Modeling of Hurricane Impacts

Interim Report 5
September–December 2007

Dano Roelvink (P.I.), Ad Reniers,
Ap van Dongeren, Jaap van Thiel de
Vries, Jamie Lescinski, Robert McCall

UNESCO-IHE Institute for Water Education (Contractor)
WL | Delft Hydraulics
Delft University of Technology
University of Miami

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Roelvink, Dano
Reniers, Ad
van Dongeren, Ap
Walstra, Dirk-Jan

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UNESCO-IHE INSTITUTE FOR WATER EDUCATION
PO BOX 3015
2601 DA DELFT
NETHERLANDS

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14. ABSTRACT

This fifth interim report describes ongoing development and validation of the XBeach model as part of the MORPHOS project and other activities over the period September-December 2007 (period extended due to delay in funding)

15. SUBJECT TERMS

Surf zone, swash, overwash, wave groups, wave propagation, morphology, dune erosion

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Contents

Abstract

This interim report describes activities in the second quarter of the second year of the project 'Modeling of Hurricane Impacts'. In agreement with the funding agency, the work was carried out over the period August-December 2007. Three main lines of work are described in this report, viz. dissemination of model and results, model improvements and testing.

1   Introduction

This report is the fifth interim report of the project 'Modeling of Hurricane Impacts', contract no. N62558-06-C-2006, which was granted by the US Army Corps of Engineers, Engineer Research and Development Center (ERDC), European Research Office and administered by FISC SIGONELLA, NAVAL REGIONAL CONTRACTING DET LONDON, SHORE/FLEET TEAM. This report covers the activities over the period of March 1st, 2007 to September 1st, 2007. This period is longer than the usual 3 months since there has been a delay in awarding of the item 1002; the original due date was September 1st, 2007.

The project is being carried out by Prof. Dano Roelvink of UNESCO-IHE (Principal Investigator), Dr. Ad Reniers (Delft University and University of Miami), Jaap van Thiel de Vries and Robert McCall of Delft University of Technology and Dr. Ap van Dongeren and Jamie Lescinski of WL | Delft Hydraulics.

The various activities over the period of August-December 2007 are outlined in Chapter 2. In Chapter 3 we outline plans for the coming period.

2   Activities March–August 2006

2.1   Dissemination of XBeach

Creation of website www.xbeach.org

A domain name was registered and a first setup of a dynamic website was created using Google Groups, a wiki-like environment that is very easy to use and allows members to upload documents, files and codes and to create and edit wiki pages. A wide group of people associated loosely with the Morphos project have been invited to join; within two days 21 people have joined the group.

Presentation of results on conferences and workshops

The XBeach model was presented at the 10th International Workshop on Wave Hindcasting & Forecasting & Coastal Hazard Assessment held in Oahu in November, as part of a special session on MORPHOS. Abstracts were sent in to Ocean Sciences 2008 (Orlando) and ICCE 2008 (Hamburg); both were accepted.

Testing at ERDC

Brad Johnson and Ty Wamsley at ERDC are starting to validate XBeach against the full set of test cases for SBEACH. Ap van Dongeren has visited Brad Johnson to explain new features of the model and support has been provided to get the model running on the Linux platform used for this study.

Collaboration with ECORS group, France

A group of French universities led by the University of Bordeaux, plus several ones from UK, Australia and the US are planning a very large field experiment on the Atlantic coast of France in March 2008. In this project, sponsored by the French navy, XBeach will be applied, with help of our group, to model swash motions and resulting morphological changes on the beach. Several members of the group have obtained beta versions.

Collaboration with USGS

The USGS at St Petersburg, Fl (Abby Sallenger and David Thompson) is in the process of getting to know the model in order to compare it to field data.

Incorporation in EU FP7 project

XBeach has been proposed as central model in a large EU 7th Framework Programme project, MICORE, about storm impacts on European coasts. Several members of this team will work with XBeach within that project, which is very likely to get EU approval based upon the exceptionally high score. Most members of our team will participate in this.

Collaboration with NOPP–CSTM project

The XBeach model has been presented to the NOPP – Community Sediment Transport Model project during the last May workshop in Woods Hole. Concepts from XBeach may be implemented into the ROMS-SED environment, whereas XBeach can profit from experiences in that group.

Collaboration with individual researchers

The following persons have expressed interest and have received software and documentation:

- Peter Ruggiero, Oregon State University
- Gerben Ruessink, Utrecht University
- Rui Tabora, University of Lisbon
- Jennifer Irish, Texas A&M University
- Sean Vitousek, University of Hawaii
- Damien Sous, ISITV, France
- Francois Sabatier, CEREGE, France

Papers in preparation

Dano Roelvink, Ad Reniers, Ap van Dongeren, Jaap van Thiel de Vries, Jamie Lescinski, Dirk-Jan Walstra. Modelling of coastal processes under storm conditions, to be submitted to Coastal Engineering.

2.2   Implementation under LINUX and parallelization

Additional modifications were made to the code to improve performance and reduce platform dependence. In the previous version, output file under Linux differed from those under Windows. That has now been removed, pthereby producing a single type of binary output files that can be easily read into Matlab or Fortran and can be transported across platforms, without the use of any external libraries.

With support by Willem Vermin of the Dutch national computer center SARA we have started to parallelize the code using automatic domain decomposition and MPI.

2.3   Implementation of space– and time–varying offshore boundary conditions

The Xbeach model has been expanded with functionality to account for surface elevation variations on the time scale of surges and tides, and for wave energy variations on the time-scale of wave groups (including associated bound wave surface elevations). The inputs on the boundary can be derived from larger area (flow) models such as Adcirc and from larger area wave models (such as SWAN or ST-WAVE).

We impose tidal (including surge) records on four corners of the domain. There can be multiple situations, namely a difference in tidal elevation on the seaward side and the bayward side of the barrier island, or a spatially uniform waterlevel, or a longshore gradient of the tidal elevation. These different situations are controlled with just a few parameters, which can be specified by the user.

We are imposing wave energy boundary conditions from 2D SWAN (for now) spectra or parameterized spectra on the seaward side of the domain following Van Dongeren et al. JGR 2003). Along this boundary we may have more than one spectrum (longshore variation) for which we account using a masking technique cf. Groeneweg et al. ICCE 2004). These functionalities have now been thoroughly tested and are fully functional in the latest update.

2.4   Implementation of non–uniform gridsize

The numerical method has been extended to allow non-uniform gridsizes in x and y direction, though the restriction to rectilinear grids remains. The user can now specify input files with x, y and bottom level, in the same format as the existing file for bottom level. Extensive tests have been carried out to verify the correct implementation. These will be reported in a separate report.

2.5   Overwash modeling

Model description

To model the overwash deposits at barrier islands during extreme conditions XBEACH has been extended with a multiple sediment class formulation. This allows for the tracking of sediment but also for assigning different sediment characteristics such as grain size diameter, fall velocity, mobility, etc. This extension is still under development and will be implemented in later standard releases. For each sediment class, i, the equilibrium sediment concentration, $c_{eq}^{*}(i)$, is calculated according to the Soulsby-van Rijn formulation.

The actual concentration then depends on the mismatch with the equilibrium concentration in combination with the available fraction at that location. It is assumed that a top-layer of 10 cm depth is readily available for sediment pick-up. So based on the fractions of the various sediment classes present in the top-layer the equilibrium concentration per sediment class can be expressed as:

$$c_{eq}(i) = frc(i,1)c_{eq}^{*}(i)$$

where the index 1 refers to the top layer and frc the fraction of a specific sediment class. Next the advection-diffusion equation is solved independently for the different sediment classes leading to class dependent sediment transport rates, S_i, from which the bottom changes per sediment class, Δz_i, can be derived:

$$\Delta z_i = \frac{\Delta t}{1 - n_p} \left[\frac{\partial S_{i,x}}{\partial x} + \frac{\partial S_{i,y}}{\partial y} \right]$$

Changes in fractional composition of the sediment classes in the top-layer due to sediment deposition are then calculated by:

$$frc^{n+1}(i,1) = \frac{\Delta z_i}{D_z} + \frac{D_z - \Delta z}{D_z} frc^{n}(i,1)$$

and similarly for erosion:

$$frc^{n+1}(i,1) = \frac{\Delta z_i + D_z}{D_z} frc^{n}(i,1) - \frac{\Delta z}{D_z} frc^{n}(i,2)$$

where the number 2 refers to the layer immediately below the top layer. D_z is the constant layer thickness of 10 cm and Δz is the total change in bed elevation (all classes combined and positive

upward) at time step *n+1* where n represent the time index. Next the underlying layers are updated according to:

$$frc^{n+1}(i,j) = \frac{D_z + \Delta z}{D_z} frc^n(i,j) - \frac{\Delta z}{D_z} frc^n(i,j+1)$$

for erosion and:

$$frc^{n+1}(i,j) = \frac{D_z - \Delta z}{D_z} frc^n(i,j) + \frac{\Delta z}{D_z} frc^n(i,j-1)$$

during sedimentation where the subscript *j* refers to the individual layers. In case of erosion, sediment is thus moving from the bottom layers towards the top layer and vice versa.

Proof of concept

To test the implementation of the sediment class formulation a comparison is made with observations of pre-and post hurricane Ivan cross-barrier island profiles (see Figure 1) at Beasly Park, Florida, USA (Wang and Horwitz, 2007).

The hurricane Ivan impact is simulated with a constant surge level of *1.8* m present for *10* hours at which time the offshore incident significant wave height is kept at *10* m with a mean wave period of 12 s. The sediment class distribution used in the calculations discriminates between sand located within the frontal dune (class 1) and sand located on and behind the barrier island (class 2) (see upper panel in Figure 1). The sand on the barrier island is mostly vegetated which mitigates the erosion. Hence this sand has been given a mobility restriction that makes it more difficult to pick-up by means of a reduction factor of *0.25* on the equilibrium concentration. Grain sizes for both sand composites are the same with a D50 of 0.0035 m and a D90 of 0.005 mm. The initial sediment class distribution is presented in the top panel of Figure 1, where an intensity of 1 corresponds to sediment class one only and -1 to the presence of sediment class 2 only.

The bed-elevation and sediment class distribution after 10 hours are shown in the lower panel of Figure 1. The calculated bed-level is similar to the observations although differences are apparent. These differences can be related to the fact that the hurricane impact is simply modeled (i.e. constant conditions) and the fact that the post-survey was performed approximately 10 months after the hurricane had past. Still the overall evolution is consistent with the observations. The calculated changes in the sediment classes are also consistent with the observations of Wang and Horwitz (2007) based on a number of cores showing that the intersection of the new washover with the pre-hurricane sediment occurs approximately at the original bed level.
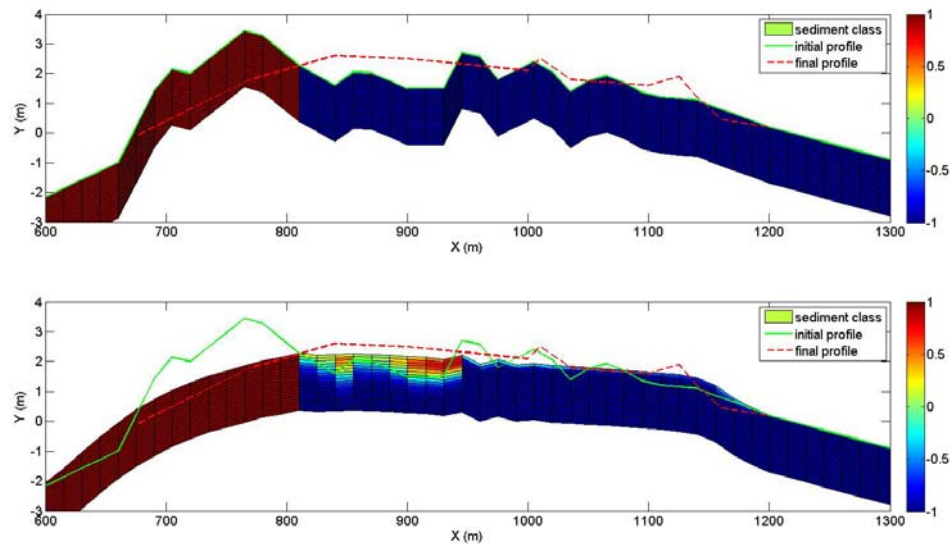
Figure 1 Top panel: Initial pre-hurricane bed elevation (green line) and sediment class distribution. A value of 1 corresponds to 100% of sediment class 1, a value of 0 to 50% of class 1 and 50 % of class 2, and a value of -1 corresponds to 100 % of sediment class two. Post-hurricane bed elevation (dashed red line) given as a reference. Bottom panel: Calculated bed-evolution (corresponding to the position of the top layer) and corresponding sediment class distribution showing the thickness of the wash-over layer located behind the initial dune. Pre- (green line) and post-hurricane (red dashed line) bed elevation given as a reference.

Reference: Ping Wang And Mark H. Horwitz (2007). Erosional and depositional characteristics of regional overwash deposits caused by multiple hurricanes. Sedimentology (2007) 54, 545–564. doi: 10.1111/j.1365-3091.2006.00848.x

2.6   Validation tests new release

Since a number of upgrades have been implemented such as non-uniform grids and more boundary condition options, a number of numerical tests have been repeated to ensure the model still runs correctly.

Long wave propagation (1D)

A free long wave with amplitude 0.01 meter and a wave period of 80 seconds is send into a flume with uniform depth of 5 meter and a length of 1000 meter. At the end of the flume a fully reflective wall is imposed whereas at the start of the flume a weakly reflective boundary condition is applied. The grid is non uniform along the flume with Δx is approximately 15 meter at the start of the flume and 5 meter at the end of the flume. The total number of grid points is 107.

As the wave has reached the wall a standing wave with double amplitude should evolve. The velocity amplitude should also double and becomes $2\sqrt{gh}a_{in}$ = 0.028 m/s. The wave length remains the same and is $\sqrt{gh}T$ = 560 meter. Figure 1 and 2 show the XBeach results after respectively the wave has just reached the reflective wall at the end of the flume and a long period of time. The simulation results are in agreement with the expected output.
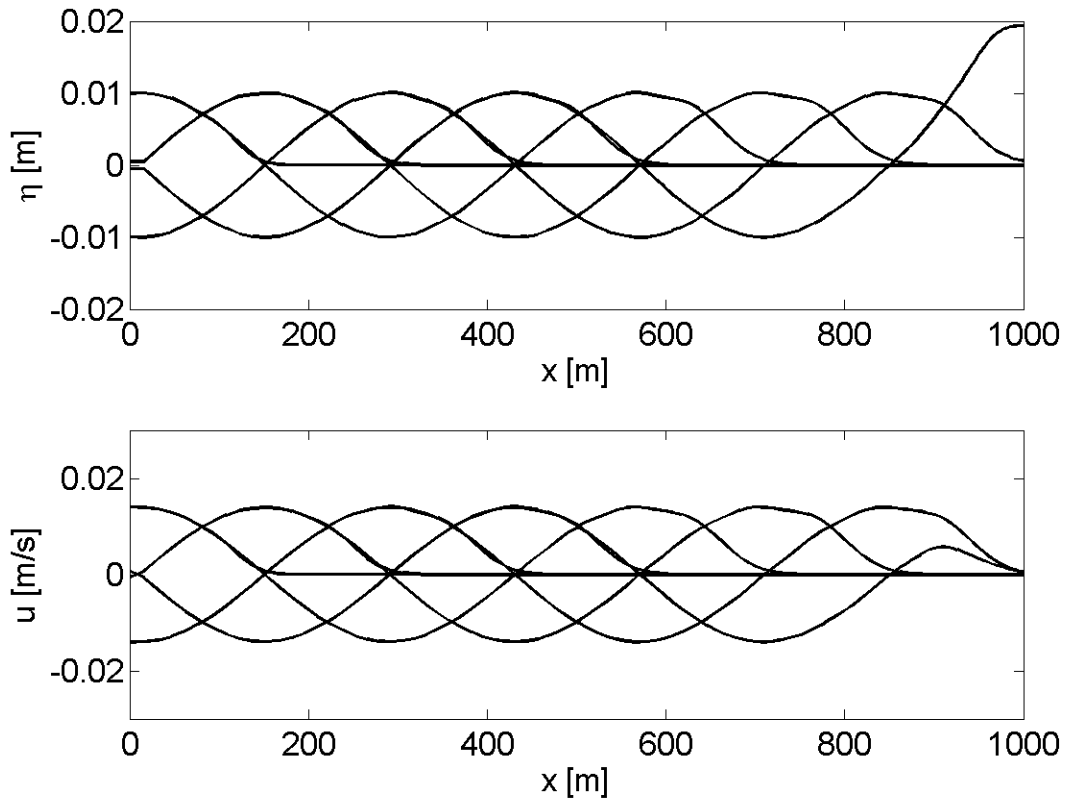

Figure 1 Snapshots of water surface elevations and flow velocities at T/4 intervals. The wave just hits the wall at the flumes end.
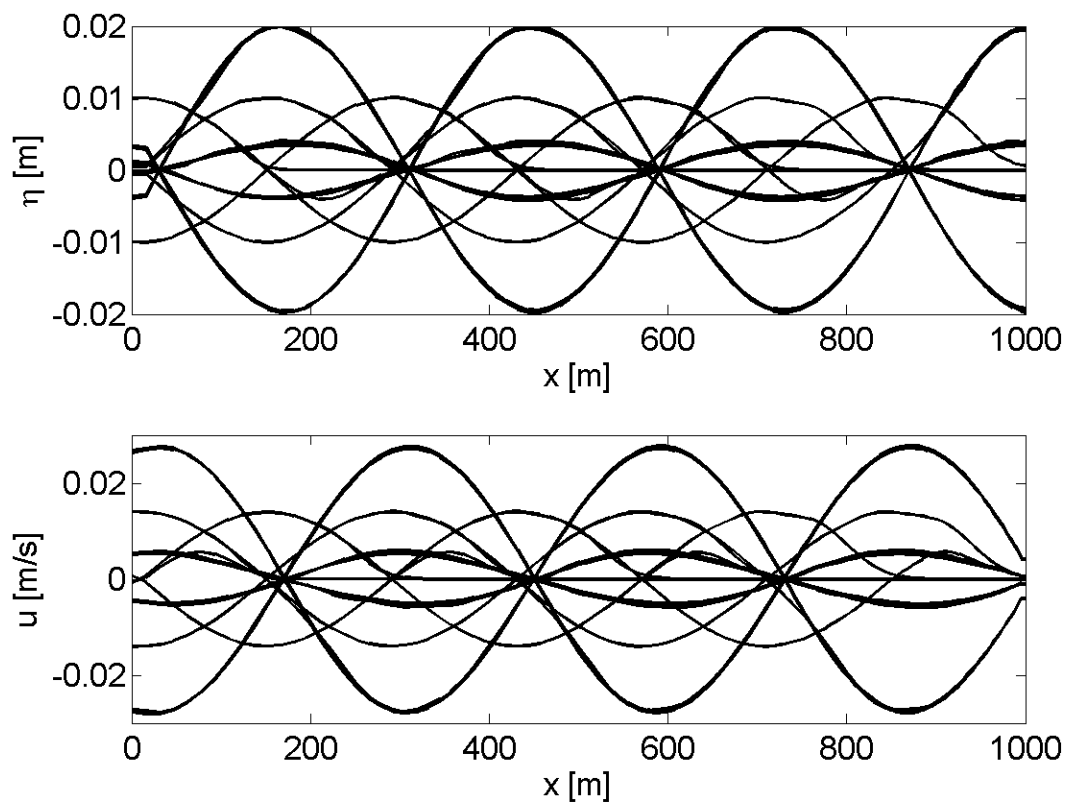
Figure 2 Snapshots of water surface elevations and flow velocities at T/4 intervals after a long period

Carrier and Greenspan (1D)

To validate the run up -and run down of non-breaking long waves a comparison was made with the analytical solution of the NSWE from Carrier and Greenspan (1958), which describes the motion of a harmonic long wave on a plane sloping beach without friction.

A free long wave with a wave period of 32 seconds and wave amplitude of half the wave breaking amplitude ($a_{in} = 0.5 * a_{br}$) propagates over a beach with constant slope equal to 1/25. The wave breaking amplitude is computed as $a_{br} = \dfrac{1}{\sqrt{128\pi^3}} s^{2.5} T^{2.5} g^{1.25} h_0^{-0.25} = 0.0307$ meter, where s is the beach slope, T is the wave period and h0 is the still water depth at the seaward boundary. The grid is non uniform and consists of 160 grid points. The grid size Δx is decreasing in shore ward direction and is proportional to the (free) long wave celerity ($\sqrt{gh}$). The minimum grid size in shallow water was set at $\Delta x = 0.1$ meter.

To compare XBeach output with the analytical solution, the first are non-dimensionalized with the beach slope s, the acceleration of gravity g, the wave period T, a horizontal length scale L_x and the vertical excursion of the swash motion A. The Horizontal length scale L_x is related to the wave period via $T = \sqrt{L_x / gs}$ and the vertical excursion of the swash motion A is expressed as $A = \dfrac{a_{in}\pi}{\sqrt{0.125 sT \sqrt{g/h0}}}$.

Figure 3 and 4 compare the XBeach results with the analytical solution from Carrier and Greenspan. The agreement is quite good, though there are small deviations in the water level near the water line and the flow velocities seem to lag slightly on the analytical solution during the second part of the run down. Since the analytical solution is stationary, numerical output over multiple waves is shown in Figure 3 and 4, verifying that also the numerical solution is stationary.
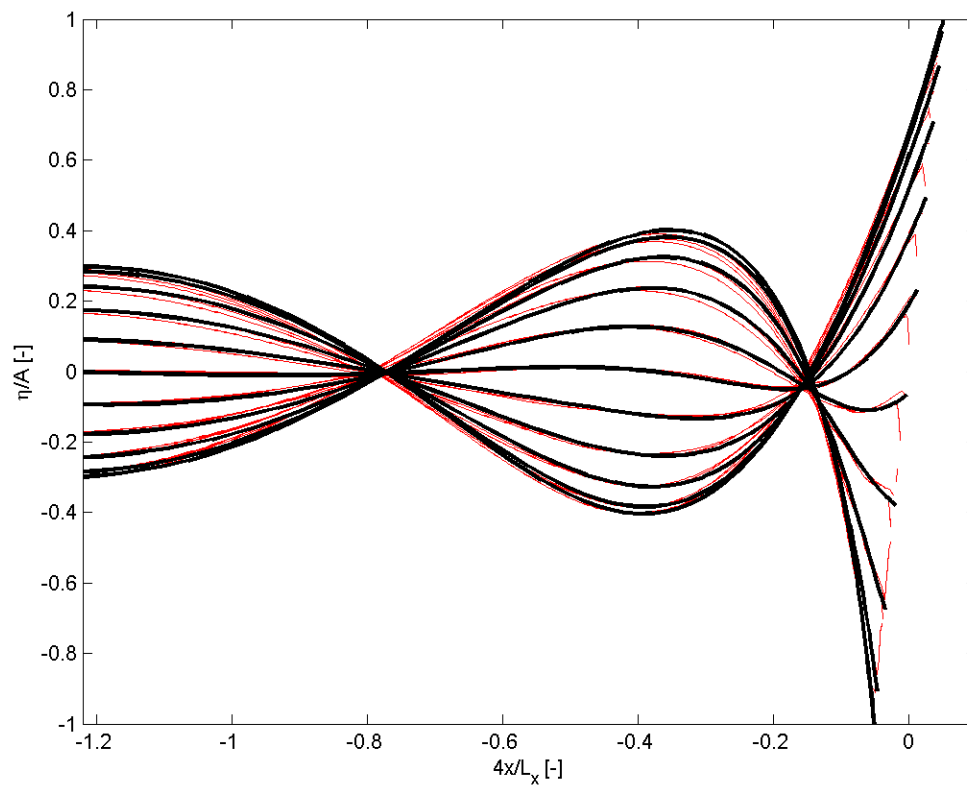
Figure 3 Dimensionless water surface elevations from XBeach compared with the analytical solution from Carrier and Greenspan for a standing wave on a plane sloping beach
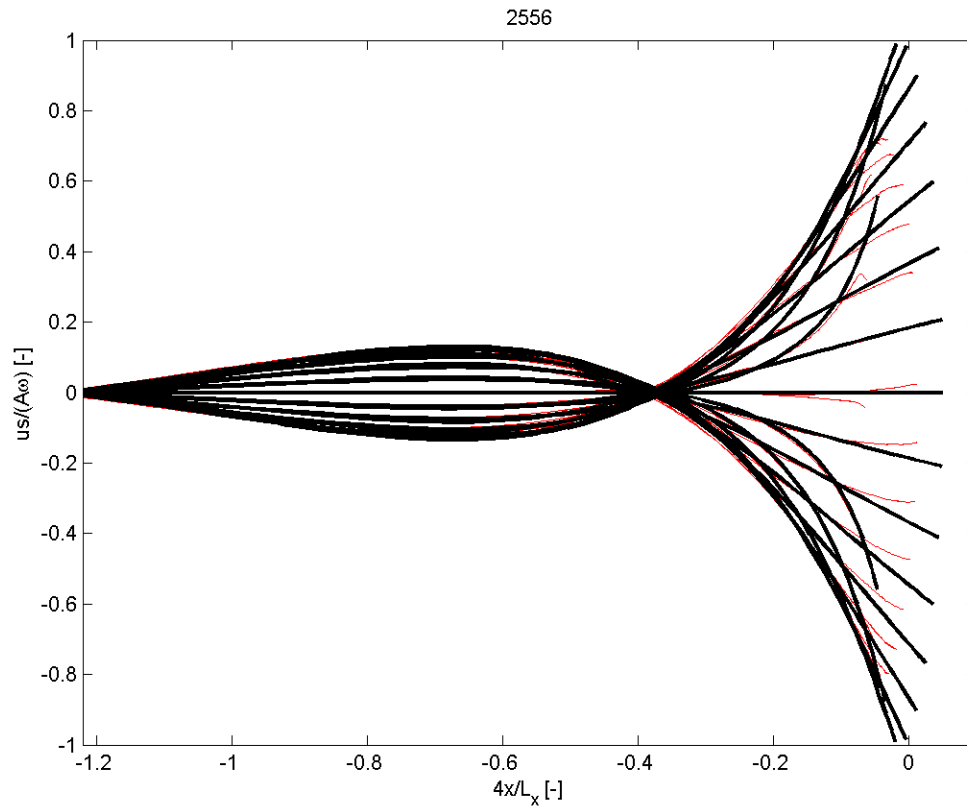
Figure 4 Dimensionless flow velocities from XBeach compared with the analytical solution from Carrier and Greenspan for a standing wave on a plane sloping beach

2.7 Delta flume experiment (1D)

In order to validate the dune erosion processes in XBeach, a detailed comparison is made with a large scale physical dune erosion test (1D) conducted in the Delta flume in 2006.

The test studied, is six hours in duration and profile measurements were obtained after 0.l, 0.3, 1.0, 2.0 and 6.0 hours. Detailed measurements of wave transformation, near dune flows and sediment concentrations are available for comparing with model results. In the physical model test, Hm0 = 1.5 m and Tp = 4.90 seconds. The still water level was set at 4.5 meters above the flume's floor and the wave paddle was equipped with active wave reflection and second order steering. Further details may be found in Van Gent et al., 2008 and Van Thiel de Vries et al., 2008

The XBeach simulation is performed on a non-uniform grid in which the grid size Δx is decreasing in shore ward direction and is proportional to the (free) long wave celerity ($\sqrt{gh}$). The minimum grid size in shallow water was set at Δx = 1 meter. Short wave transformation is computed from the default dissipation model (Roelvink 1993) and the roller model is activated. The equilibrium sediment concentration is obtained from Soulsby Van Rijn (Soulsby, 1997) and critical bed slopes for avalanching below and above the water surface are respectively 0.10 and 1.0. The simulation was run for 0.6 hours and a morphological factor of 10, which agrees with a morphodynamic test with 6 hours duration.

Figure 5a-e show a comparison of XBeach results with measurements from the Delta flume experiment. Overall there is quite good agreement between measurements and simulations. Wave heights in the near dune area are accurately predicted (Figure 5a), whereas further off shore the long wave height is underestimated whereas the short wave height is slightly overestimated. The depth and time integrated flows compare reasonable with the measurements (Figure 5b). Offshore, XBeach seems to underestimate the measurements whereas just in front of the dune face the flow seems to be overestimated by XBeach. It is stated however that measured depth averaged flows just in front of the dune should be interpreted with care since only limited observation points over depth were available to construct this flow velocity (Van Thiel de Vries et al., 2008). The orbital flow velocities compare reasonable with measurements (Figure 5c) though the overall trend is that XBeach underestimates the orbital flows. The profile evolution and dune face retreat in time are predicted quite good with the XBeach model (Figure 5e). This is quite remarkable since the test averaged sediment concentrations are significantly underestimated by the model (Figure 5d). An explanation is found in sand that is transported by avalanching.
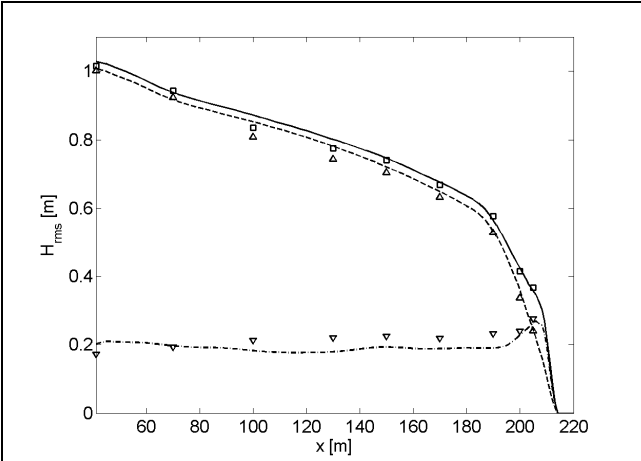
Figure 5a: Comparison of test averaged measured and simulated wave height transformations for respectively, total wave height (solid line & squares), short wave height (dashed line & upward triangles) and long waves (dashed-dotted line & downward triangles). Lines are simulations and markers represent measurements.
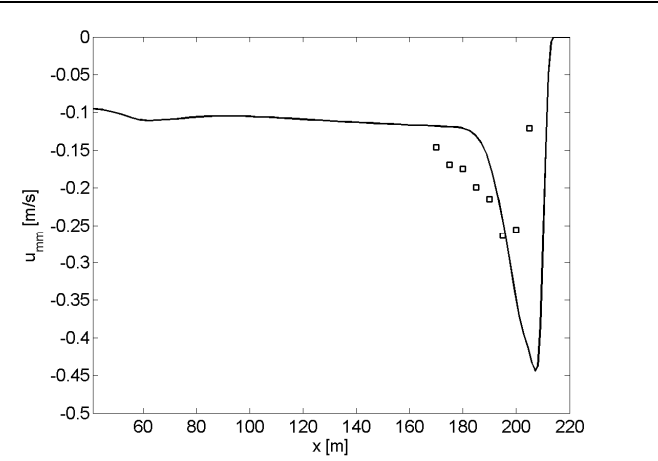

Figure 5b: Comparison of measured and simulated time and depth averaged Eulerian flow velocities as function of the cross shore position. Lines are simulations and markers represent measurements.
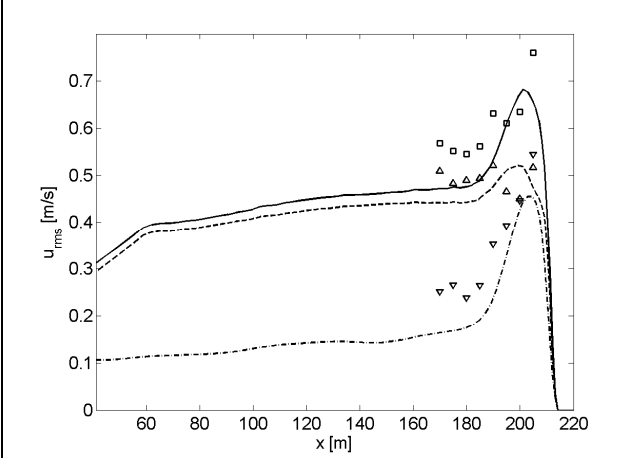

Figure 5c: Comparison of measured and simulated test averaged orbital flow velocities for respectively, total orbital flow (thick line & squares), short wave orbital flow (dashed line & upward triangles) and long wave orbital flow (dashed-dotted line & downward triangles). Lines are simulations and markers represent measurements.
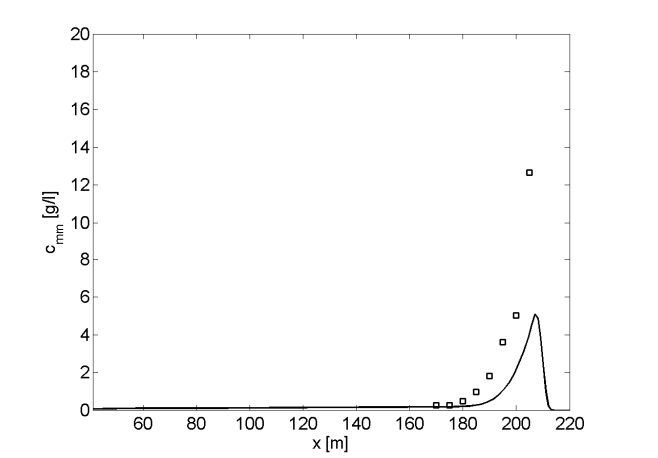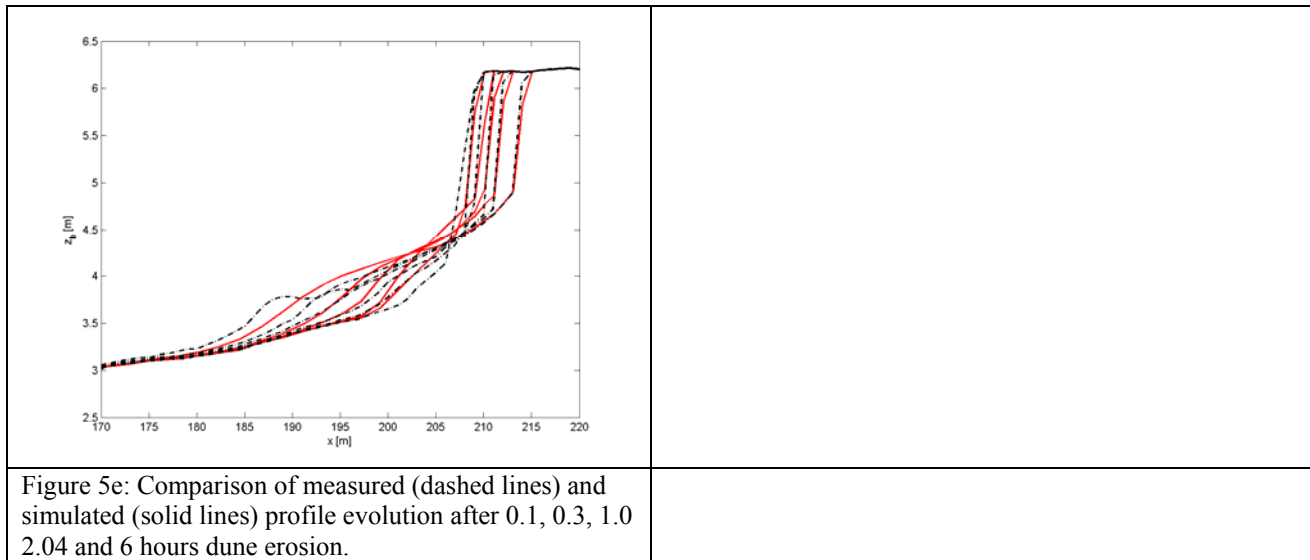

Figure 5d: Comparison of measured and simulated test averaged sediment concentrations as function of cross shore position. The Line shows simulations and markers represent measurements.

Figure 5e: Comparison of measured (dashed lines) and simulated (solid lines) profile evolution after 0.1, 0.3, 1.0 2.04 and 6 hours dune erosion.

References:

Carrier, G. F., and H. P. Greenspab (1958), Water waves of finite amplitude on a sloping Beach, *Journal of fluid mechanics*, *4*, 97-109.

Roelvink, J. A. (1993), Surf beat and its effect on cross-shore profiles, Ph.D. Thesis thesis, Delft University of Technology, Delft, Netherlands.

Soulsby, R. L. (1997), *Dynamics of marine sands*, Thomas Telford, London.

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, *submitted to Coastal Engineering*.

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, *submitted to Coastal Engineering*.

2.8 Obliquely incident regular wave groups on planar beach.

This test case was designed to check the seaward and lateral boundary conditions, especially concerning diffraction effects in the generated edge waves and to check the development of the longshore current. The depth runs from 10 m below MSL to + 2.5 m, the incident wave height is 2 m, short wave period 10 s and group period 80 s, with a direction of 30 deg w.r.t. the shore normal.The patterns shown in Figure 3 show that the short wave energy propagates into and out

of the model without any noticeable disturbances. The LF water level shown in the second panel from the left shows small regions of somewhat disturbed edge wave patterns at the lateral boundaries, but quite uniform behaviour elsewhere. For the long wave velocity any disturbances are very small, and the longshore current is allowed to develop freely.
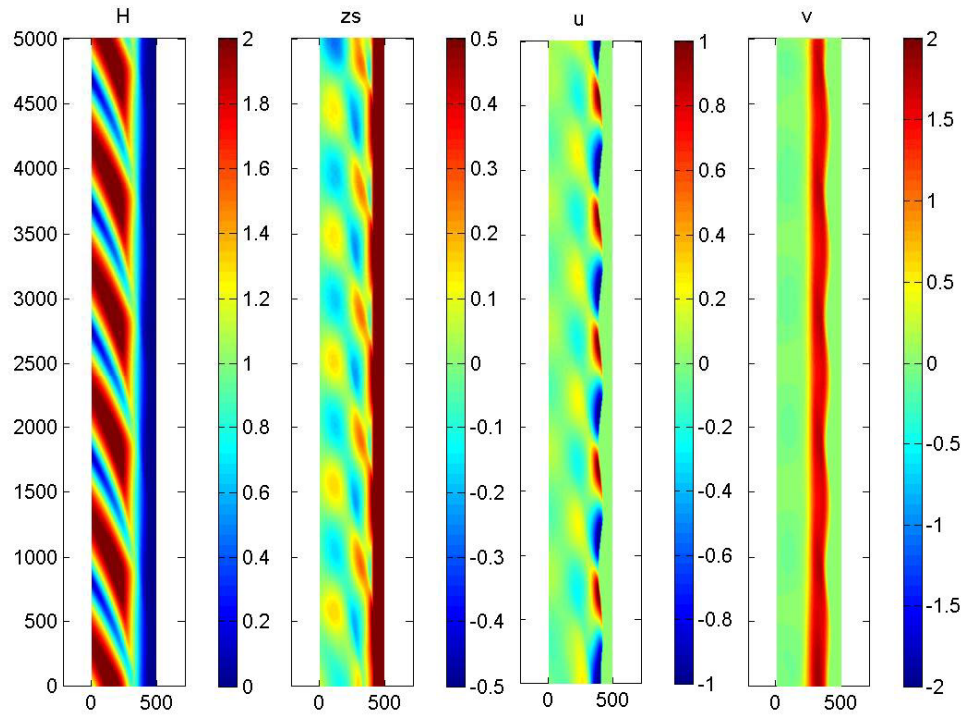

Figure 3 Schematic test of development of edge waves and longshore current. From left to right: short wave height, LF water level, LF cross-shore velocity, LF longshore velocity (snapshot)

2.9   Extreme inundation

The Xbeach model was applied to the case over overwash over a dune due to a rising tide. A 2D domain was constructed with a synthetic dune and two bodies of water ("sea" and "bay") on either side. The initial water level at the sea side was 0.8 m and at the bay side - 2 m. The dune has a crest elevation of + 2 meters with a gap which depressed the crest height locally by 1 meter and rests on an otherwise flat bottom at - 4 m. The domain spans 600 meter across and 400 meters along the dune with grid sizes of 4 meters crossdune and 10 meter along the dune.

The water level at the sea side was forced to rise monotonically to +1.5 meters. When the level reaches +1 meter, the dune starts to overflow, and causes erosion in the gap. Figure x shows the progression of the morphodynamic change (black solid line) at the center line of the domain

under the water level (blue solid line), while the initial bathymetry is the blackdotted line. The model results show the development of an overwash fan at the bay side of the dune, but also the development of anti-dunes which are caused by the supercritical flow through the gap. The red line in the figure is the Froude number which fluctuates but in the early stages of the overwash process is well above one. The anti-dunes migrate upstream and cause undulations in the flow, which shows intermittent patterns of super and subcritical flow (hydraulic jumps). At the end of the simulation the dune is severely eroded, at place below the original flat bottom level.
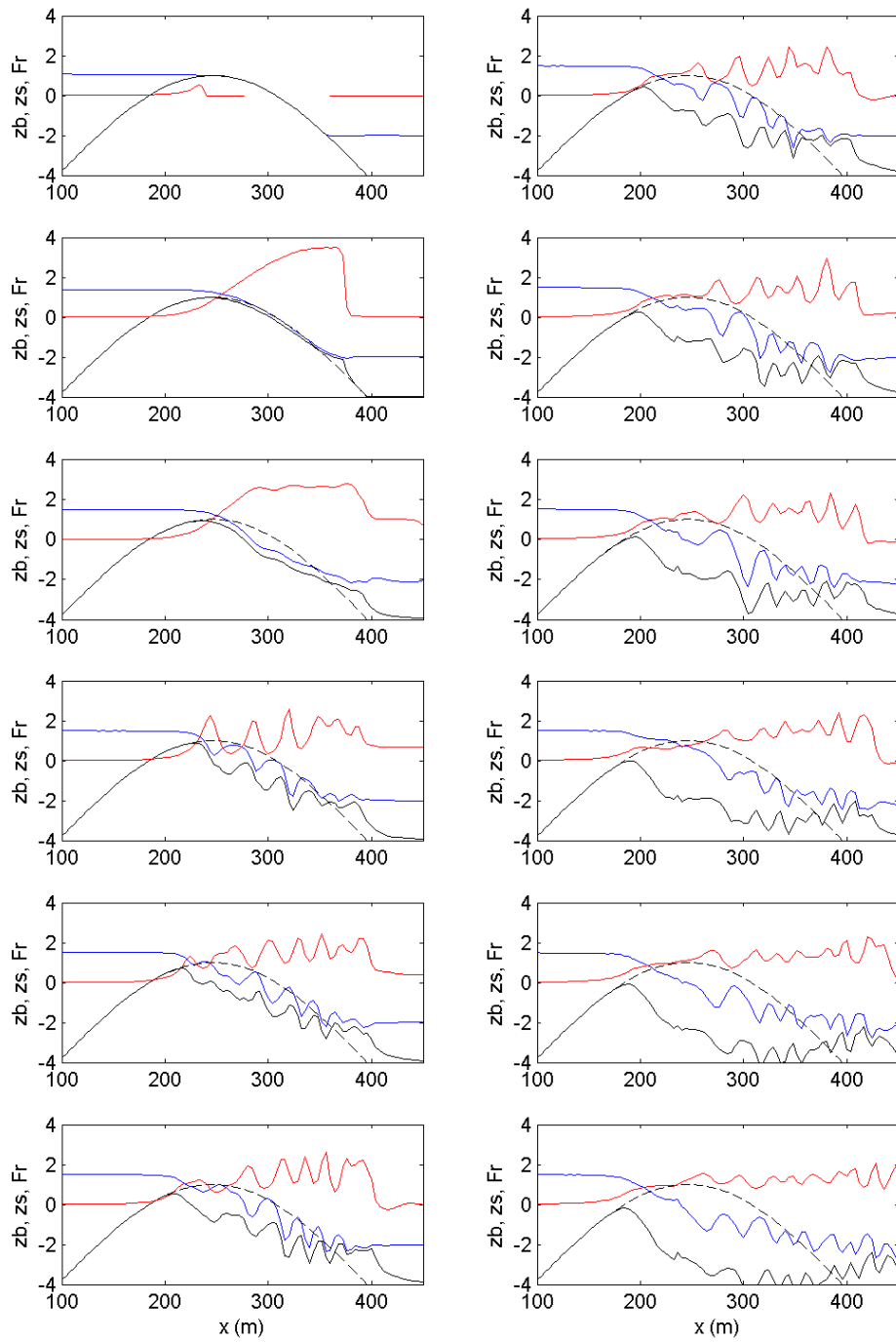
Figure 4 Development of center cross-section of extreme inundation test. Black dashed: initial profile; black: actual bottom profile; blue: actual water level; red: Froude number.
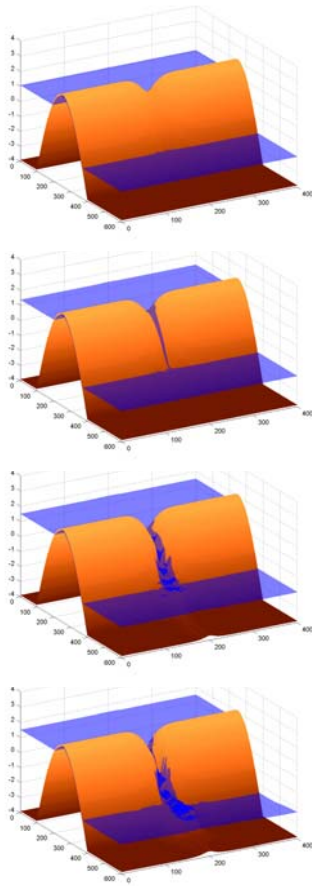
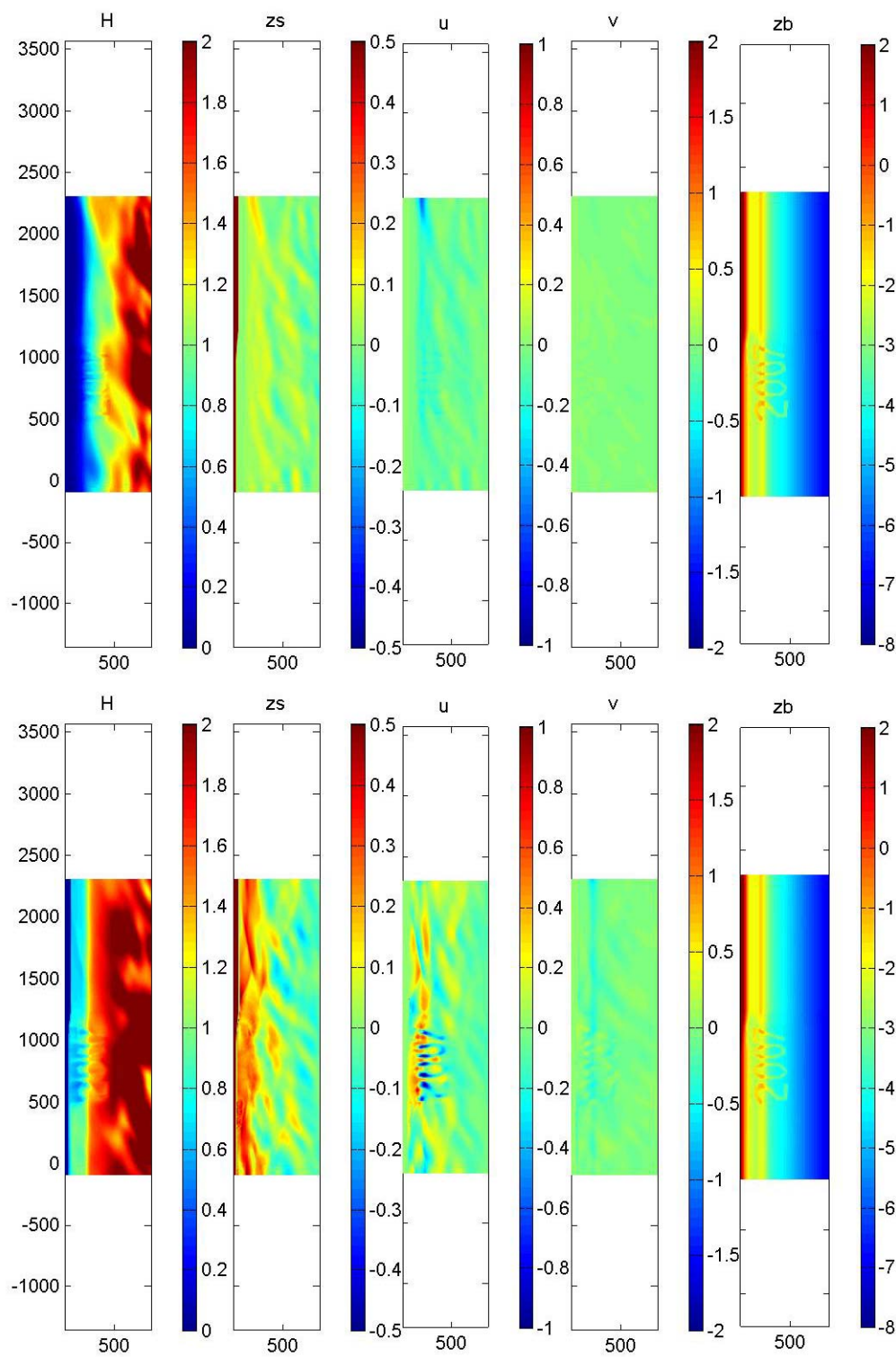Figure 5 shows 2D images of the dune overwash process at some of the stages of the process at Figure 4.

Although these results are very preliminary and much needs to be checked, the behaviour of the model appears to be physically correct and robust.
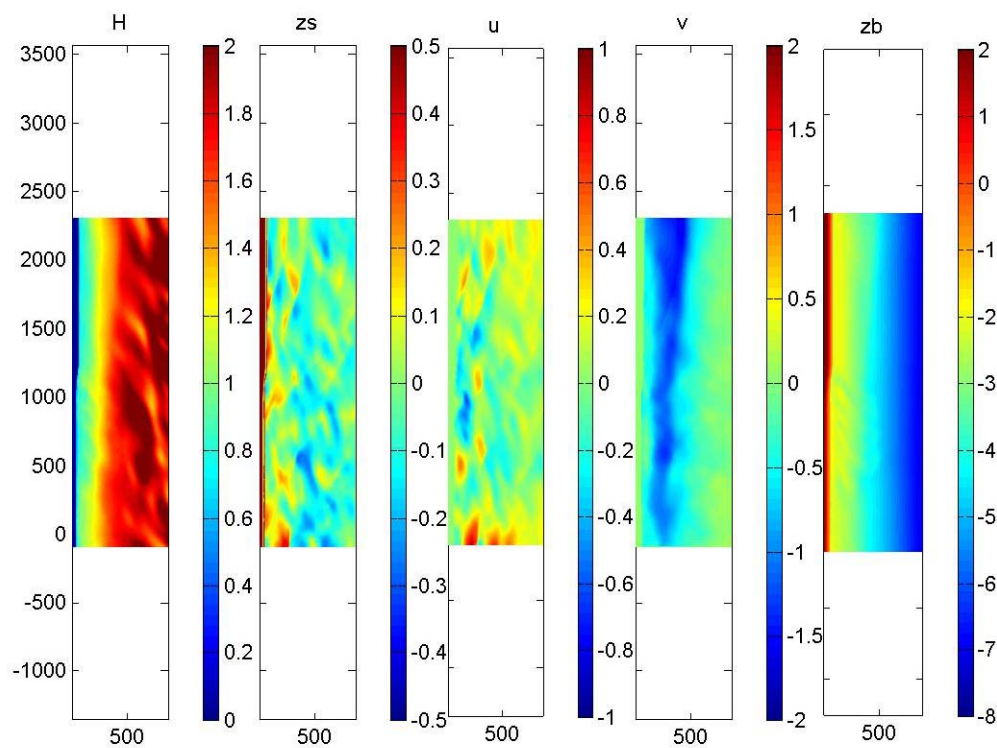
Figure 5 3D images of different stages of the breaching process.

2.10   Modeling of a disturbed beach at Duck, NC.

As a test of the applicability of XBeach for real-life cases we tested the behaviour of the beach at Duck with a 1m- high disturbance in the shape of the number 2007, under attack by waves with a Jonswap spectrum, Hm0 of 2.8 m, Tp of 10 s and angle of incidence 30 deg. w.r.t. shore-normal. The model was run for approx. 20 minutes with a morphological factor of 100, representing approx. 33 hours of morphological change. The model shows a robust behaviour and produces qualitatively correct flow patterns with strong onshore flow of the shallow areas and rip currents in between the numbers. After some time the feature is smeared out and the bar is straightened again.

In the figures below three snapshots are shown, with from left to right the short wave height H, the long wave height zs, the long wave velocities u and v, and the bed level zb.

Plans for coming period

For the coming period we plan the following activities:

- Preparation of an updated user manual
- Testing wave-current interaction in present release
- Implementing layered bottom representation
- Assisting in testing by ERDC, especially for the SBEACH test suite.
- Implementation of parallel version
- Testing against data for Monterey Bay, in collaboration with Univ. of Miami and Naval Postgraduate School
- Testing against Duck data
- Presenting results at Ocean Sciences