridge Hoek van Holland.

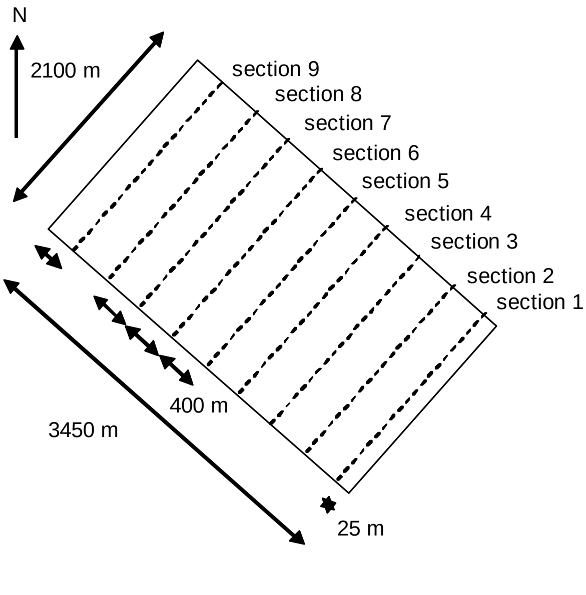

Figure 1B. Schematic plan view of the sounding area and sections

ANALYSIS OF BATHYMETRY DATA

Since 1982 yearly bathymetric surveys were carried out by Directorate North Sea (DNZ) of Rijkswaterstaat. Soundings before 1991 were not available on tape and were digitized from maps or microfilm, and thus are less reliable. Data collection before 1991 was carried out with the less-accurate single beam method, while data collection after 1991 was carried out with the more accurate multi-beam method. Soundings were carried out based on fixed tide gauges at Hoek van Holland; using this data an amplitude correction was carried out.

Two datasets were obtained, the first spanning the period 1982 to 1997, the second covering the period 1991 to 2000. Comparison of the two datasets shows that the second dataset (1991 to 2000) is somewhat out of line with the first (1982 to 1997), as the z-values are about 0.1 to 0.15 m lower.

The morphological development of the ridge is shown (1982, 1991, 1995 and 2000) for cross-sections 3 and 4, see Figure 2.

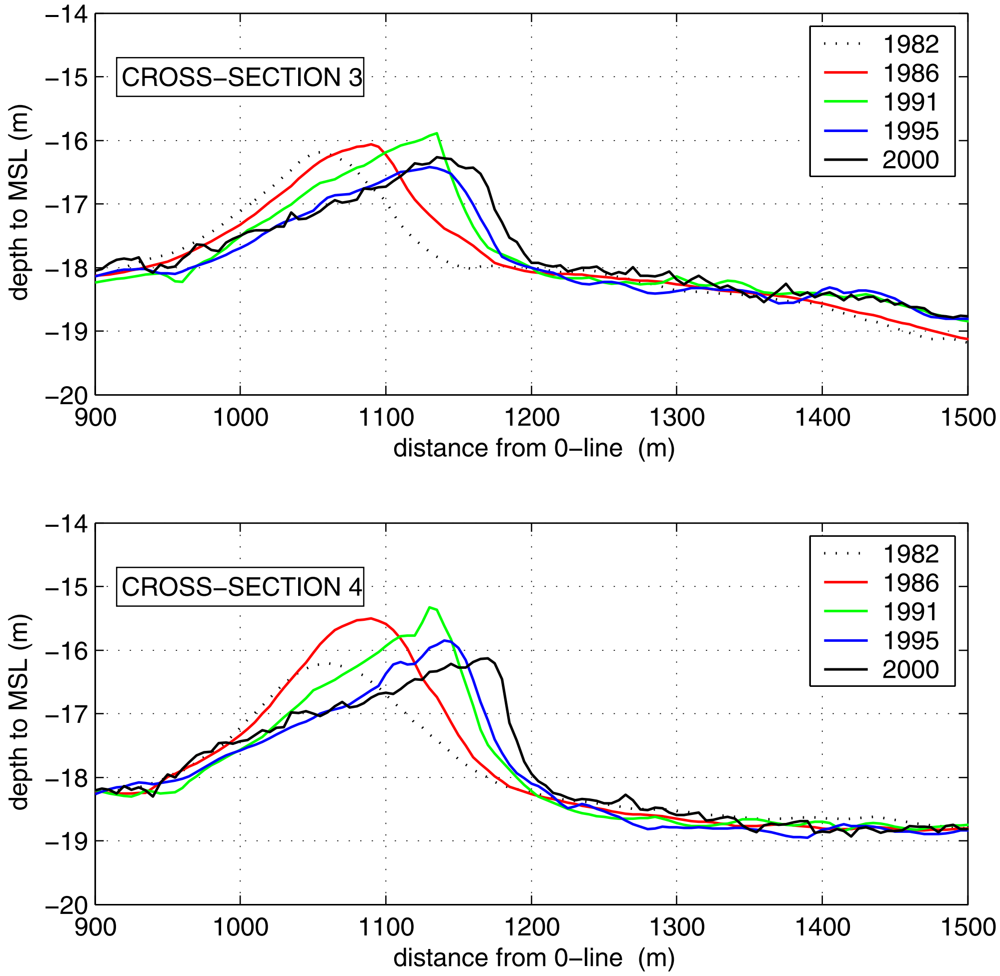

Figure 2. Measured bed level developments for Sections 3 and 4.

Analysis of the soundings between 1982 and 2000 shows a clear reduction of the ridge height in time and a net migration of the ridge in flood direction to the north. The rate of migration reduces with increasing depth. The average migration of crest of the ridge in northern direction is about 5.50 m per year and the average decrease in height is about 0.1 m per year. Between 1992 and 1993 a southward migration of the ridge and increase in height were observed. From sedimentation and erosion volumes it was found that overall, between 1982 and 2000, more sediment was eroded at the southern side of the ridge than accreted at the northern side of the ridge; hence, sediment was lost from the study area. However, between 1986 and 1999 a net gain of sediment was observed in the study area. Between 1991 and 2000 sediment was lost from the study area. Sedimentation/erosion plots show annually changing patterns per year with, on average, erosion taking place at the top of the ridge and sedimentation directly north of the ridge.

MODELS USED

The DELFT3D modelling system developed by WL | Delft Hydraulics has been used to simulate the morphological processes. It can simulate flows, waves, sediment transport and morphological developments. The modelling system consists of several modules. Herein, a short description is given of FLOW and WAVE. Using the DELFT3D-WAVE module, the evolution of wind-generated waves can be simulated. The WAVE module is either based on HISWA or SWAN; SWAN, an acronym for Simulating Waves Nearshore, is a third generation, spectral wave model that computes the non-steady propagation of short crested waves over an uneven bottom, considering wind action, dissipation due to bottom friction, wave-breaking, refraction, shoaling and directional spreading. The SWAN model takes into account the following physics: wave propagation in time and space, shoaling due to current and depth, refraction and frequency shifting; wave generation by wind; dissipation by white-capping, depth-induced breaking and bottom friction; non-linear wave-wave interactions; wave-induced set-up; wave-blocking by flow. The wave conditions (i.e. wave forces based on the energy dissipation rate or the radiation stresses, orbital velocities) calculated in DELFT3D-WAVE module are used as input for the DELFT3D-FLOW module, to compute wave-driven currents, enhanced turbulence, bed-shear stress and stirring up by wave breaking. Herein, SWAN has not been used, but a constant wave height in the computational domain has been used.

The FLOW-module is a hydrodynamic simulation program, which calculates non-steady flow and transport phenomena resulting from tidal and/or meteorological forcing on a curvilinear, boundary fitted grid. The numerical system of the program solves the unsteady shallow water equations in two or three dimensions. Typical applications of DELFT3D-FLOW includes simulations of tide and wind driven flows, stratified and density driven flows, river flow, transport of dissolved material and pollutants.

The shallow water equations are based on the three-dimensional Navier-Stokes equations for incompressible free surface flow, under the assumption of shallow water and Bousinesq. In the vertical momentum equation the vertical accelerations are neglected, which lead to the hydrostatic pressure equation. The system of partial differential equations for conservation of mass and momentum is solved with a finite difference method on the model grids.

The sediment-online module is an add-on with the DELFT3D-FLOW module which concerns simultaneous computation of flows and transports and simultaneous feedback to bottom changes. This module was recently updated based on the TR2004 sand transport formulations (Van Rijn et al. 2004). The most important improvements involve a bed-roughness predictor for the previously user-specified current-related and wave-related bed roughness parameters and a refined predictor for the suspended sediment size. The reference concentration of the suspended sediment concentration profile was recalibrated. The hydronamic flow calculations are always carried out using the correct bathymetry. Morphodynamic developments take place on a time scale several times longer than typical flow changes, leading to long simulation times in case of morphological predictions. To shorten the simulation time, a morphological time scale factor can be used, whereby the speed of the changes in the morphology is scaled up to a rate where it begins to have a significant impact on the hydrodynamic flows.
DELFT3D uses a sigma-coordinate system for the vertical grid, whereby the vertical grid consists of layers bounded by two sigma planes, which are not strictly horizontal but follow the bottom topography and the free surface. As a result a smooth representation of the topography is obtained. For a sigma coordinate grid the number of layers is constant over the entire horizontal computational area, irrespective of the water depth. The distribution of the relative layer thickness is usually non-uniform. This allows for more resolution in the zones of interest such as the near surface area (important for e.g. wind-driven flows) and the near bed area (sediment transport). Due to the use of a sigma coordinate grid, only the number of layers and relative thickness of each layer has to be specified. Herein, a vertical grid of 20 computational layers with a logarithmic layer distribution and a relative bottom layer thickness of 2% of the water depth is used.

MODEL RUNS FOR IDEALIZED RIDGE SCHEMATIZATION

The idealized sand ridge consists of a symmetric ridge (sediment size of d_{50}=0.3 mm; d_{90}=0.6 mm) at a depth comparable to the actual sand ridge near Hoek van Holland. A symmetric Gaussian-shaped sand ridge was created for the simulations, which roughly resembles the ridge characteristics at Sections 3 and 4 in 1991 (Fig. 2), i.e. a mean depth outside the ridge of about -17.8 m to MSL, a ridge height of about 3 m and a ridge width of about 400 m. The formula which was used to create the Gaussian shape reads:

$$z_b = H \cdot \exp(-x^2 / L^2) \quad (1)$$

with L being the e-folding distance in x-direction over which the height decreases with a factor 1/e, and H being the height of the ridge. Here, L is taken as 100 m and H is taken as 3 m, the top of the ridge is located at 1150 m from the first boundary. The tidal flow is represented by a sinusoidal function ($U=U_0+U_1\cos(\omega t)$; $h=h_0+\zeta\cos(\omega t)$) with and without a net current (drift U_0), thus representing a propagating tidal wave as in the Dutch coastal zone. Phase differences between horizontal and vertical tides are not taken into account. These simulations were carried out to gain insight in the physical processes at the sand ridge and to study the effect of tides, waves and basic model settings on the

morphological development (over 5 years) of an idealized sand ridge. To reduce the computational time, the numerical simulations are run over a much shorter period of 273 hours; the morphological changes are speed up to that of the 5 year period using a morphological scale factor. The simulation period of 273 hours includes a spin-up period of 33 hours to allow the model to adapt itself to the boundary conditions. During the spin-up period no bed level updating takes place; the effective simulation time is therefore 240 hours, in this period 20 complete tidal cycles of 12 hours are simulated. The physical parameters used are: Coriolis acceleration set up for 52 °N; acceleration of gravity set to 9.81 m/s^2; air density set to 1.000 kg/m^3; water density set to 1025 kg/m^3; salinity set to 31 ppt and water temperature set to 15 °C.
A spationally constant wave height was used. The effects of four different wave conditions were studied: H_s = 1.50 m, T_p=5.0 s, direction 315 °N; H_s = 2.0 m, T_p=5.5 s, direction 315 °N; H_s = 2.5 m, T_p=5.7 s, direction 315 °N and H_s = 3.0 m, T_p=6.0 s, direction 315 °N.

Basic processes
In unidirectional flow over a sand ridge the velocity profiles at both sides of the top of the ridge have a different shape; the velocity profiles upstream of the top of the ridge are characterized by increased velocities in the near-bed zone (bulgy shape due to decreasing water depth), while downstream of the top the velocity profiles are characterized by a dip (reduced velocities in the near-bed zone due to increasing water depth and deceleration processes), see Figure 3.

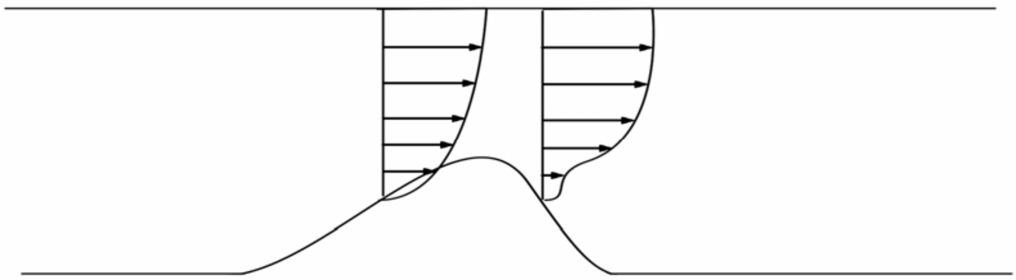

Figure 3. Velocity profiles over sand ridge

With tidal flow, the direction of the flow changes with the turning of the tide which has its consequences on the time-averaged velocity profiles at both sides of the ridge. At maximum flood and at maximum ebb, the velocity profiles show increased velocities at the upstream flank and show reduced near-bed velocities at the downstream flank. As the flow during flood and ebb is in opposite direction, the upstream and downstream locations are at opposite sides of the top; the bulgy velocity profiles change to dipped velocity profiles when the flow reverses. The time-averaged velocity profiles at both flanks show near-bed velocities as given in Figure 4 for the north flank and opposite for the south flank of the ridge. The time-averaged near-bed velocities on both flanks are in the direction of the top of the ridge.

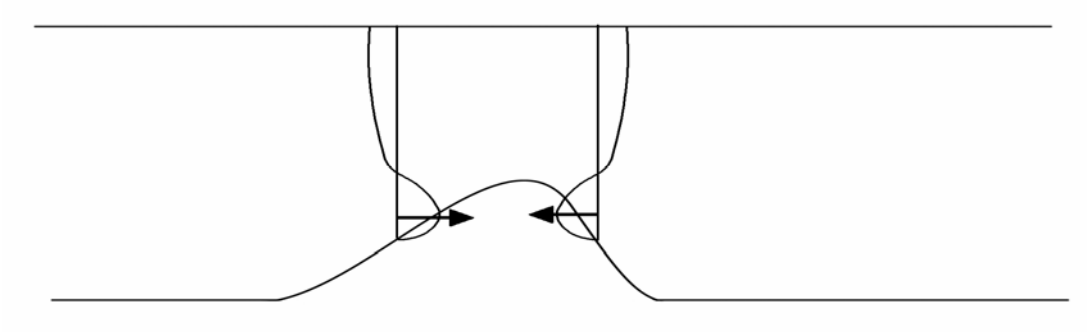

Figure 4. Time-averaged velocity profiles at flanks of the ridge

This mechanism results in vertical growth of the ridge when bed-load transport is dominant (particles remain in top region of the ridge). When suspended-load transport is dominant the particles may be transported beyond the top region resulting in flattening of the ridge. The tidal range with shallower water depths during ebb also affects velocities, transports and morphology. Herein, two important mechanisms, related to the shallower water depth during ebb, are discussed. The bed shear stress depends on water depth, as follows:

$$\vec{\tau}_b = \frac{g\rho\vec{U}\left|\vec{U}\right|}{C^2} \quad \text{and} \quad C = 18\log\left(\frac{12h}{k_s}\right) \qquad (2)$$

with: τ_b=bed shear stress [N/m^2]; g= gravitational acceralation [m/s^2]; ρ= water density [kg/m^3]; U =velocity [m/s]; C=Chézy coefficient [m$^{1/2}$/s]; k_s=equivalent roughness of Nikuradse [m].

The effect of waves also depends on the water depth. Waves intensify the stirring action of the fluid motion in the near-bed region which leads to larger sediment concentrations and larger transports; with shallower water the effect will be greater and transports will be larger. Thus with equal depth-averaged ebb- and flood-velocities, transports in ebb direction are larger than transports in flood direction due to wave action.

Model results for idealized ridge

Figure 5 shows the 5 year bottom profile development from simulations without waves using symmetric tides with velocity amplitudes of 0.50, 0.75 and 1.00 m/s. It can be seen that the ridge migrates in the ebb-direction. Furthermore it is found that the ridge increases in height for simulations with velocity amplitudes of 0.50 and 0.75 m/s and that the height is approximately unchanged with a velocity amplitude of 1.00 m/s. The latter simulation shows small boundary-related disturbances in morphology, which are not found from simulations with smaller velocity amplitudes. From this figure it is found that when suspended transport rates become significantly larger than the bed-load transport rates or when the suspended-load transport is not confined to the ridge vicinity only, the suspended-load transport dominates the effect of bed-load transport leading to flattening of the ridge height.

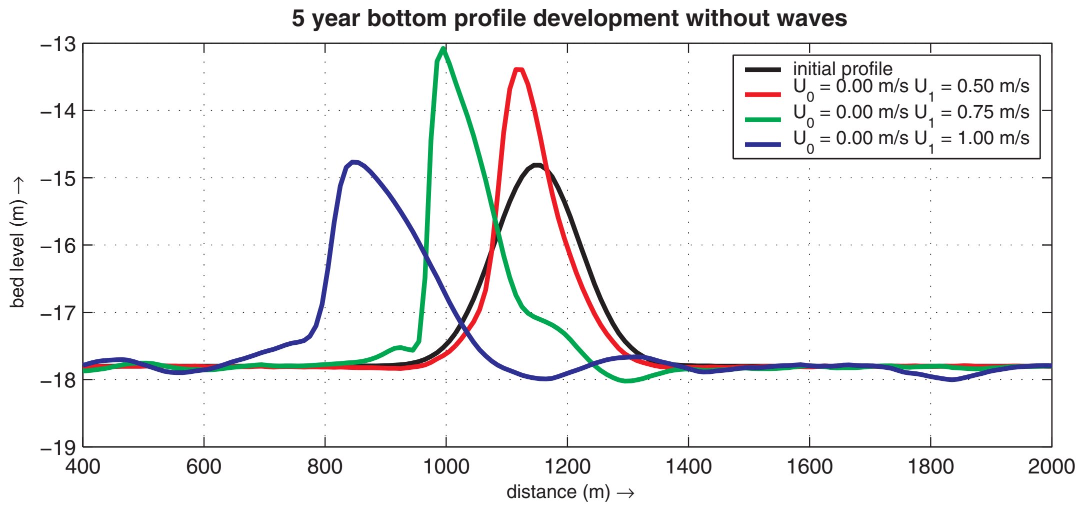

Figure 5. Five-year bottom profile development with symmetric tides.

The increase in ridge height, which is observed from simulations with velocity amplitudes of 0.50 and 0.75 m/s, can be related to the dominant effect of the bed-load transport. The time-averaged bed-load transports are in top-direction at both flanks of the ridge.

Figure 6 shows the 5 year bottom profile development from simulations using tides with velocity amplitudes of 0.50, 0.75 and 1.00 m/s and a net current of 0.05 m/s in flood direction. It can be seen that the ridge migrates in the flood-direction and that the ridge increases in height with velocity amplitudes of 0.50 and 0.75 m/s, while the height is approximately unchanged with a velocity amplitude of 1.00 m/s. The latter simulation shows relatively large boundary-related disturbances in morphology, which are not found from simulations with smaller velocity amplitudes.

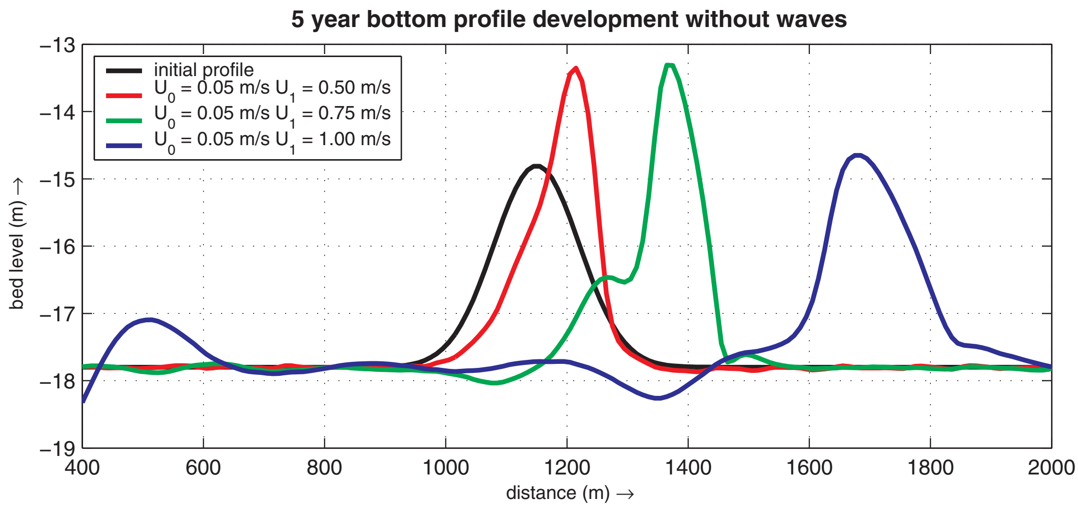

Figure 6. Five-year bottom profile development with tides with a net current of 0.05 m/s.

Using a net current of 0.10 m/s, it is found that the ridge completely erodes using a velocity amplitude of 1.00 m/s, which is due to boundary effects. From the simulations with velocity amplitudes of 0.50 and 0.75 m/s it is found that the ridge migrates in the flood direction and that the shape of the ridge is affected strongly; a rather sharp-edged forward-leaning ridge is obtained with a steep flood flank. The ridge increases in height with velocity amplitudes of 0.50, while the height is approximately unchanged with a velocity amplitude of 0.75 m/s.

Figure 7 shows the 5 year bottom profile development from simulations for a tide with a velocity amplitude of 0.75 m/s and a net current of 0.05 m/s, with H_s = 0.00 / 1.50 / 2.00 / 2.50 / 3.00 m. It can be seen that the northward migration decreases to almost no migration with increasing waves, which is due to the increased stirring effect with increasing waves (especially during ebb with lower water depths and hence more effective wave stirring) and the subsequent effect on transports. The ridge also becomes more asymmetric with increasing waves. The simulation without waves and with relatively small waves shows a small kink in the ebb flank, which needs furhter study. Waves also affect the shape of the ridge: with waves the top of the ridge becomes less peaked, than without waves due to the increased suspended-load transports; with increasing wave height and subsequent increasing suspended-load transports, the ridge develops asymmetrically.

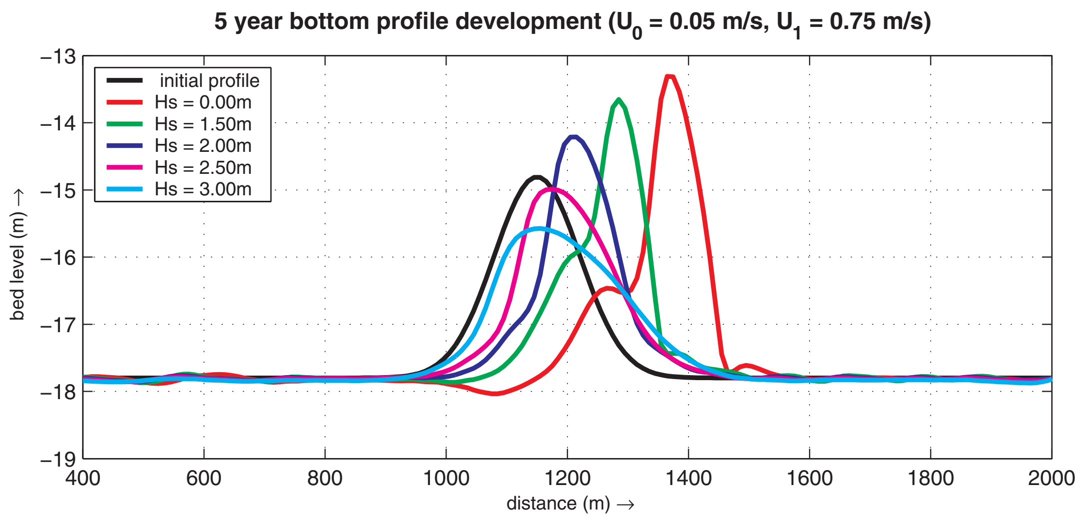

Figure 7.   Five-year bottom profile development with waves (U_0 = 0.05 m/s; U_1 = 0.75 m/s)

Figure 8 shows the 5 year bottom profile development for simulations in 1DH (1 layer approach) and 2DV mode (multi-layer approach) with a net current of 0.10 m/s in flood direction and waves (H_s = 2.50 m, T_p = 5.75 s). Both simulations show the migration in flood-direction and a reduction in height of the ridge. The 1DH simulation over-estimates the reduction in height as the modification of the velocity profiles is not modelled. Furthermore it is found that the migration using the 1DH model approach is significantly smaller than using the 2DV model approach and that the ridge develops much more asymmetrically using the 1DH model approach than using the 2DV model approach.

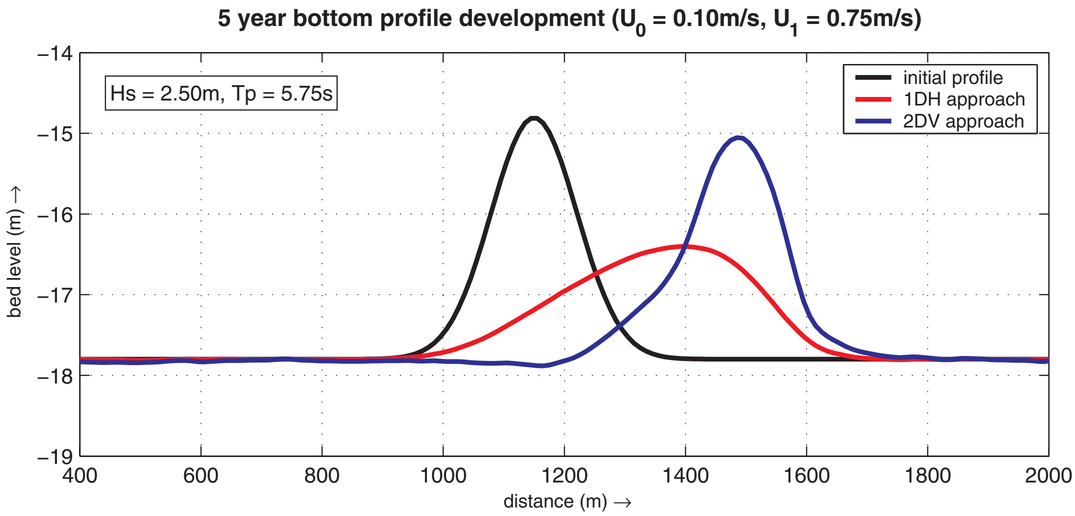

Figure 8. Five-year bottom profile development using 1DH and 2DV approach with waves (H_s = 2.50m, T_p=5.75 s)

Synthesis of results for idealized ridge

With symmetric and weak asymmetric tides (drift < 0.10 m/s) the ridge increases in height due to the net effect of the deformation of velocity profiles over the ridge (2DV approach); the time-averaged near-bed velocities at both flanks are in the direction of the top and so is the net bed-load transport which causes the ridge to increase in height. This bed-load transport related effect can be found with tidal amplitudes up to 0.75 m/s, above which the ridge will decrease in height as the suspended-load transport dominates the bed-load transport and sediments are moved outside of the region from where they can be brought back to the top with the bed-load transport.

The observed migration in ebb direction with symmetric tides (no net current) is due to the shallower water depth during ebb, which causes higher velocities and transports in ebb direction. Also the bed shear stress during ebb is higher as it is related to water depth. The magnitude of the northward drift determines the average suspended-load transport over the ridge and thereby determines the migration of the ridge; with a small drift the ridge migrates in ebb-direction due to the shallower water depth during ebb. With increasing net current (0.05–0.10 m/s) in the flood direction, the effect of the shallower water is cancelled out and the ridge migrates in flood-direction.

Waves stir up sediments which lead to larger suspended load transports. The effect of waves increases with diminishing water depth and therefore suspended transports during ebb (shallower water) are increased more than suspended-load transports during flood. The effect of waves is amplified with increasing wave heights, the migration (in ebb direction) therefore increases with increasing wave height for tides without a net current. The migration for tides with a net current is in flood direction as the shallow water effect is cancelled out due to the dominant suspended load transports in flood direction. With

a net current the migration in flood direction is reduced significantly with increasing wave height due to the increased suspended load transports during ebb. Waves furthermore affect the shape of the ridge; with increasing wave height the ridge becomes less peaked and more asymmetric.
It is found that with larger waves ($H_s > 3.00$m) the decrease in height is larger using 10 vertical layers in comparison with results from simulations using 20 and 30 layers; with large waves greater vertical resolution is required.
With a variable bed roughness (bed roughness predictor) the migration of the ridge was found to be smaller than with a constant bed roughness of $C = 65\ m^{1/2}/s$ due to the smaller transport rates at maximum flood flow. The reduction in height of the ridge is larger with a variable bed roughness, but the shape develops less asymmetrically than with a constant bed roughness, especially with waves.
It has been shown that with a 1DH (depth-averaged) model approach the ridge cannot increase in height as the modification of the velocity profiles is not modelled. As a result the depth-averaged model cannot simulate the net near-bed velocities in the direction of the top of the ridge leading to an increase in height of the ridge.

MODEL RUNS FOR ARTIFICIAL RIDGE NEAR HOEK VAN HOLLAND

The basis for the model application is the DELFT Holland Coastal Zone model, abbreviated as HCZ-model. The HCZ-model, obtains its boundary conditions from a well calibrated model covering the entire North-Sea (Roelvink et al., 2001).
Boundary conditions for the 2DV and 2DH models used in this study were derived from the HCZ-model using an automated nesting procedure. Next, input reduction techniques were applied for tidal- and wave-input. To reduce computation time, a representative, morphological tide was derived giving an optimal representation of the neap-spring averaged sediment transports. The morphological tide was derived using a weighting procedure with data points distributed over the area including the ridge.
Other model parameters are, as follows. Salinity: a constant salinity of 31 ppt is imposed at the open sea boundaries. At the discharge locations the salinity value is set to zero. Wind: a constant representative wind is applied: wind speed 7 m/s from 240° N (Southwest). Waves: the single representative wave condition from Walstra et al. (1997) is applied: significant wave height of 2.25 m, period of 6.6 s, direction 315 °N.
Sediment: d_{50} equal to 0.3 mm, d_{90} of 0.6 mm.

Figure 9 shows the computed bottom profile development and time-averaged bed-load and suspended load transports between 1986 and 1991 for Section 3 using 1DH, 2DV, 2DH and 3D model approaches. It can be seen that all simulations show a reduction in height of the ridge, while measurements show an increase in ridge-height of about 0.25 m. Both multi-layer simulations (2DV and 3D) show a significantly smaller reduction in height than the 1DH and 2DH simulations. The computed migration of the ridge from all model approaches is in north-western direction and is in good agreement with measurements showing a migration of about 75 m. It is found that the migration is slightly larger using the single-layer model approaches (1DH and 2DH) than with the 2DV and 3D model approaches. The migration from the 3D simulation is slightly smaller than the migration from the 2DV simulation, with the single layer simulations it is the other way around; the migration from the area model approach (2DH) is slightly larger than migration from the line model approach (1DH).

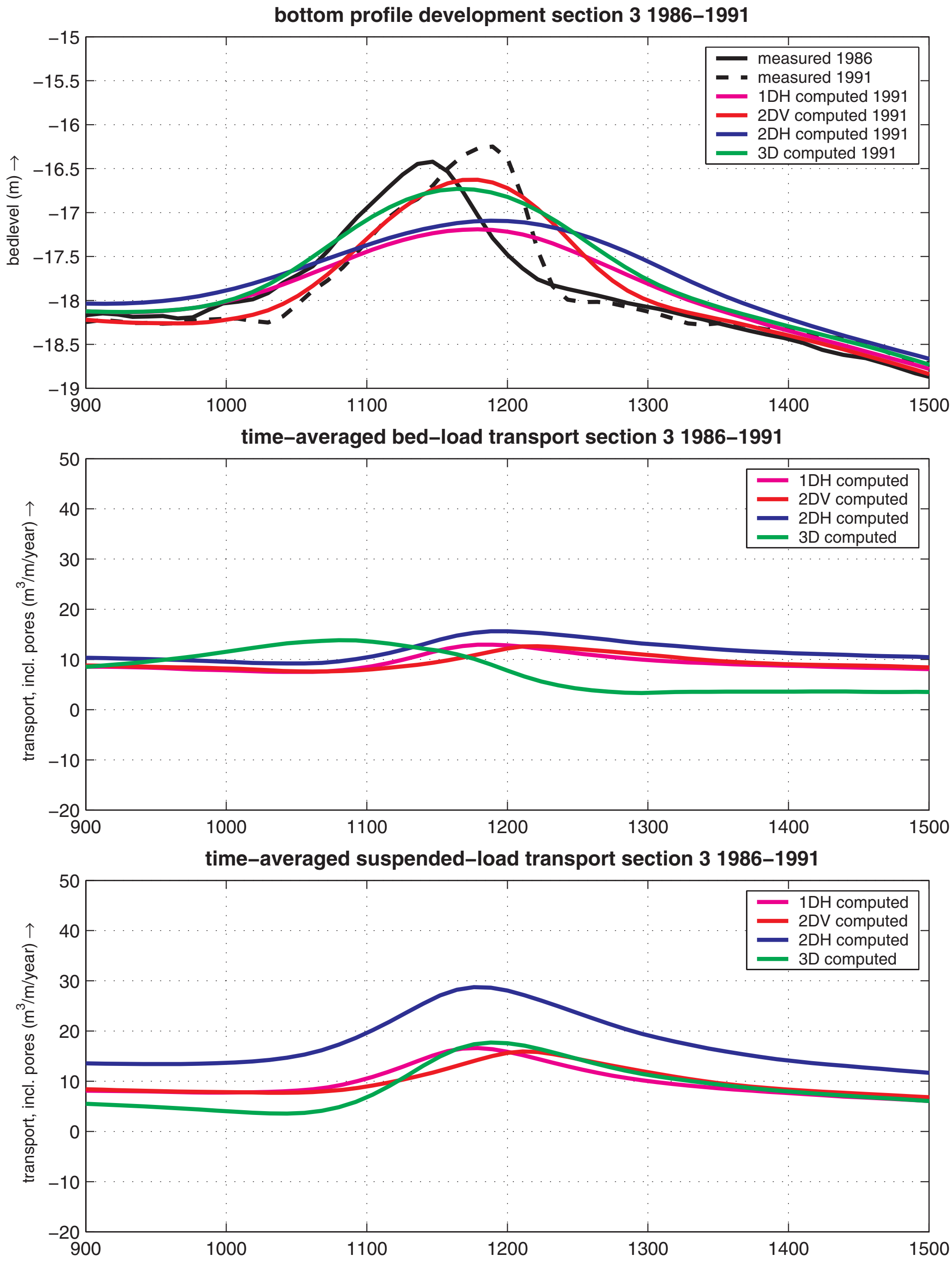

Figure 9 Computed bottom profile development and time-averaged bed-load and suspended load transport between 1986 and 1991 for Section 3 using 1DH, 2DV, 2DH and 3D simulations.

Time-averaged bed-load transport from the 1DH, 2DV and 2DH simulations is about 10 m^3/m year, incl. pores and increases at the top of the ridge to about 15 m^3/m year, incl. pores after which it decreases to about 10 m^3/m year, incl. pores. The time-averaged bed-load transports from the 3D simulation is about 10 m^3/m year, incl. pores but is at its maximum at the southern slope of the ridge and decreases at the top and is about 5 m^3/m year, incl. pores north of the ridge. Time-averaged suspended load transport from the 1DH, 2DV and 3D simulation is about 8 m^3/m/yr, incl. pores south and north of the ridge and is about 15 m^3/m/yr at the top of the ridge. Time-averaged suspended-load transport from the 2DH simulation is about 7.5 m^3/m/yr, incl. pores higher than from the 1DH, 2DV and 3D simulations.

Computed bed profiles (Section 3) for the period 1991 to 2000 using 1DH, 2DV, 2DH and 3D model approaches show a decrease in height of about 0.25 m and a northward migration of about 50 m. The decrease in height of the ridge from both the 2DV and the 3D simulations is in reasonable agreement with measurements, while the 1DH and 2DH simulations over-estimate the decrease in height. The computed migration of the ridge from all model approaches is about 100 m in north-western direction and is over-estimated in comparison with the measurements.

CONCLUSIONS

It has been shown that with a 1DH (depth-averaged) model approach the growth and migration of a sand ridge can not be simulated properly as the modification of the velocity profiles can not be modelled. This latter effect can only simulated by using a 2DV (two-dimensional vertical) or a 3D model approach.

Based on runs for an idealized ridge, the observed migration in ebb direction with symmetric tides (no net current) is due to the shallower water depth during ebb, which causes higher velocities and transports in ebb direction. Also the bed shear stress during ebb is higher as it is related to water depth. With increasing net current (0.05–0.10 m/s) in the flood direction, the effect of the shallower water is cancelled out and the ridge migrates in flood-direction.

Waves stir up sediments which lead to larger suspended load transports. The effect of waves increases with diminishing water depth and therefore suspended transports during ebb (shallower water) are increased more than suspended load transports during flood. The effect of waves is amplified with increasing wave heights, the migration (in ebb direction) therefore increases with increasing wave height for tides without a net current. The migration for tides with a net current is in flood direction as the shallow water effect is cancelled out due to the dominant suspended load transports in flood direction. With a net current the migration in flood direction is reduced significantly with increasing wave height due to the increased suspended load transports during ebb. Waves furthermore affect the shape of the ridge; with increasing wave height the ridge becomes less peaked and more asymmetric.

Based on runs for the sand ridge in the North Sea, it can be seen that the computed migration of the ridge is in north-western direction and is in good agreement with measurements showing a migration of about 75 m. It is found that migration is slightly larger using the single-layer model approaches (1DH and 2DH) than with the 2DV and 3D model approaches. Computed bed profiles (Section 3) for the period 1991 to 2000 using 1DH, 2DV, 2DH and 3D model approaches show a decrease in height of about 0.25 m and a northward migration of about 50m. The decrease in height of the ridge from both the 2DV and the 3D simulations is in reasonable agreement with measurements, while the 1DH and 2DH simulations over-estimate the decrease in height.

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