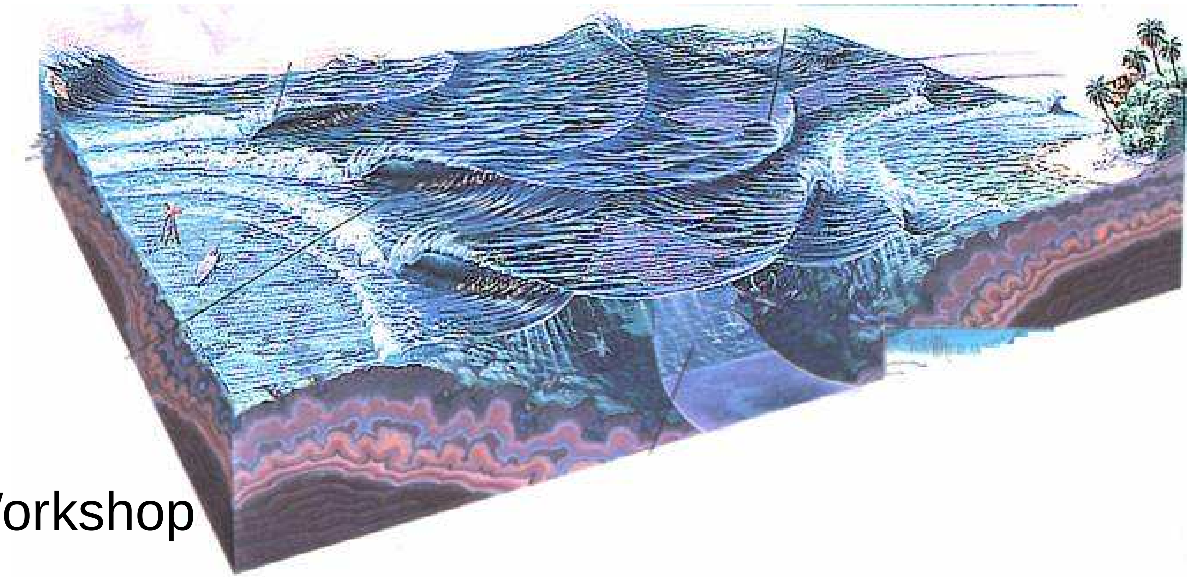
Nearshore wave-flow modelling with SWASH



12th Waves Workshop

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Environmental Fluid Mechanics Section

TUDelft

Delft University of Technology

Motivation

- Goal: to develop a model that is capable of simulating wave motion (with current) in coastal waters up to the shore.
- Different levels of wave modelling:
  - phase-averaging: statistical properties, spectral, SWAN.
  - phase/wave-resolved: linear (MSE) and nonlinear (NLSW, Boussinesq, Serre, Green-Naghdi).
- Non-hydrostatic wave-flow models (Navier-Stokes):
  - permit wave breaking, runup, undertow, etc. derived from first principles and well-founded semi-empirical modelling, and
  - appear to be very robust and are not prone to unstable.

Methodology

- The simplest modelling for wave transformation is the nonlinear shallow water (NLSW) equations.
- NLSW-type models exhibit conservation properties and are able to deal with breaking/bore capturing, dike breach flooding, and tsunami inundation, among others.
- With the inclusion of non-hydrostatic pressure, many other wave phenomena (dispersion, surf beat, triads, etc.) can be described in a natural manner as well.
- Water depth can be divided into a number of layers and thereby take into account vertical variation (e.g. undertow).
- Also, they improve their frequency dispersion by increasing the number of layers.

Summary of conclusions

- SWASH is a first push toward a quasi-operational, open source non-hydrostatic model suitable for simulation of coastal waves and runup.
- In case of nearshore wave modelling, SWASH appears to be accurate, fast, robust and well tested.
- The computational algorithm combines efficiency and robustness allowing application to large-scale, real-life problems.
- Very few tunable parameters needed.

Introduction to SWASH

- Many variants (numerics) of non-hydrostatic models have been proposed in the literature, exposing excellent features such as frequency dispersion and nonlinear effects.
- However, no advances have been made in assessing those models at an engineering level with observations under realistic nearshore conditions.
- Over the past 10 years, strong efforts have been made at Delft University to advance the state of wave modelling and flooding simulations for coastal engineering.
- SWASH: it is essentially applicable in coastal regions up to the shore: Simulating WAves till SHore.

SWASH – physics

SWASH accounts for the following physical phenomena:

- propagation, frequency dispersion, shoaling, refraction and diffraction,
- flooding, wave runup, moving shoreline,
- nonlinear wave-wave interactions (surf beat, triads),
- wave-induced currents and wave-current interaction,
- wave breaking,
- bottom friction, and
- subgrid turbulence and vertical mixing.

SWASH – numerics

- Fully explicit; Courant-based time step restriction (but not severe!).
- Vertical terms are semi-implicitly integrated using a $\theta-$scheme ($\frac{1}{2} \leq \theta \leq 1$).
- Staggered grid in space and time; second order in time and no amplitude error.
- Finite differences in horizontal and finite volumes in vertical.
- Advection approximation by means of first or second order upwind schemes with(out) flux limiting (BDF, Fromm, MUSCL, QUICK, minmod, etc.).

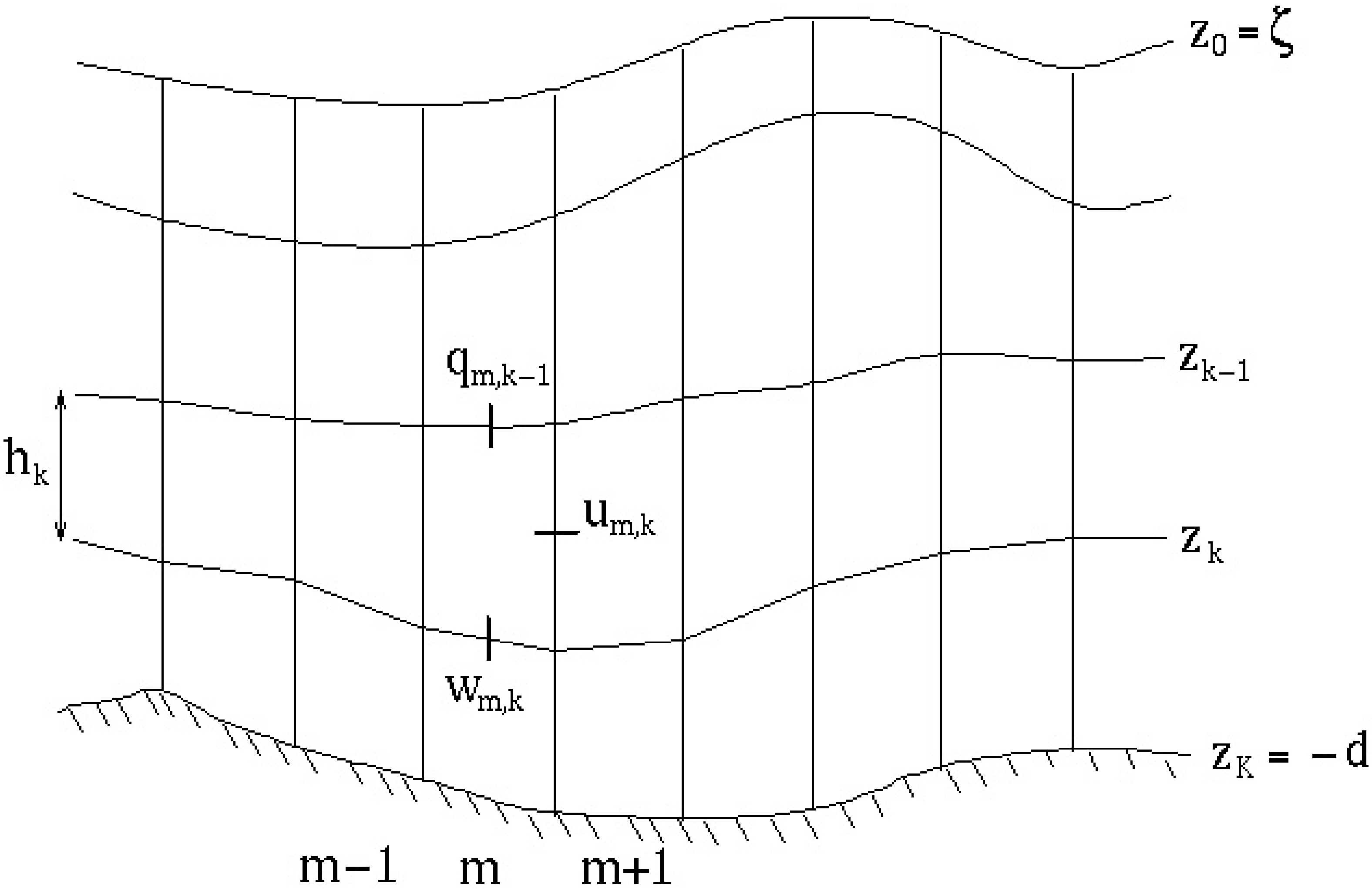
– continued –

- Advection terms are approximated such that momentum conservation is ensured. Important for wave breaking!
- Surface elevation through depth-averaged continuity equation ensuring global mass conservation.
- A simple approach is adopted that tracks the moving shoreline by ensuring
  - non-negative water depths and
  - using first or second order upwind water depths in the momentum flux approximations. Flux limiters (MUSCL, minmod, Van Leer, etc.) may be employed.

– continued –

- For accuracy reason, the pressure is split-up into hydrostatic and non-hydrostatic parts.
- Second order projection method where correction to the velocity field for the change in non-hydrostatic pressure is incorporated (local mass conservation).
- Either SIP (depth-averaged mode) or (M)ILU-BiCGSTAB (multi-layered mode) iterative solver is employed for the solution of the pressure Poisson equation.

General layer concept



SWASH – functionalities

- Wave makers:
  - Fourier series, time series, or
  - 1D, 2D spectrum; parametric (PM, Jonswap or TMA), SWAN or observations.
- Weakly reflective, Sommerfeld, sponge layers.
- Rectilinear or orthogonal curvilinear.
- Cartesian or spherical coordinates.
- 1D-mode (flume) or 2D-mode (basin).
- Depth-averaged or multi-layered mode.

– continued –

- Physics: bottom friction (Chezy, Manning) and turbulent mixing (Smagorinsky, Prandtl mixing length, $k - \varepsilon$).
- Hydrostatic or non-hydrostatic.
- Many outputting (same flexibility as SWAN):
    - points, curves, maps, verticals, etc.,
    - many quantities: water level, velocity, discharge, pressure, runup, friction, k, ε, etc.
    - ASCII files (tables, blocks) and binary Matlab files (blocks).

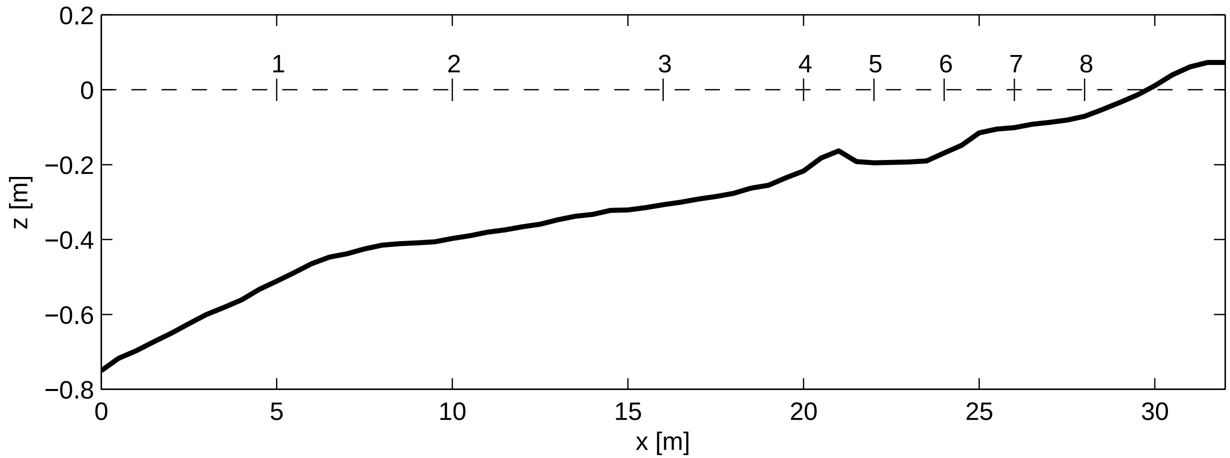
Open source, easy-to-use model

- Freely available under the GNU GPL license at Sourceforge: http://swash.sf.net
- Easy accessible to promote ease-of-usage:
  - ANSI Fortran90, fully portable on virtually all kind of machines
  - simple datastructures, easy-to-understand
  - easy to install, no special libraries (except MPI)
  - light and flexible, easy to maintain
  - relatively quick to set up and user-friendly in operation
- The same "touch and feel" as SWAN.

Testing and validations

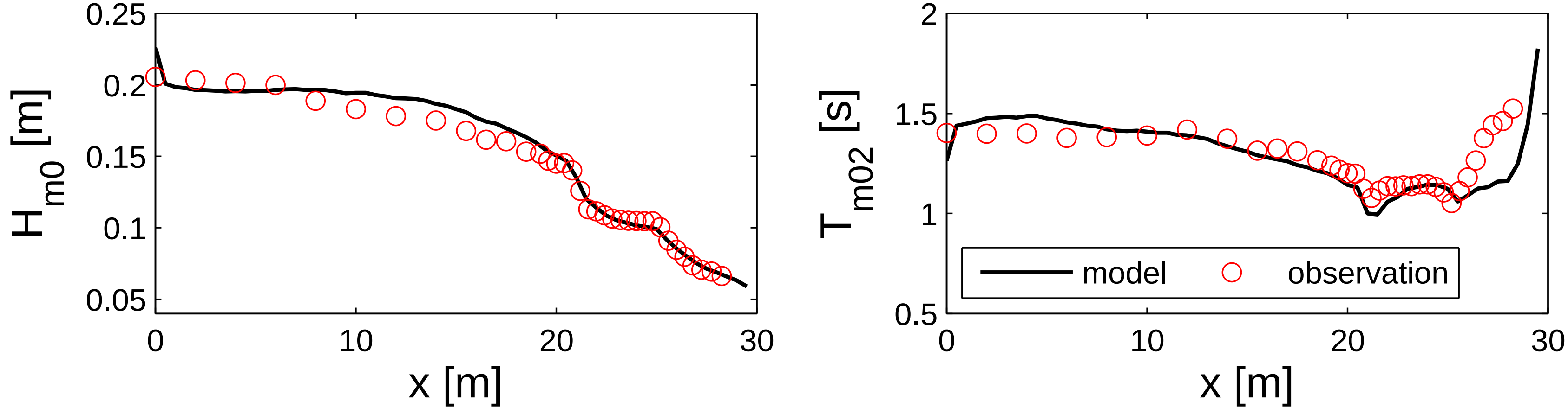
- Testbed: 50 well-documented analytical and laboratory tests including propagation, runup, dam break, hydraulic jumps, vertical mixing, etc.
- Many simple configurations:
  - flumes (2DV) and basins (2DH/3D),
  - bars (Beji-Battjes, Boers, Hiswa) and shoals (Berkhoff/elliptic, circular).
- Testing of different functionalities.
- More advanced validation: conical island, rip current, Petten, Hiswa.

Irregular wave breaking in a barred surf zone

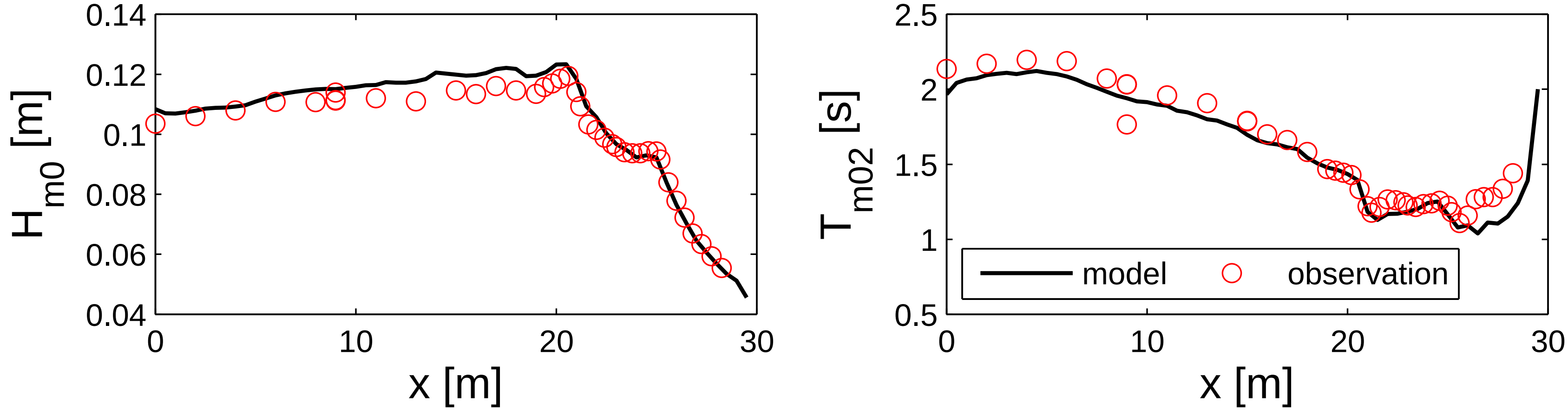


- Boers (1996); wave conditions 1B and 1C.
- Depth-averaged, 1D, $\Delta x = $ 0.03 m (150 gridpoints per wave length).
- Initial time step = 0.001 s; CFL = 0.5.
- Manning n = 0.027.

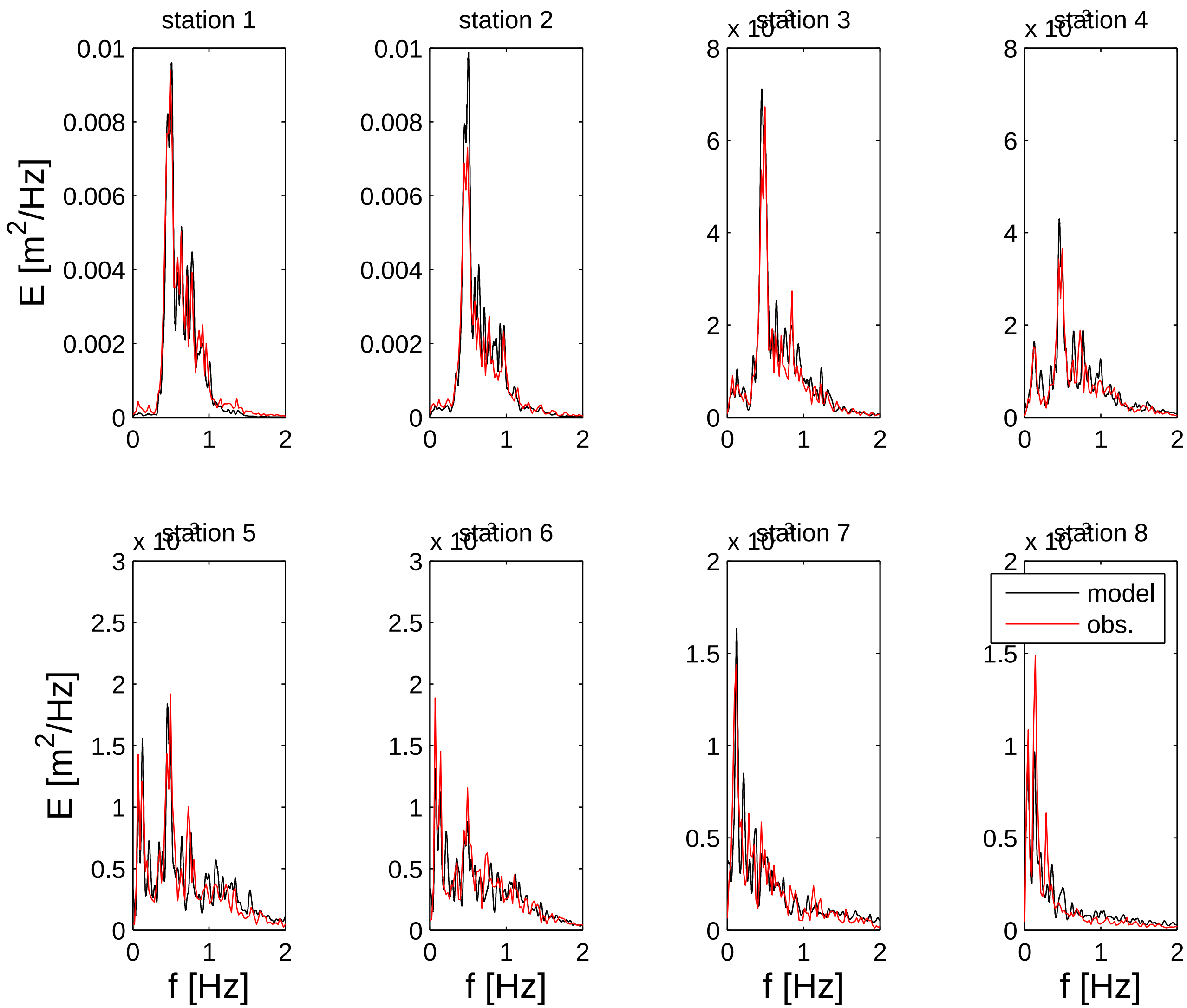
Boers 1B (H_{m0}=0.206 m, T_p=2.03 s)



Boers 1C (H_{m0}=0.103 m, T_p=3.33 s)

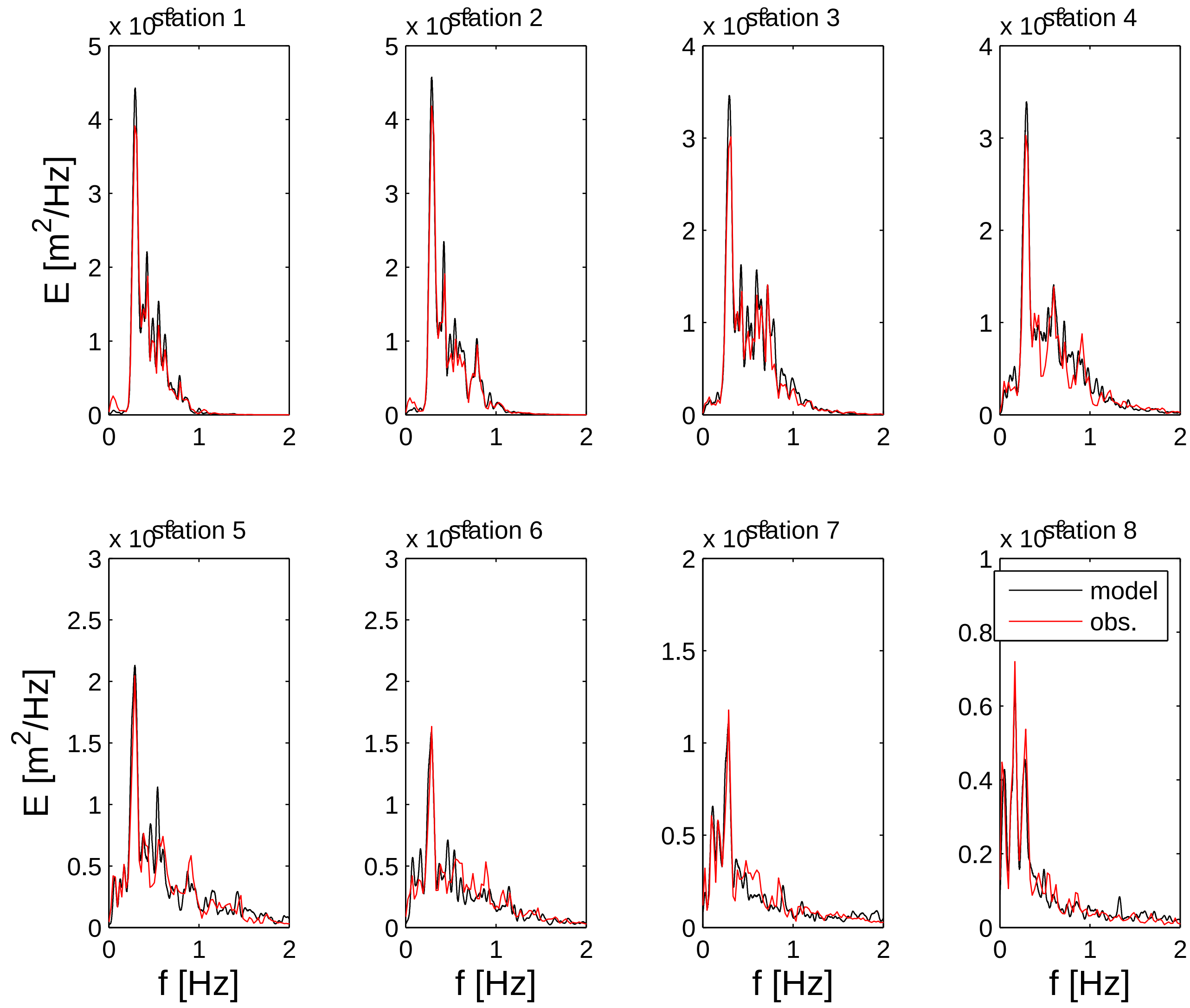


Boers 1B

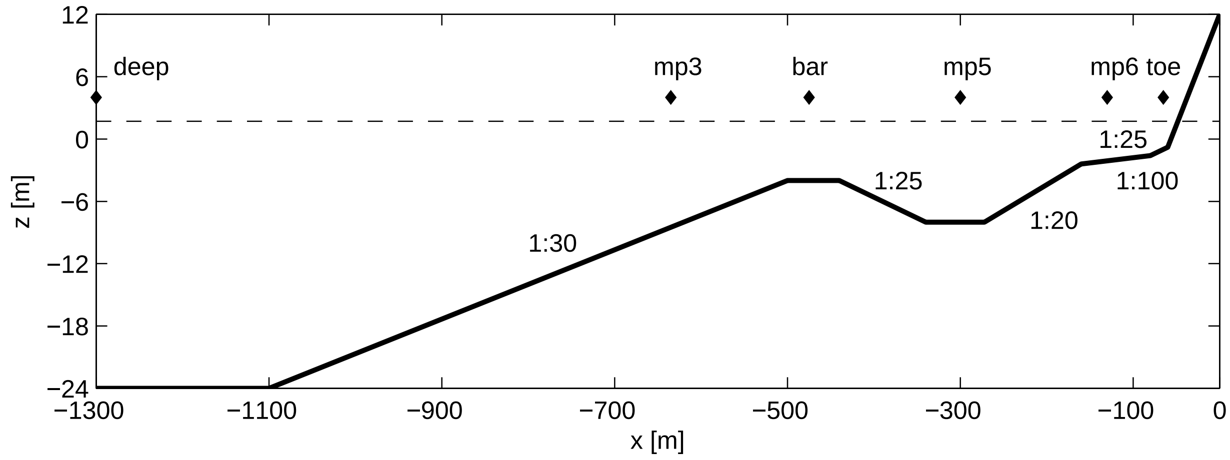


station 1
station 2
station 3
station 4
station 5
station 6
station 7
station 8
x 10^-3
E [m^2/Hz]
f [Hz]
model
obs.

Boers 1C

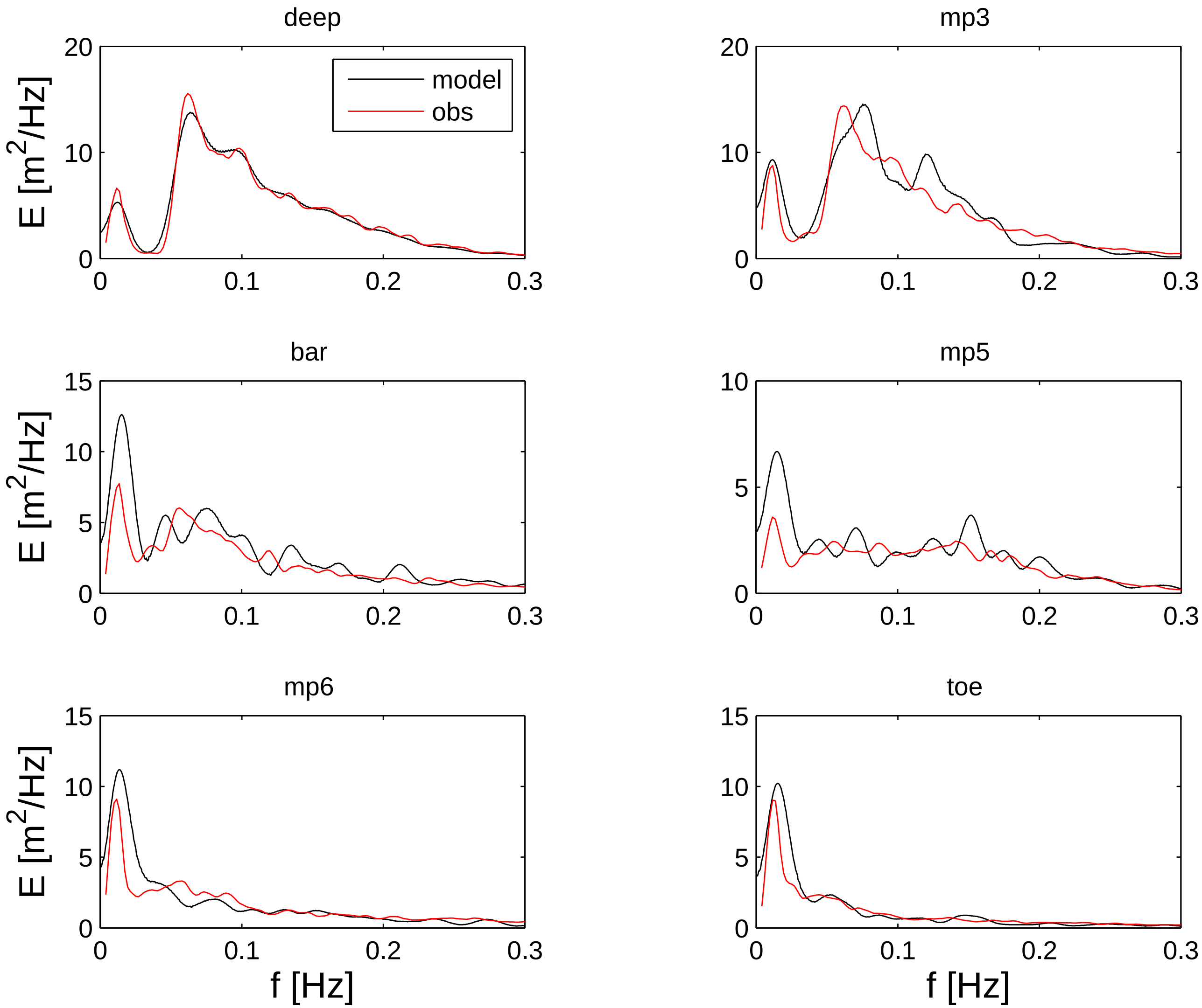

station 1
station 2
station 3
station 4
station 5
station 6
station 7
station 8
x 10
E [m²/Hz]
f [Hz]
model
obs.

Wave transformation over a shallow foreshore



- Measurements from Van Gent and Doorn (2000).
- $\Delta x = 1$ m (200 gridpoints per wave length).
- 2 equidistant layers.
- No bed roughness.
- Initial time step = 0.02 s; CFL = 0.5.

storm condition; H_{m0} = 4.4 m, T_p = 16.2 s



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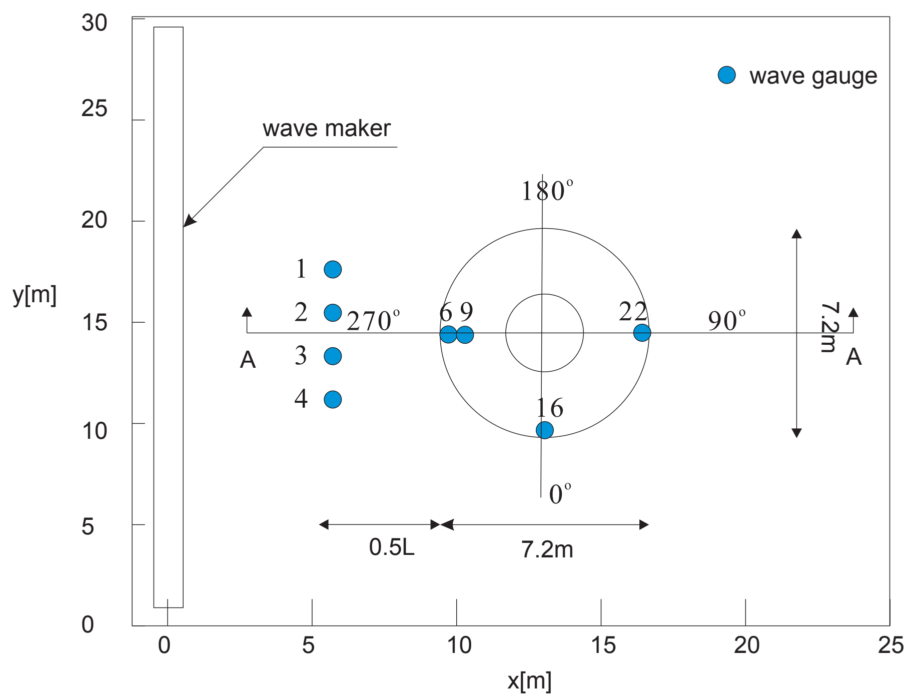
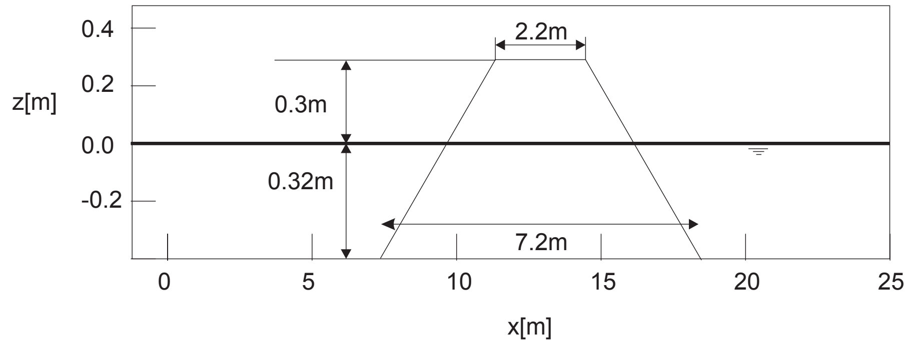
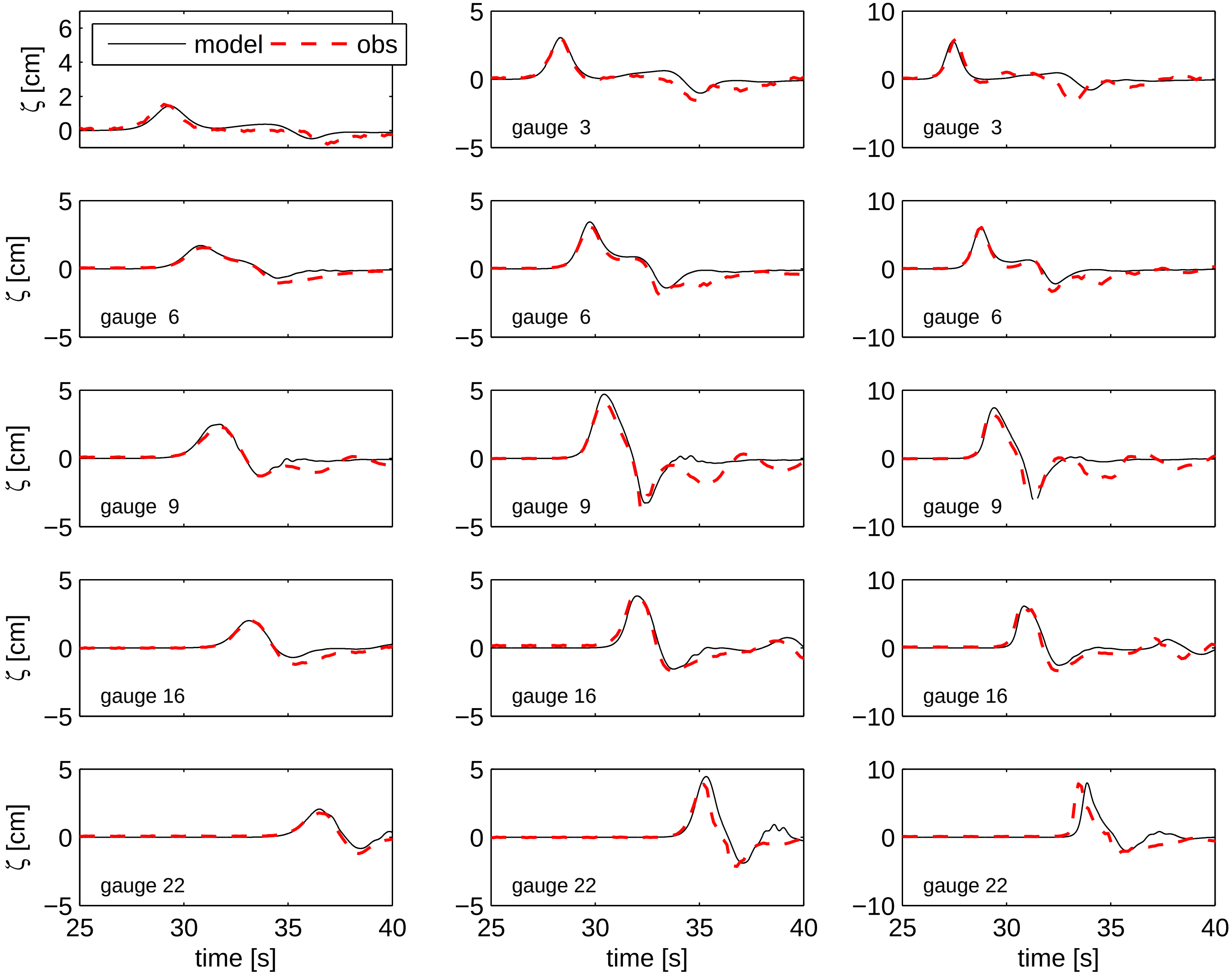
Runup of solitary wave on conical island

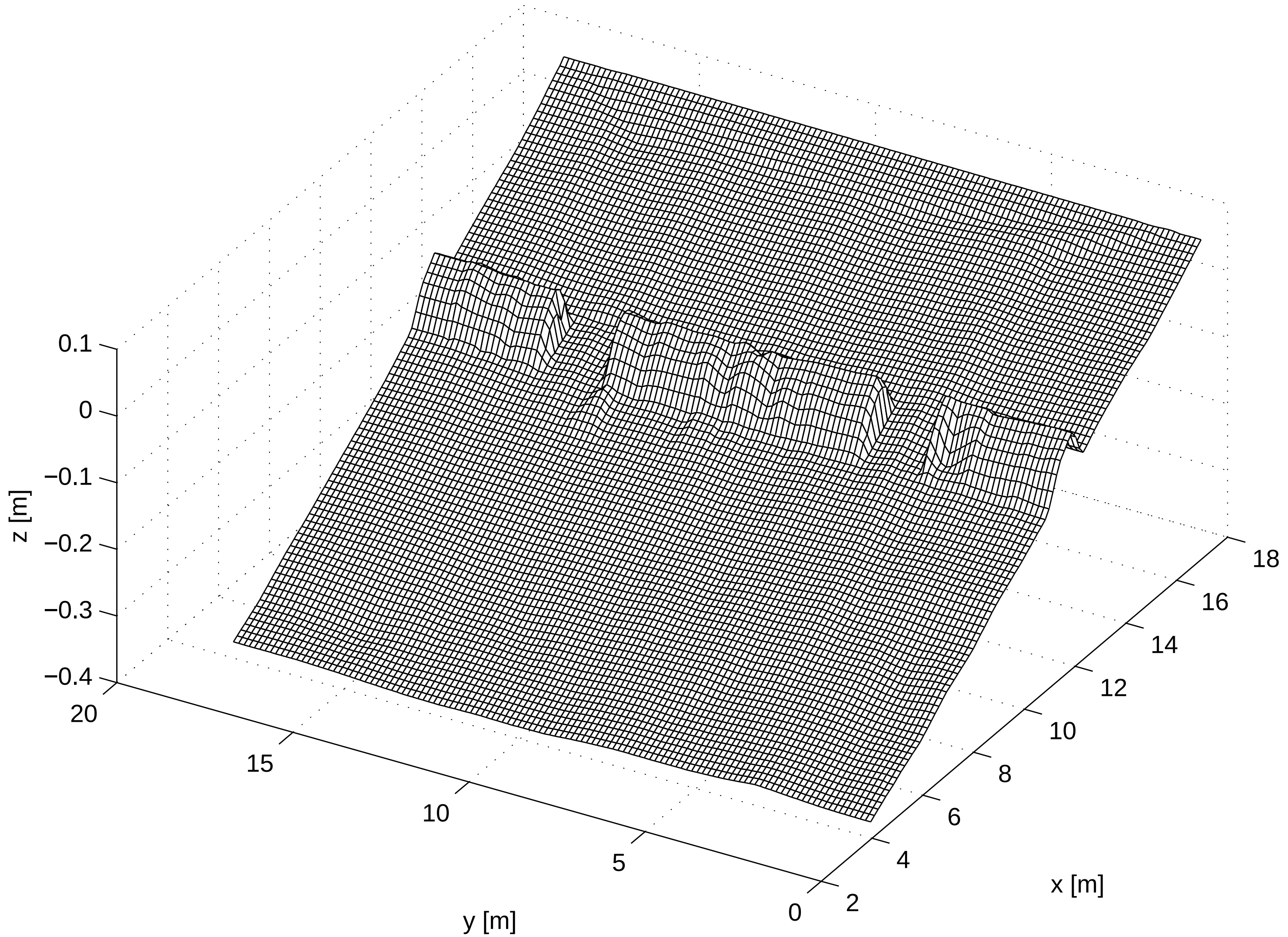




Conical island



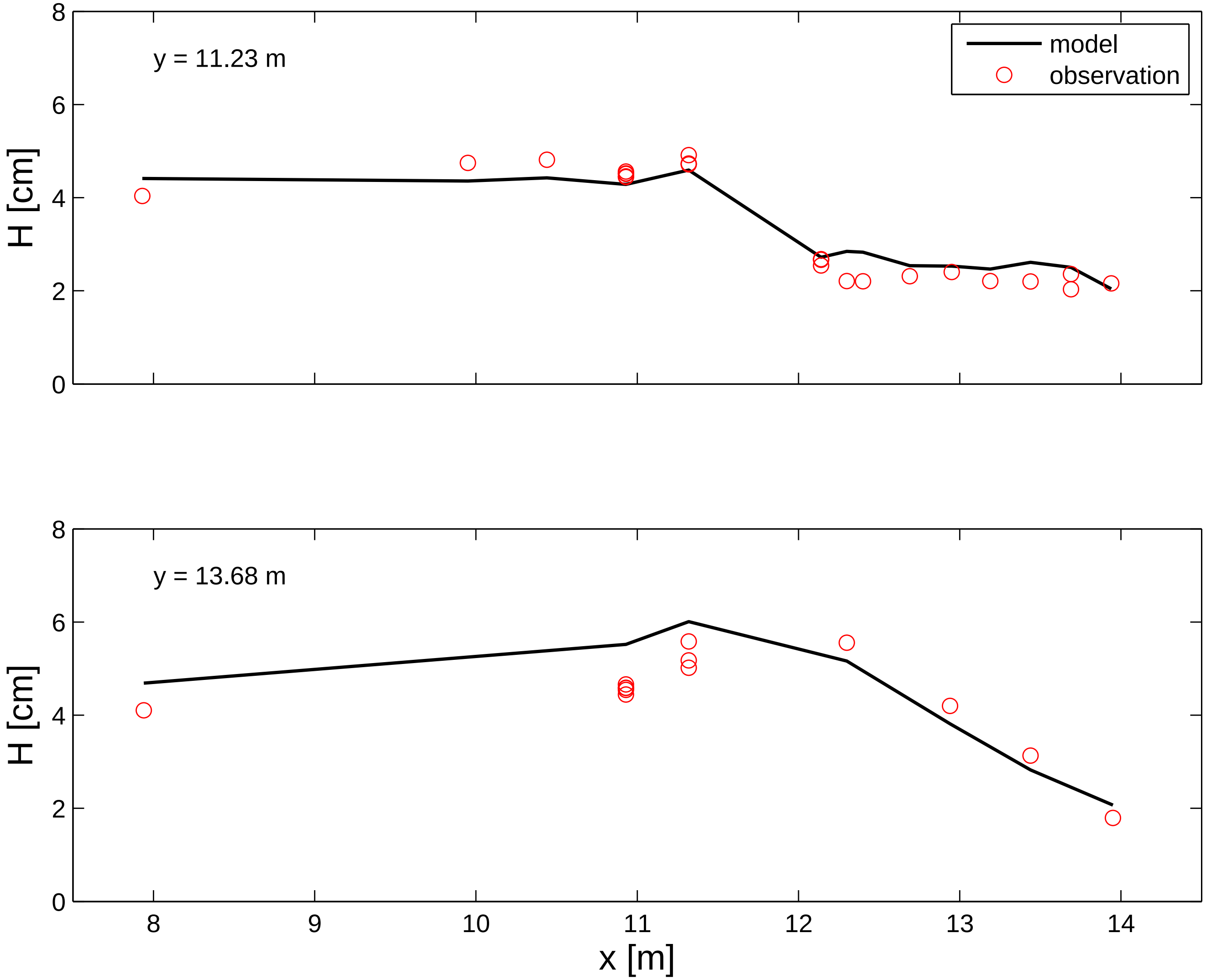
Circulation and rip current induced by bar breaks



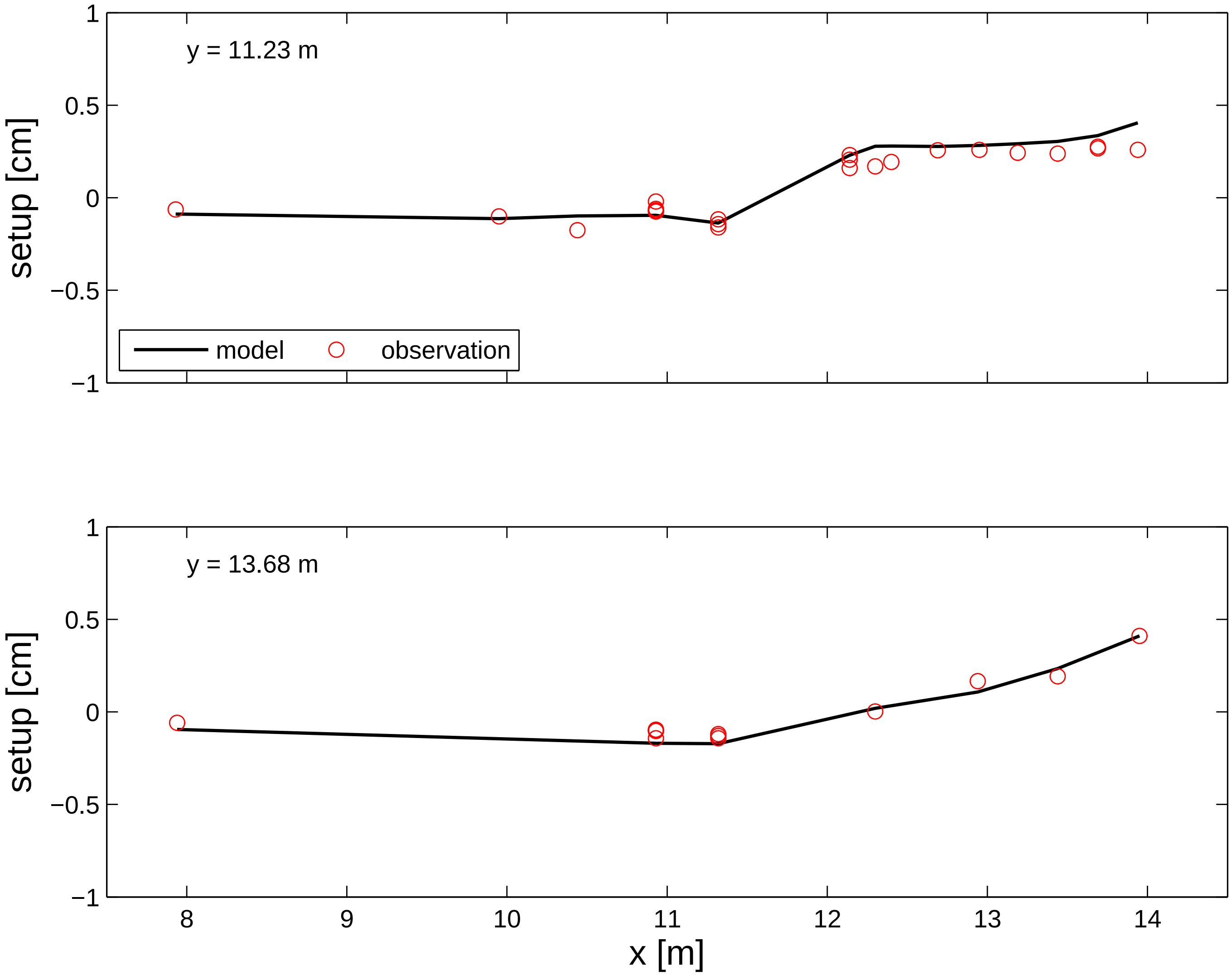
Rip current (2)

- Measurements from Haller et al. (2002).
- Monochromatic, normally incident wave: $H = 4.75$ cm, $T = 1$ s (test B).
- Depth-averaged.
- Manning n = 0.019.
- Smagorinsky subgrid model C_s = 0.1.
- $\Delta x = \Delta y =$ 0.05 m (30 gridpoints per wave length).
- Initial time step = 0.005 s; CFL = 0.5.

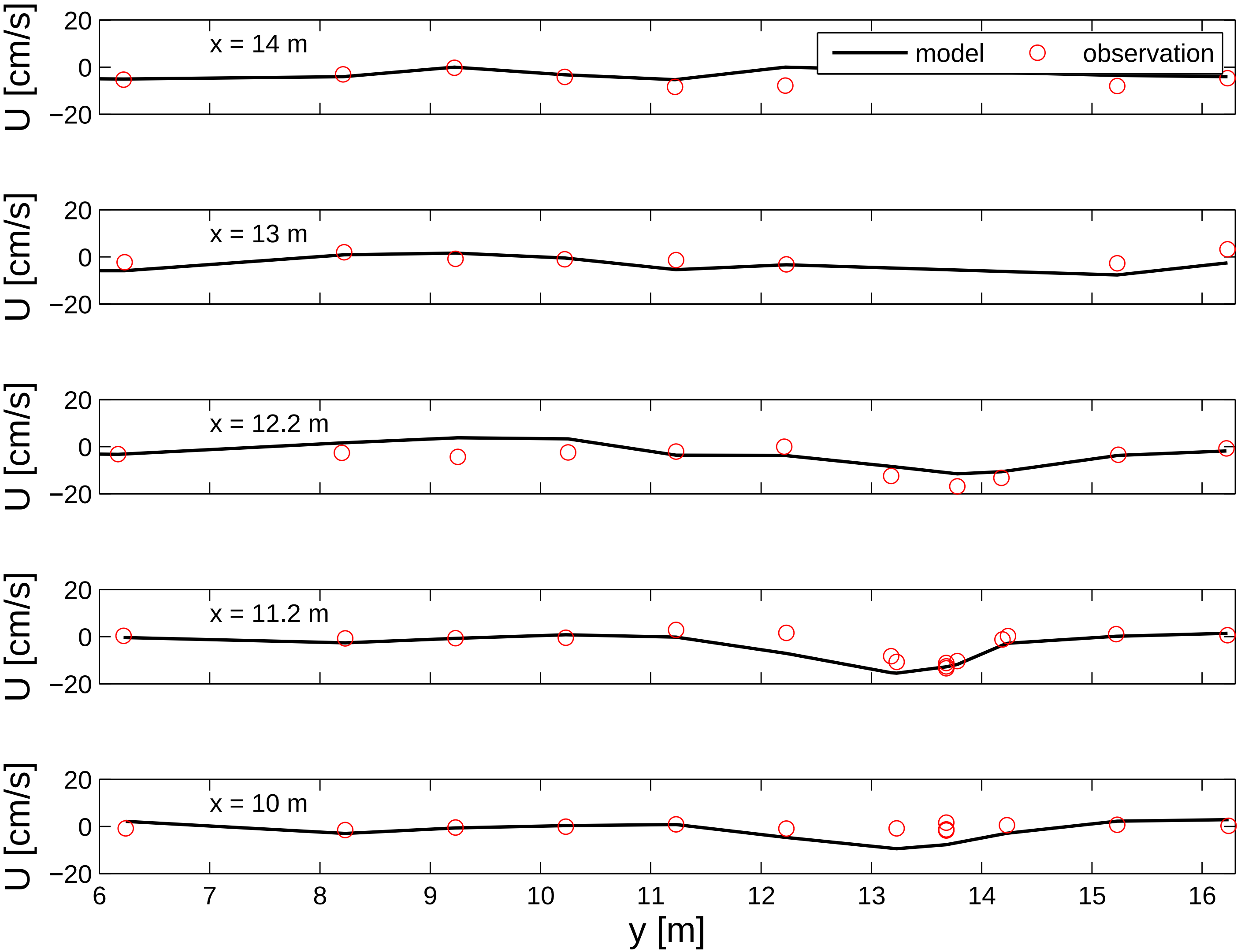
Rip current (3)



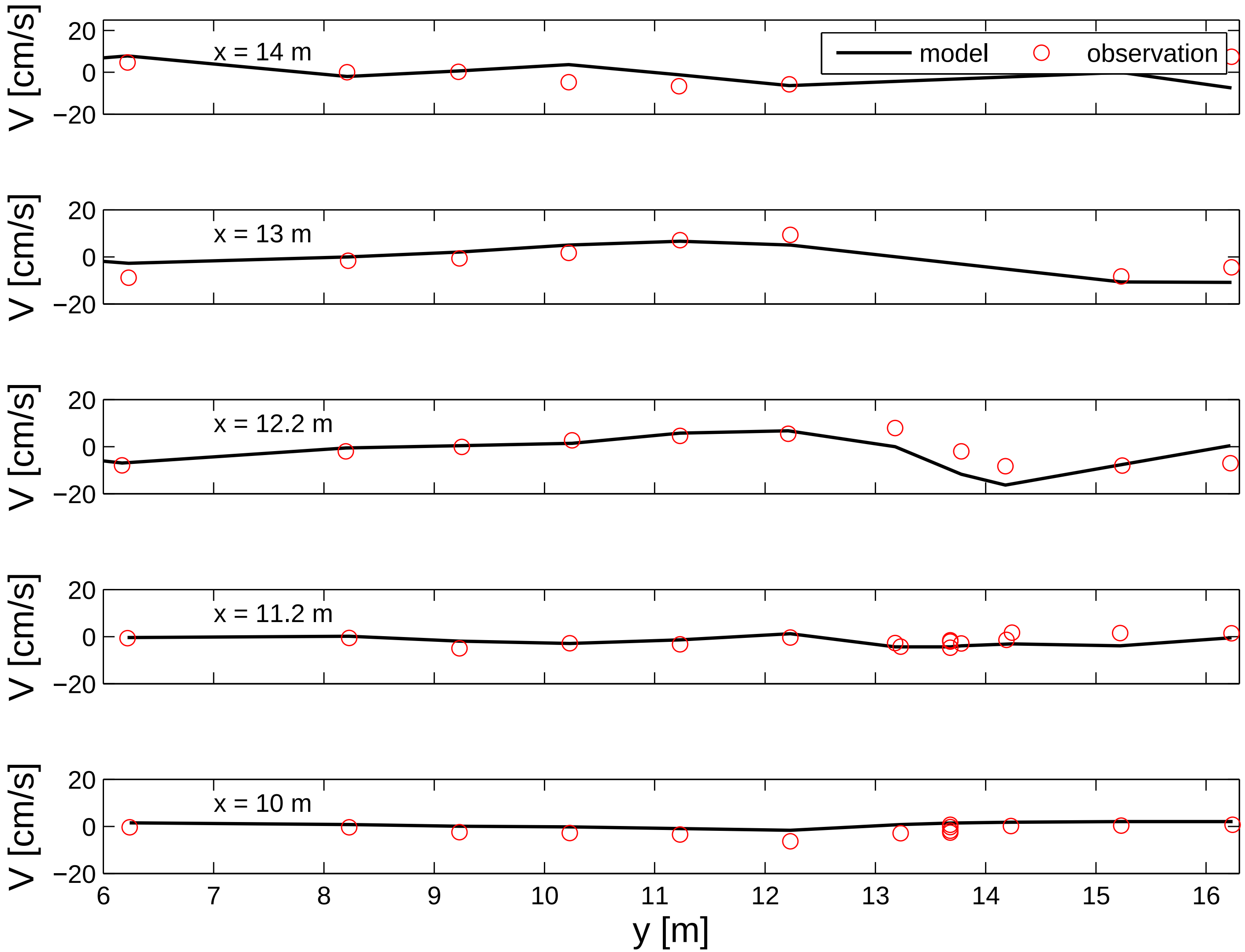
Rip current (4)



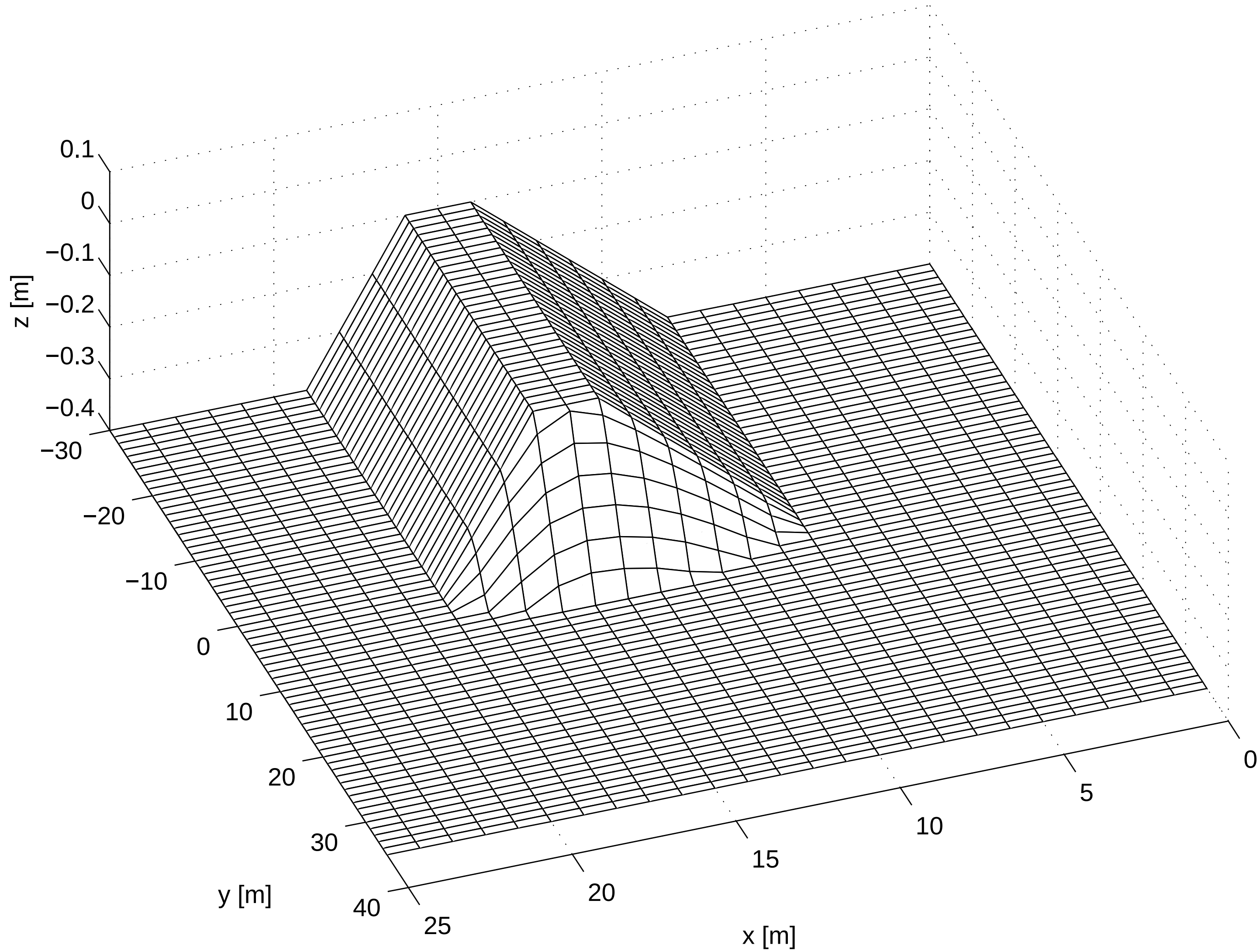
Rip current (5)



Rip current (6)



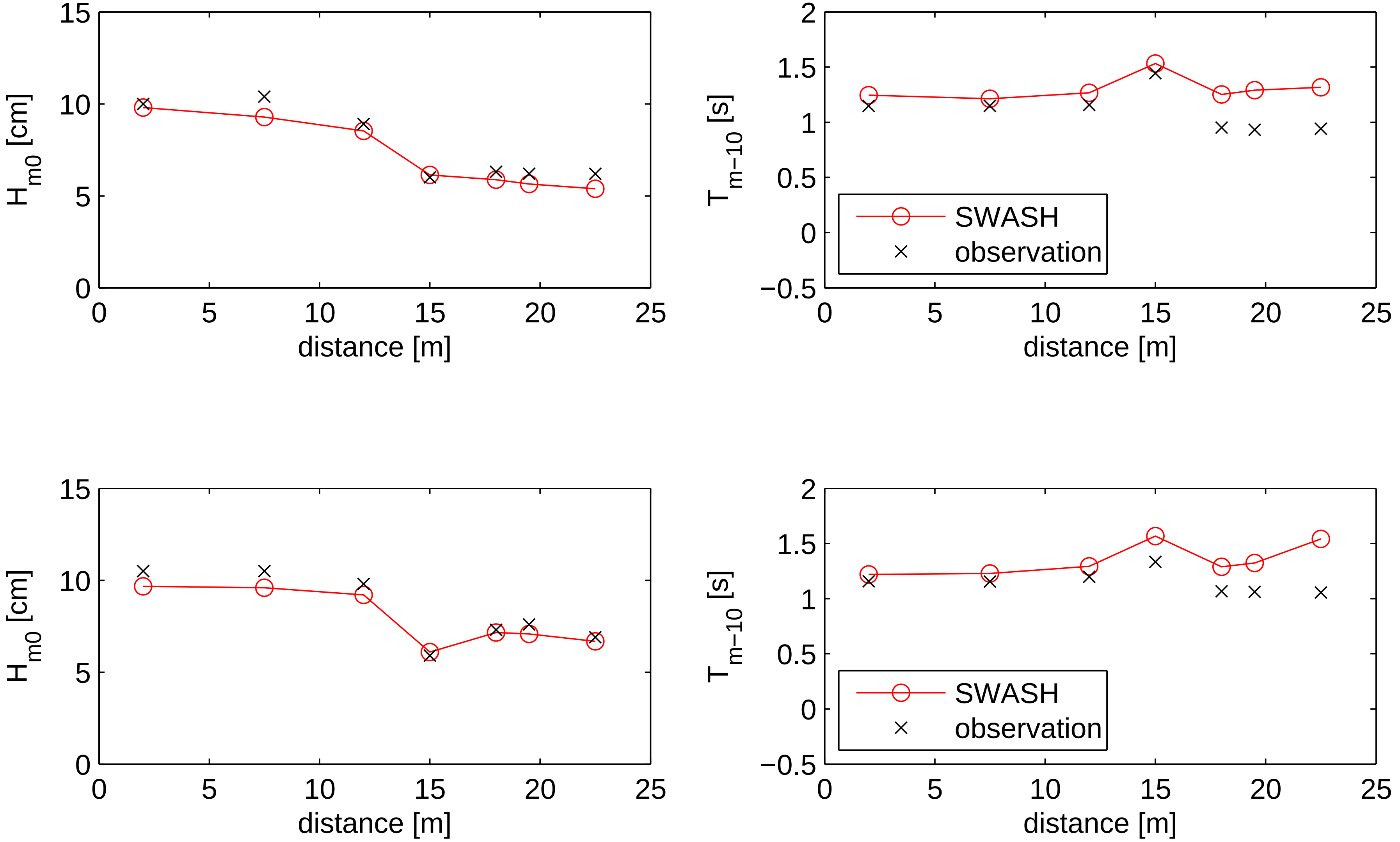
Multi-directional waves propagating through a barred basin



HISWA (2)

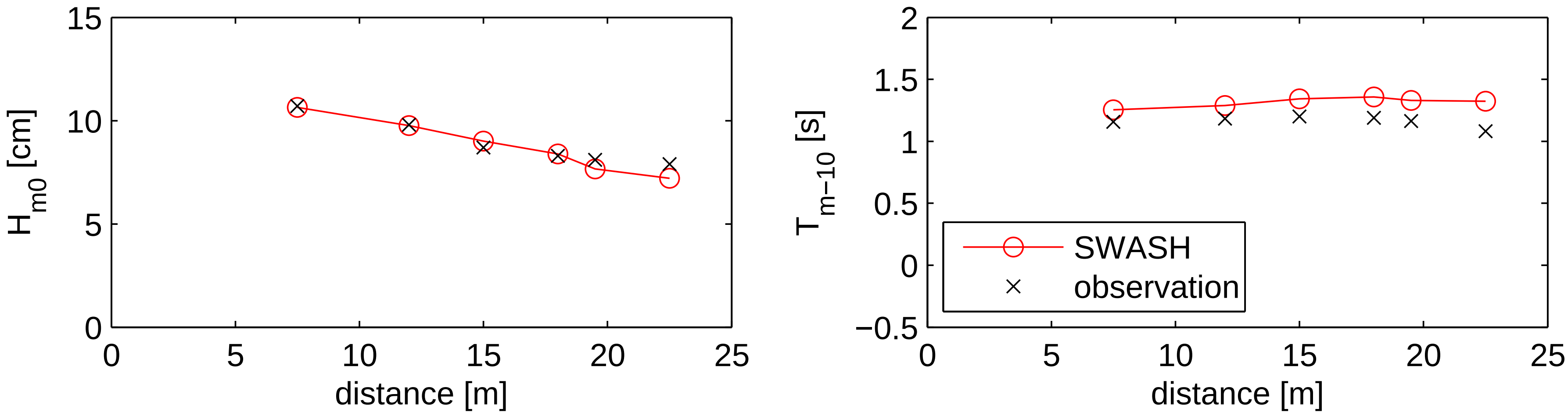
- Dingemans (1987); case me35.
- 2D Jonswap spectrum: $H_{m0} = 10$ cm, $T_p = 1.24$ s, $\cos^4(\theta)$.
- $\Delta x = 5$ cm, $\Delta y = 3$ cm.
- Initial time step = 0.005 s; CFL = 0.7.
- 2 equidistant layers.
- Smagorinsky model C_s = 0.1.
- Manning n = 0.02.

HISWA (3)

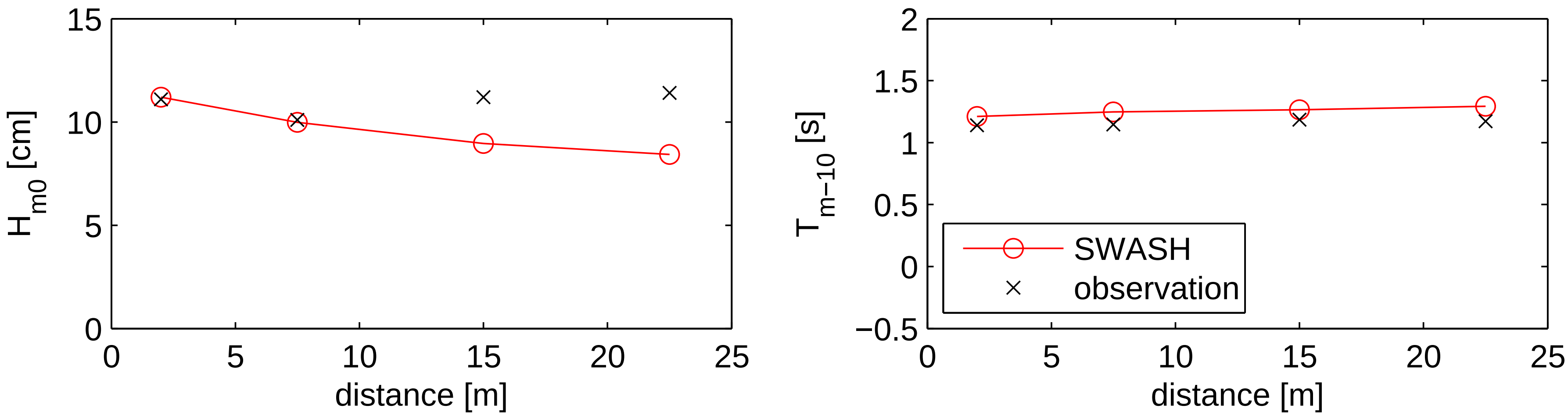


15
10
5
0
H_{m0} [cm]
0 5 10 15 20 25
distance [m]
2
1.5
1
0.5
0
−0.5
T_{m-10} [s]
SWASH
observation
0 5 10 15 20 25
distance [m]

HISWA (4)

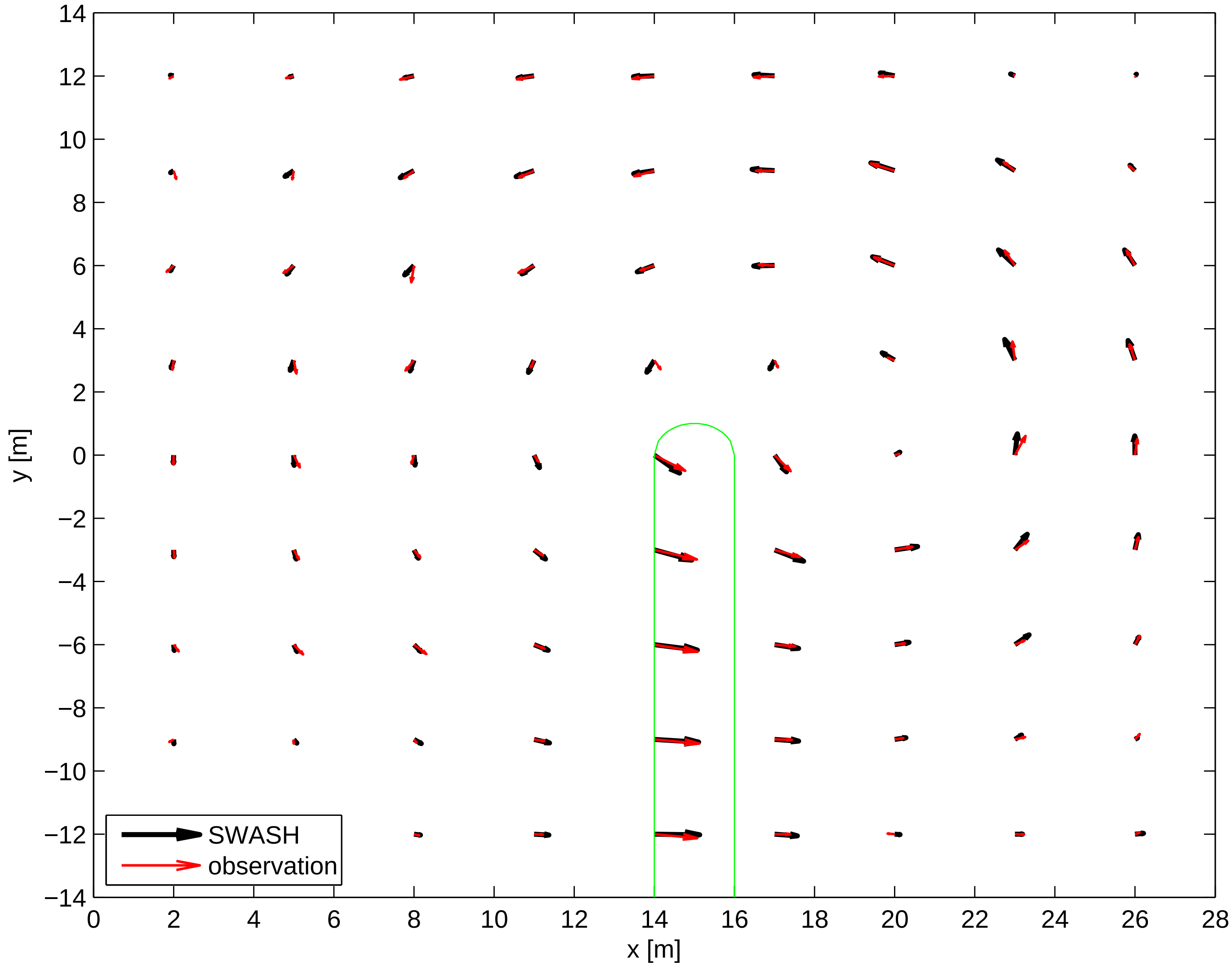


15
10
5
0
H_{m0} [cm]
0
5
10
15
20
25
distance [m]
2
1.5
1
0.5
0
−0.5
T_{m-10} [s]
SWASH
observation



15
10
5
0
H_{m0} [cm]
0
5
10
15
20
25
distance [m]
2
1.5
1
0.5
0
−0.5
T_{m-10} [s]
SWASH
observation

HISWA (5)



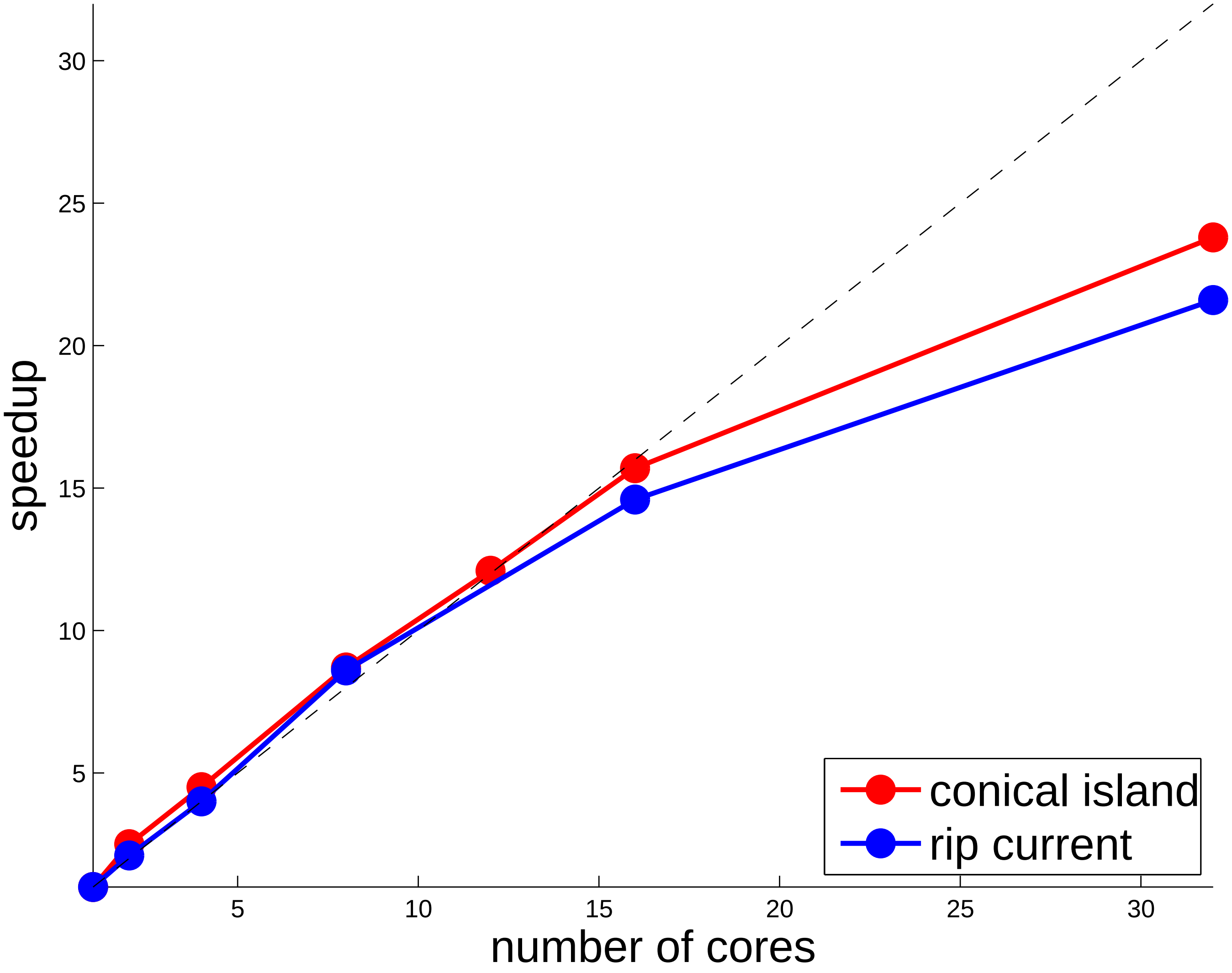
14
12
10
8
6
4
2
0
−2
−4
−6
−8
−10
−12
−14
y [m]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
x [m]
SWASH
observation

Performance

CPU time in μsec per gridpoint/time step on comparable processors:

simulation	#proc	SWASH	COULWAVE	FUNWAVE
Berkhoff shoal	1	3	21	60
	8	0.3	3.2	–
Conical island	1	2.2	–	40
	32	0.08	–	–
Rip current	1	1.6	16.4	–
	18	0.1	1.1	–
	32	0.076	–	–

Parallel efficiency - IBM Power6 cluster



Further developments and plans

- Interaction with structures: (partial) reflection, transmission.
- Wind effects on wave transformation.
- Wave-induced forces on mooring ships (PhD project).
- Extension to unstructured grids.
- OpenMP, hotstarting, NetCDF, ...
- ...

http://swash.sf.net