Modeling hurricane impacts on beaches, dunes and barrier islands

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Motivation

- 2004 Hurricane season hit Florida coast 4 times
- Congress awarded multi-million project MORPHOS3D to develop new physics-based model system to assess hurricane impacts
- Scope: wind-surge-waves-nearshore processes-impacts
- Play 'what-if?' games around Corps of Engineers projects

Figure 1 Pre- and post hurricane Ivan, Perdido Key, Florida (source: USGS)

Methodology

- Short-wave averaged but long-wave resolving modeling of waves, flow and morphology change in time-domain
- Explicit modeling of swash and overwash motions
- Detailed description of dune erosion, overwashing, breaching and full inundation in physics-based approach
- Domain from outside surfzone to backbarrier
- Driven by boundary conditions from surge and spectral wave models

Summary of conclusions

- 2DH physics-based dune erosion/overwash model
- validated for 1D dune erosion cases
- full documentation and beta version (including source code) freely available
- ready to be integrated within MORPHOS system
- can be used in stand-alone mode

Framework

- 3-year R&D Project granted through European Research Office of ERDC to Delft consortium including UNESCO-IHE, Delft Hydraulics and Delft University of Technology

- Objective:

  'the further development of MORPHOS3D through the inclusion of modeling approaches recently developed by a consortium of Delft institutes.'

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Requirements development environment

- no proprietary code used
- all developments public domain (GPL)
- easy to understand and transfer
- focus on physical processes rather than informatics, I/O
- emphasis on robustness
- focus on shallow water, swash, overwashing, breaching
- **Swash and overwashing dominated by LF motions**

- => New model: XBeach

XBeach structure (Fortran 90/95)

```
do while(par%t<=par%tstop)
        ! Wave boundary conditions
        call wave_bc (s,par,it);
        ! Flow boundary conditions
        call flow_bc (s,par,it);
        ! Wave timestep
        call wave_timestep(s,par)
        ! Flow timestep
        call flow_timestep (s,par)
        ! Suspended transport
        call transus(s,par)
        ! Bed level update
        call bed_update(s,par)
        ! Output
        call output(it,s,par)
enddo
```

Formulations

- Wave action balance
- Shallow water equations
- Advection-diffusion equation sediment
- Bed load transport
- Bed updating including avalanching

Wave action balance

- like HISWA but time-varying
- describes propagation, refraction, dissipation of wave groups for directionally spread waves
- Upwind scheme, wave propagation in all directions
- Improved boundary conditions (zero gradient alongshore or along wave crest): no shadow zone

$$\frac{\partial A}{\partial t}+\frac{\partial c_x A}{\partial x}+\frac{\partial c_y A}{\partial y}+\frac{\partial c_\theta A}{\partial \theta}=-\frac{D}{\sigma}$$

Shallow water equations

- Explicit first order scheme
- Stelling and Duinmeijer (simplest form) for accurate drying and flooding, wave runup/rundown

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\tau_{sx}}{\rho h}-\frac{\tau_{bx}}{\rho h}-g\frac{\partial \eta}{\partial x}+\frac{F_x}{\rho h}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=+\frac{\tau_{sy}}{\rho h}-\frac{\tau_{by}}{\rho h}-g\frac{\partial \eta}{\partial y}+\frac{F_y}{\rho h}$$

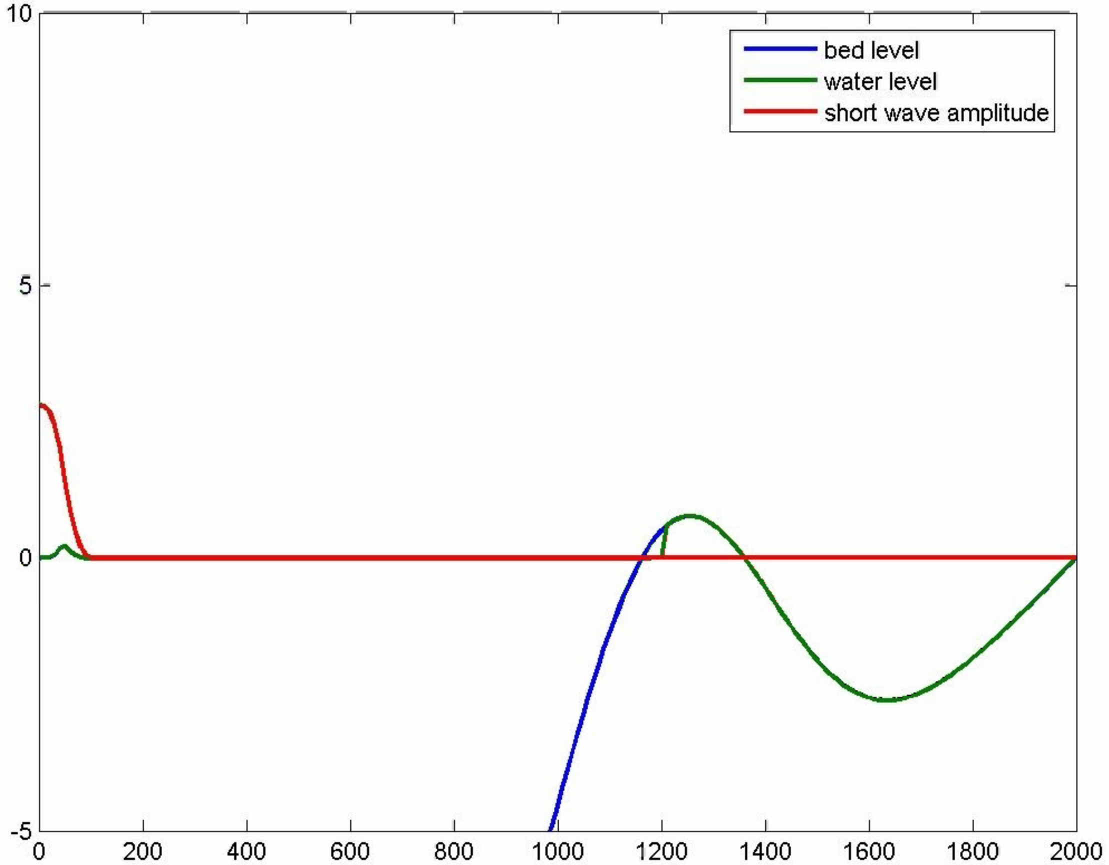
$$\frac{\partial \eta}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0$$

Combined short/long wave propagation and decay

Principle test:

overwashing

by LF waves



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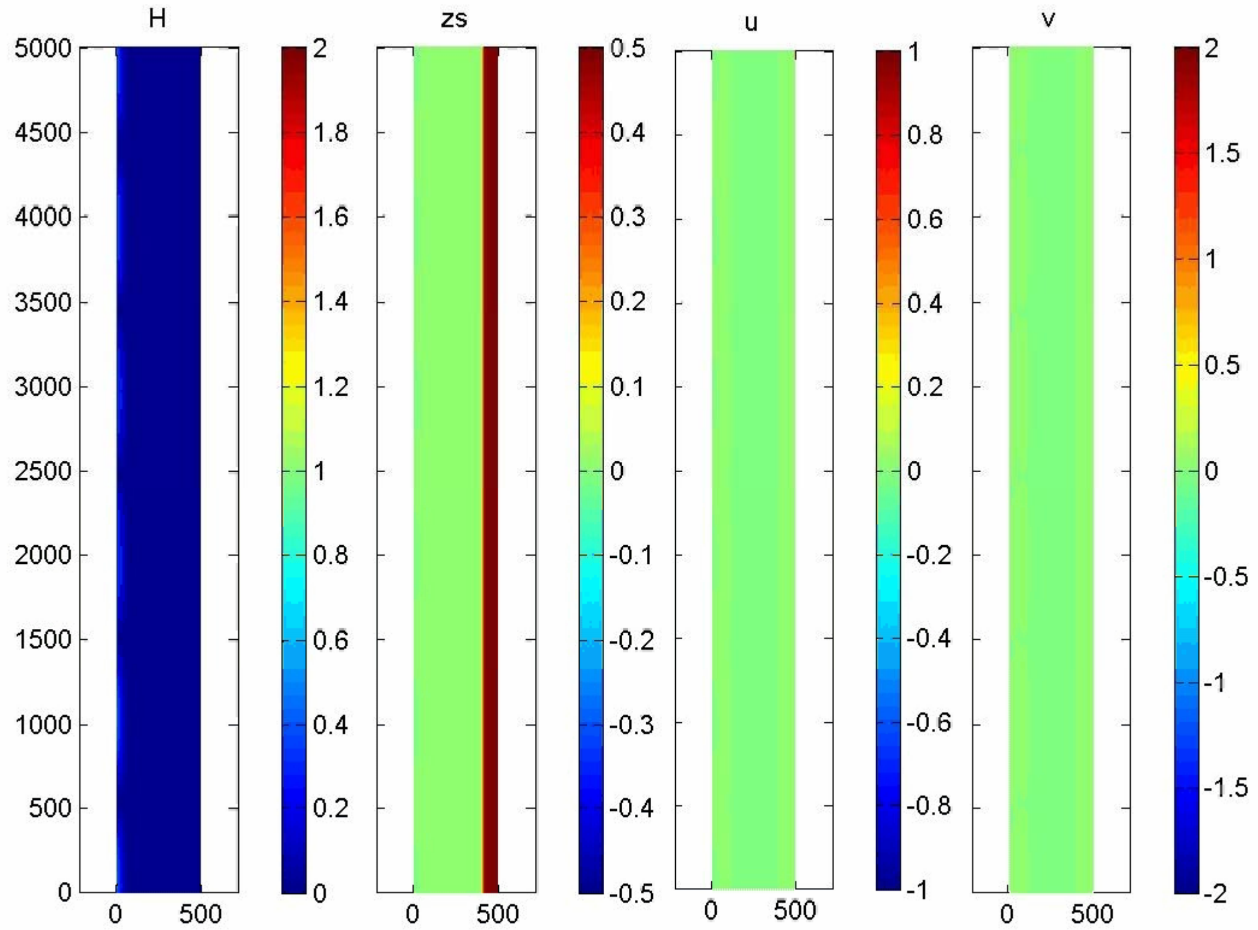
Combined short/long wave propagation and decay

- obliquely incident, regular wave groups
- 1:40 slope
- h0=10 m
  Hrms=2 m
  Tp=10 s
  dir=210 deg
  Tlong=60 s



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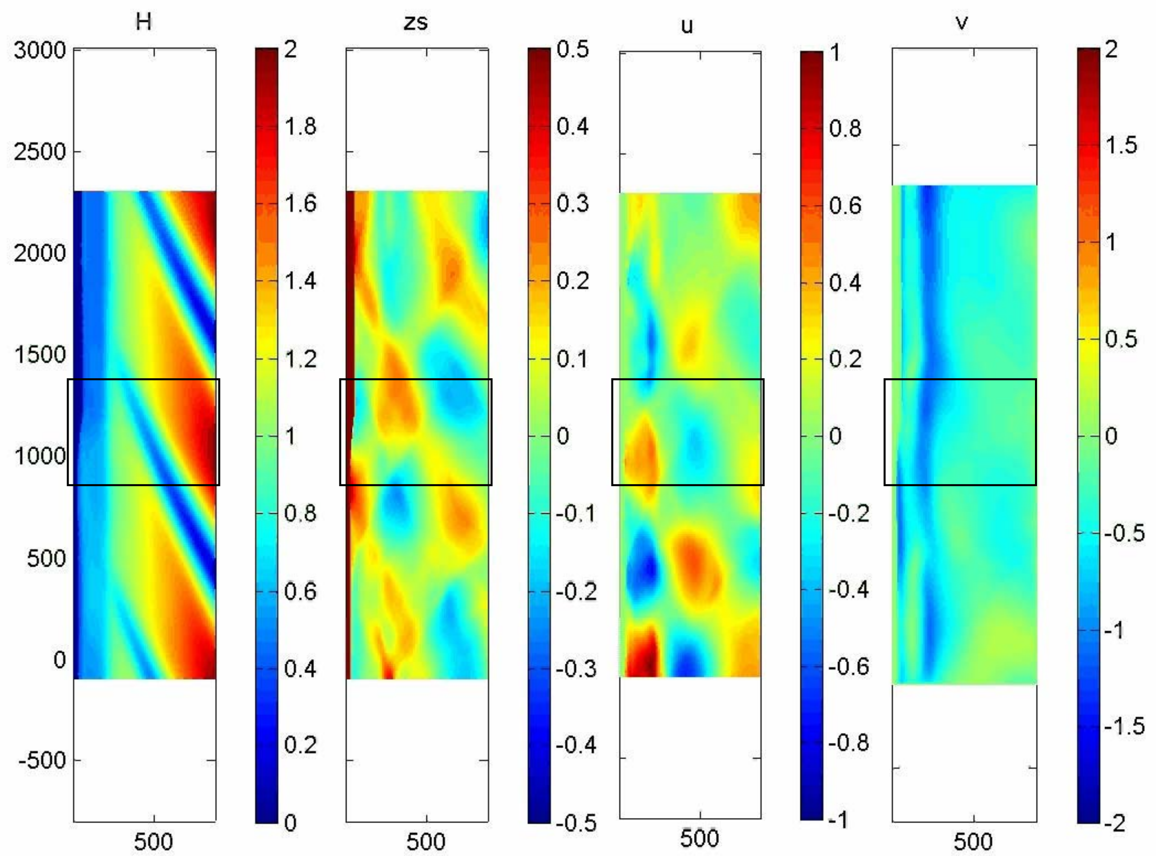
Similar for Duck bathymetry

- obliquely incident, regular wave groups
- Hrms=2 m
  Tp=10 s
  dir=60 deg
  Tlong=80 s
- need approx. one wave length extra grid to avoid disturbances



Sediment transport

- Depth-integrated advection-diffusion equation
- Equilibrium concentration determined by Soulsby-van Rijn formulations
- Velocity includes seaward return flow

$$\frac{\partial hC}{\partial t}+\frac{\partial hCu^{E}}{\partial x}+\frac{\partial hCv^{E}}{\partial y}+\frac{\partial}{\partial x}\left[D_{h}h\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{h}h\frac{\partial C}{\partial y}\right]=$$

$$=\frac{hC_{eq}-hC}{T_{s}}$$

Bottom updating

- Updating based on transport gradients:

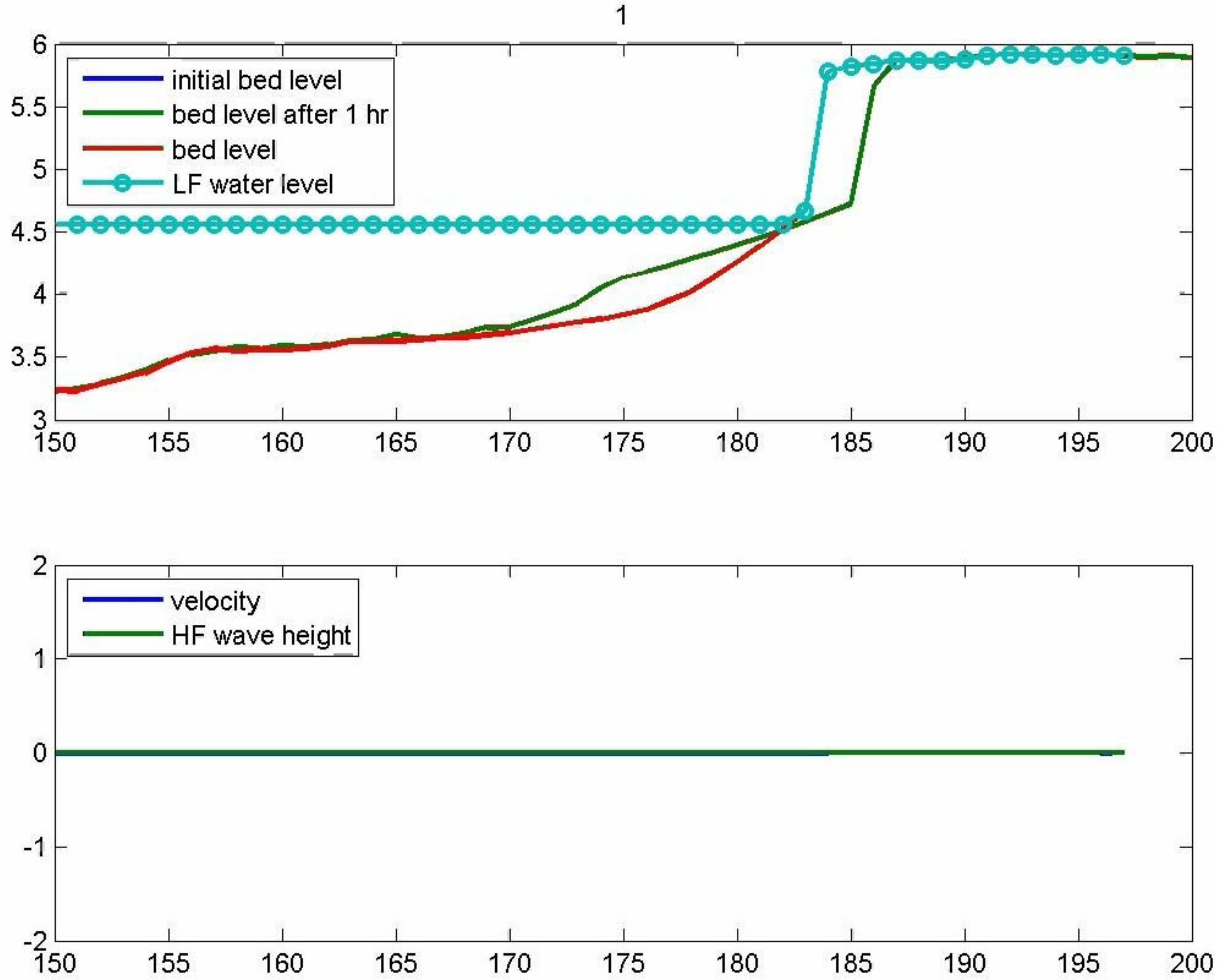
$$(1-\varepsilon)\frac{\partial z_b}{\partial t} + f_{mor}\left(\frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y}\right) = 0$$

- Plus avalanching:
  - two critical slopes: above water (~1.0) and below water (~0.15-0.3)

Dune erosion test

- Deltaflume 1993, LIP11D
- sub-test 2E: increased water level and severe waves, leading to substantial dune erosion
- Hm0=1.4 m, Tp = 5 s, water level 4.6 m (increased by 0.5 m relative to ‘normal’ conditions)

Detailed beach process model without avalanching



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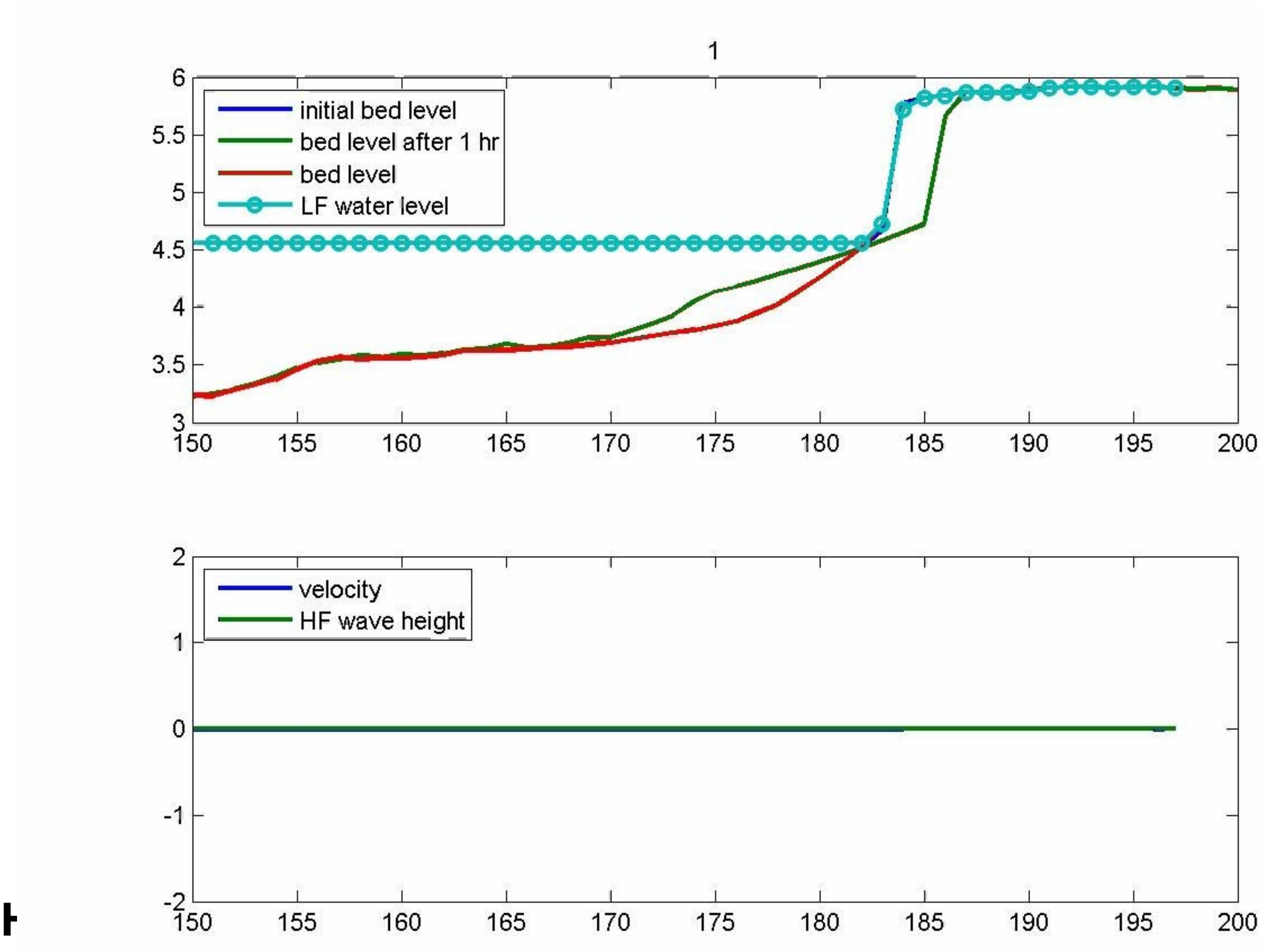
Detailed beach process model plus avalanching



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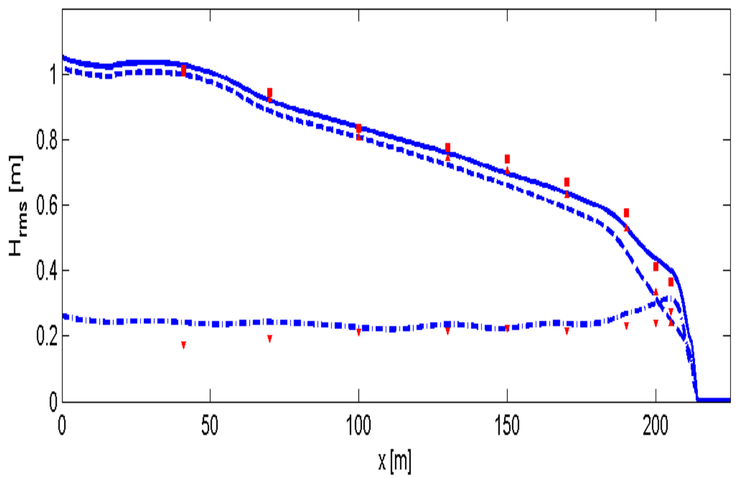
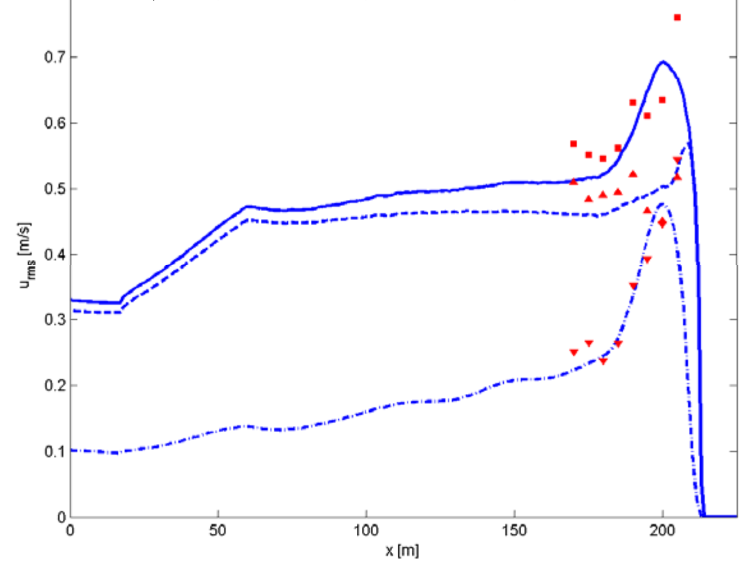
2005 Dune erosion tests Delta Flume

- Series of experiments to test influence of wave spectrum
- First comparison for test 3
- Tp=7s, Hm0=1.4 m, water level 4.6 m
- All settings as before

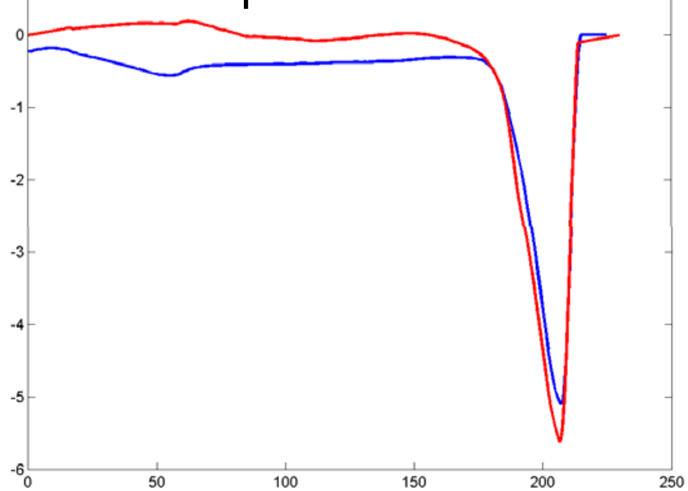
HF, LF and total Hrms



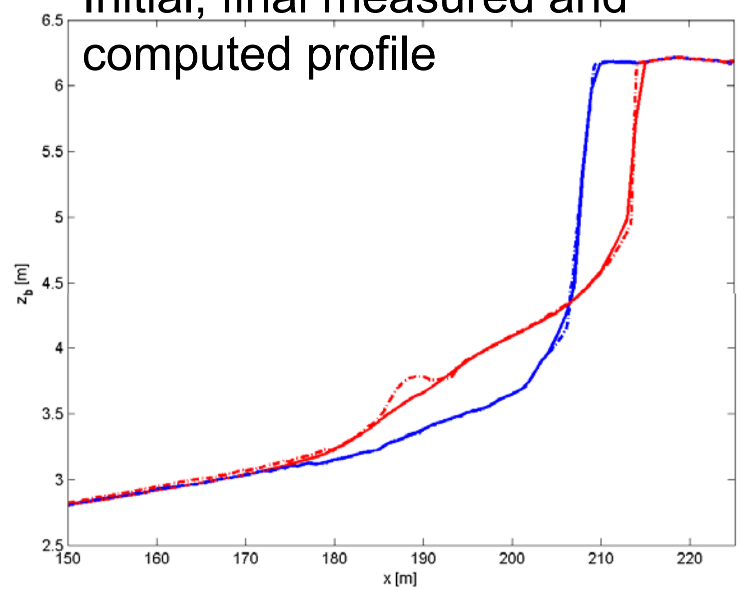
HF, LF and total Urms



Measured (red) vs computed mean transport



Initial, final measured and computed profile



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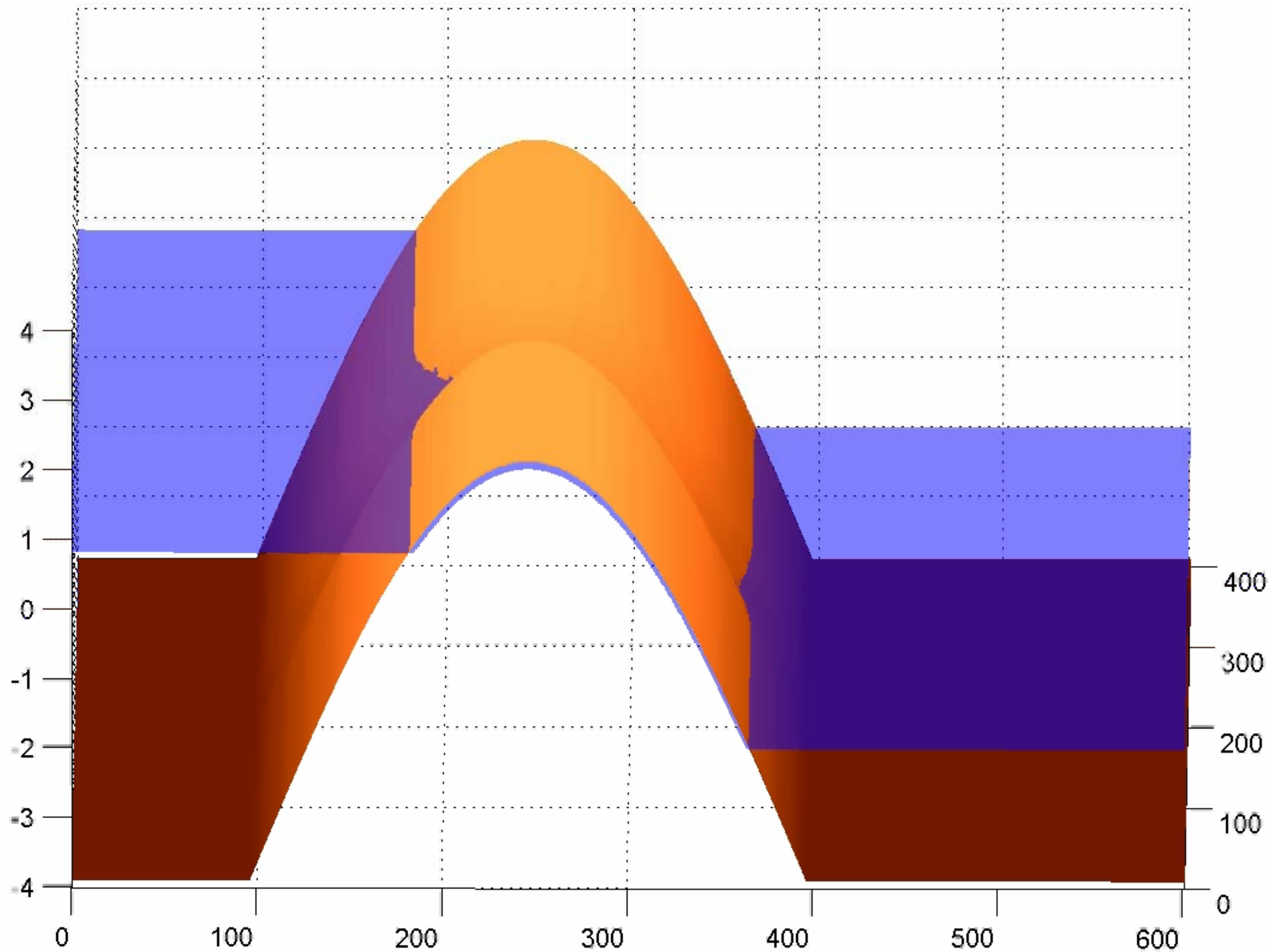
Breaching test

- 2D domain
- synthetic dune, sea and bay
- initial water level at sea 0.8 m
- bay side - 2 m
- crest elevation of + 2 m
- gap 1 m
- flat bottom at - 4 m.
- domain 600 m across by 400 m along the dune
- grid sizes of 4 m crossdune by 10 m along the dune.

Breaching



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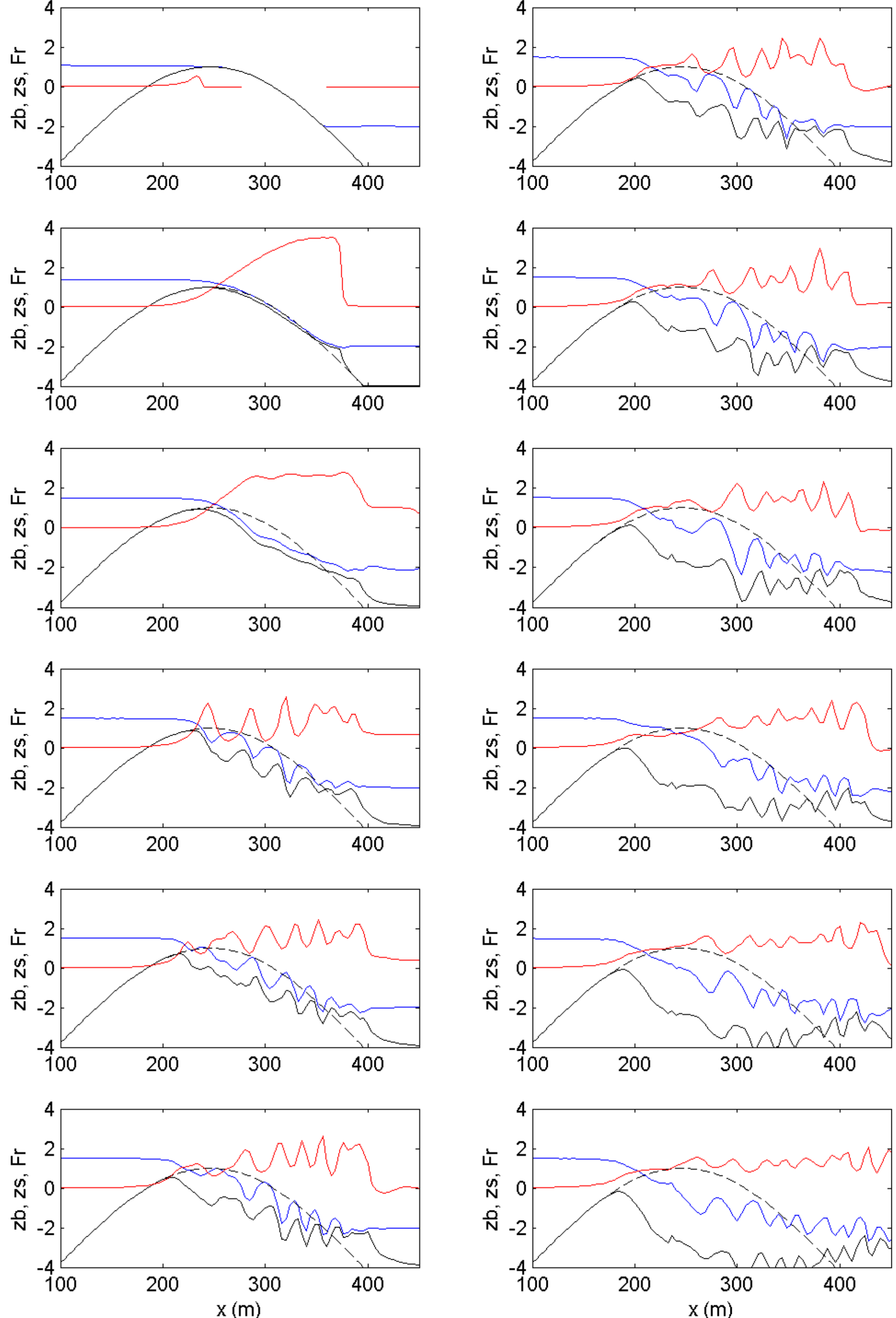
Central cross-section

- shown are bed level water level and Froude number
- starts with supercritical flow over dune
- develops into alternating sub/supercritical flow with antidunes



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Conclusions

- 2DH physics-based dune erosion/overwash model
- validated for 1D dune erosion cases
- can model different stages or impact levels seamlessly
- full documentation and beta version (including source code) freely available
- is being integrated within MORPHOS system

Ongoing work

- Generation of offshore boundary conditions for E and ς from measured spectra (Van Dongeren et al., 2003) (now testing)
- non-uniform grids (done)
- parallellization
- 1DV undertow model, wave asymmetry effects
- Further validation
  - Isabel at Duck
  - Dauphin Island
  - RCEX Monterey
  - ECORS
  - Delft test bank
  - Delta flume “berm test”
- Papers

Overwash test

- Principle test: LIP 2E test with reduced crest height