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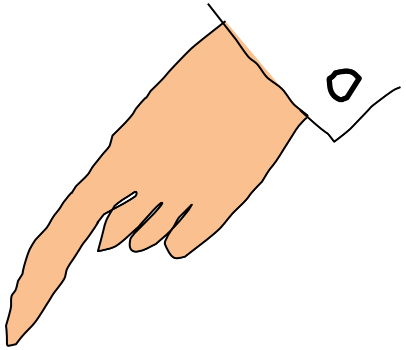
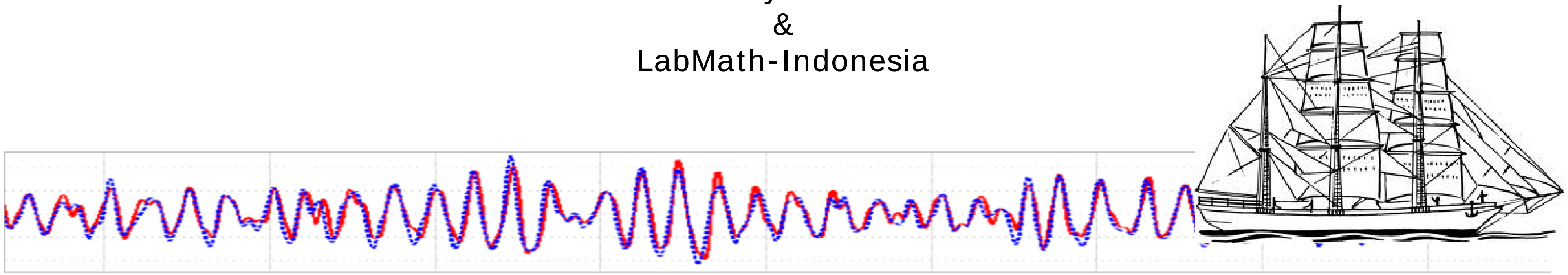


HaWaSSI
Hamiltonian Wave-Ship-Structure Interaction

Brenny van Groesen
University of Twente
&
LabMath-Indonesia



HaAB WaSSI

Analytic Boussinesq

Andonowati
Lie She Liam
Andy Schauf
Nida Latifah
Ruddy Kurnia

Variational Boussinesq Model

VBM HaWaSI

Gert Klopman
Ivan Lakhturov
Didit Adytia
Wenny Kristina
Mourice Woran

Sea states from radar images

Andreas Wijaya

LabMath-Indonesia (Bandung)

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Motivation

Modelling & simulation

- Many codes available for ‘wave‘ simulations (irrotational flow)
  - Full Euler codes : CFD
  - Approximate models to avoid direct calculation of interior Laplace problem,e.g.
    - SWASH (vertical layers), ...
    - Boussinesq-type equations (dispersion approx. with algebraic diff.operator
- With HaWaSSI we aim to exploit some basic math structures:
  - Dynamics is Hamiltonian system in surface variables (Boussinesq, exact energy conservation)
  - Laplace ←→ Dirichlet principle → consistent approximation in functional, symmetry in eqn‘s
- Two versions:
  - AB: Fourier expansion (global→ local), exact dispersion
  - VBM: pcw-lin splines in FE, optimized dispersion

Contents

Show performance

Explain math background

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Simulations for Coastal Engineering applications

Essential topics for simulation

WAVES

- DISPERSION (from deep sea to run-up at the coast)
- Nonlinearity, Breaking & set-up, freak waves
- Coastal run-up and harbour entrance
- Infragravity waves (for LNG in shallow water)
- **SHIP**
- Motion (in waves), ship-interactions, near quay
- Mooring
- Ship waves (entering harbour, coast)

Comparison with experiments

MARIN

Deltares Enabling Delta Life

TUDelft

Test Cases & simulations

Validation wave tank (1HD)

- Irregular waves above Varying bottom
- Freak waves, Focussing waves
- Deep water breaking
- Bathymetry induced breaking

Validation wave basin (2HD)

- Harbour: Limassol

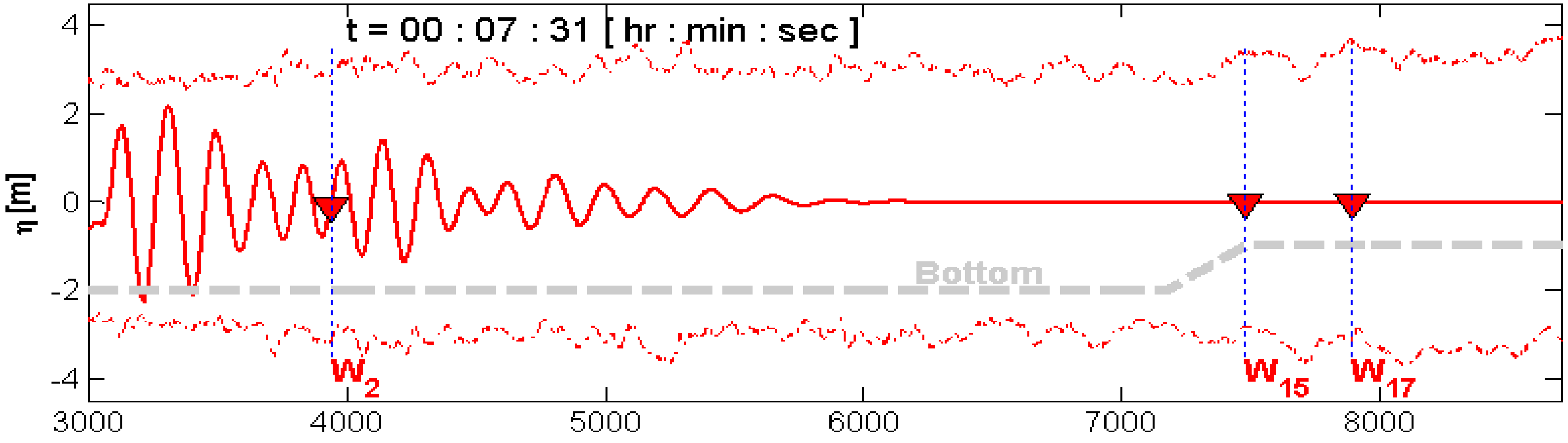
Other simulations (2HD)

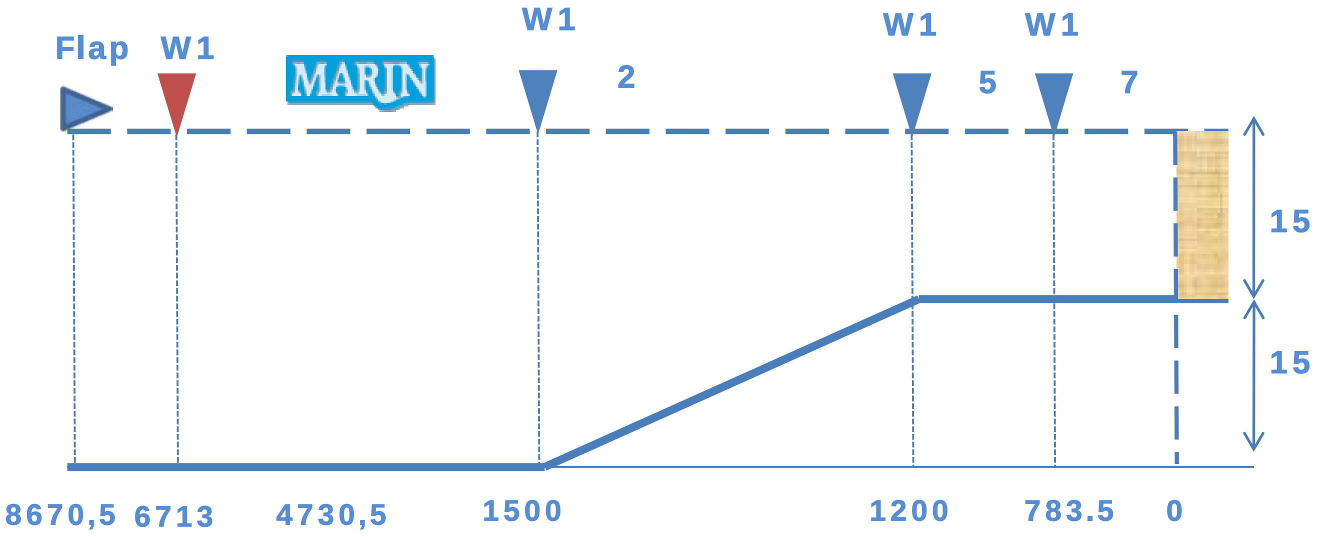
- Cilacap: infragravity waves
- Jakarta sea dike

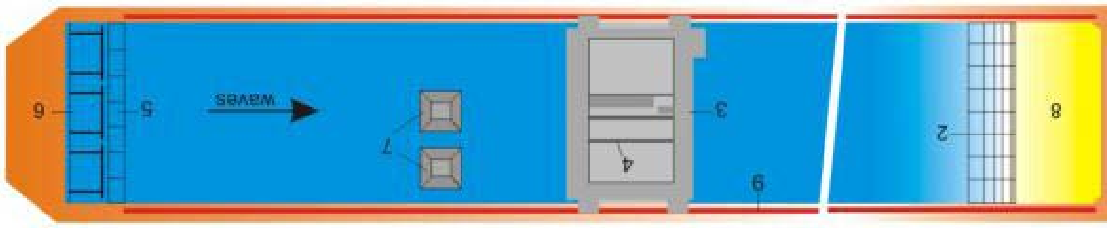
HAWAII Simulations vs Experiments

Experiment of irregular waves in MARIN hydrodynamic lab
scale of 1:50

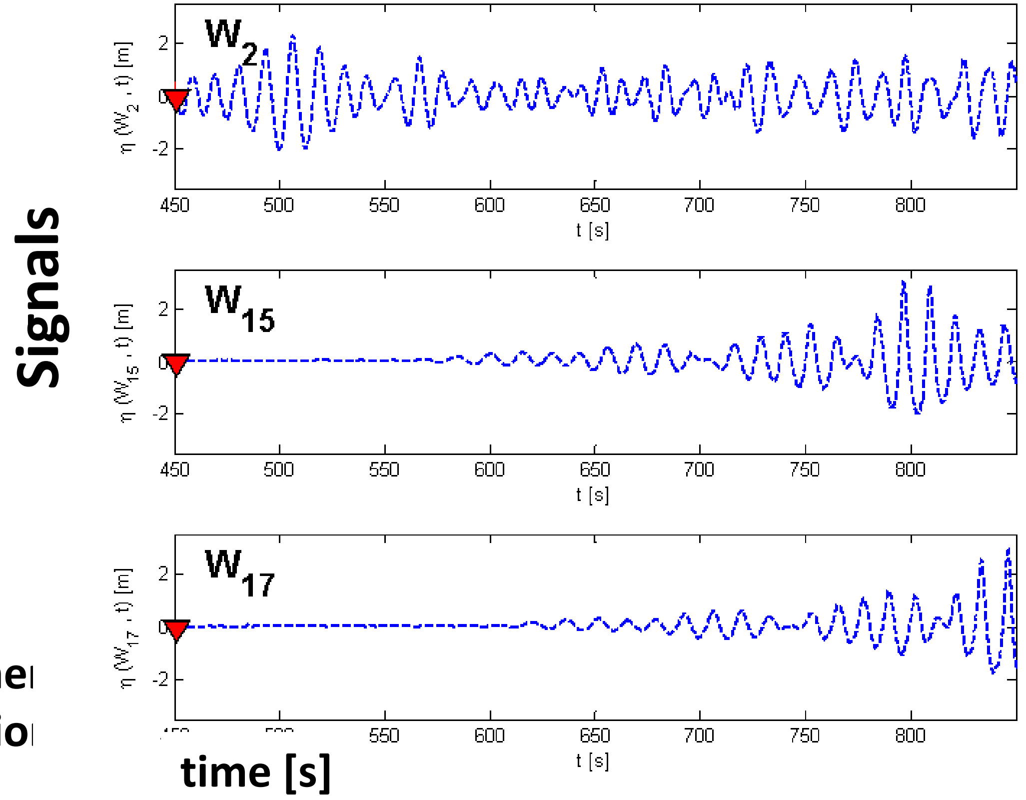
Period ≈ 12.2s
Wavelength ≈ 180m (at h = 30m)
≈ 130m (at h = 15m)







: Buoy(s)
: Experime
: Simulatio



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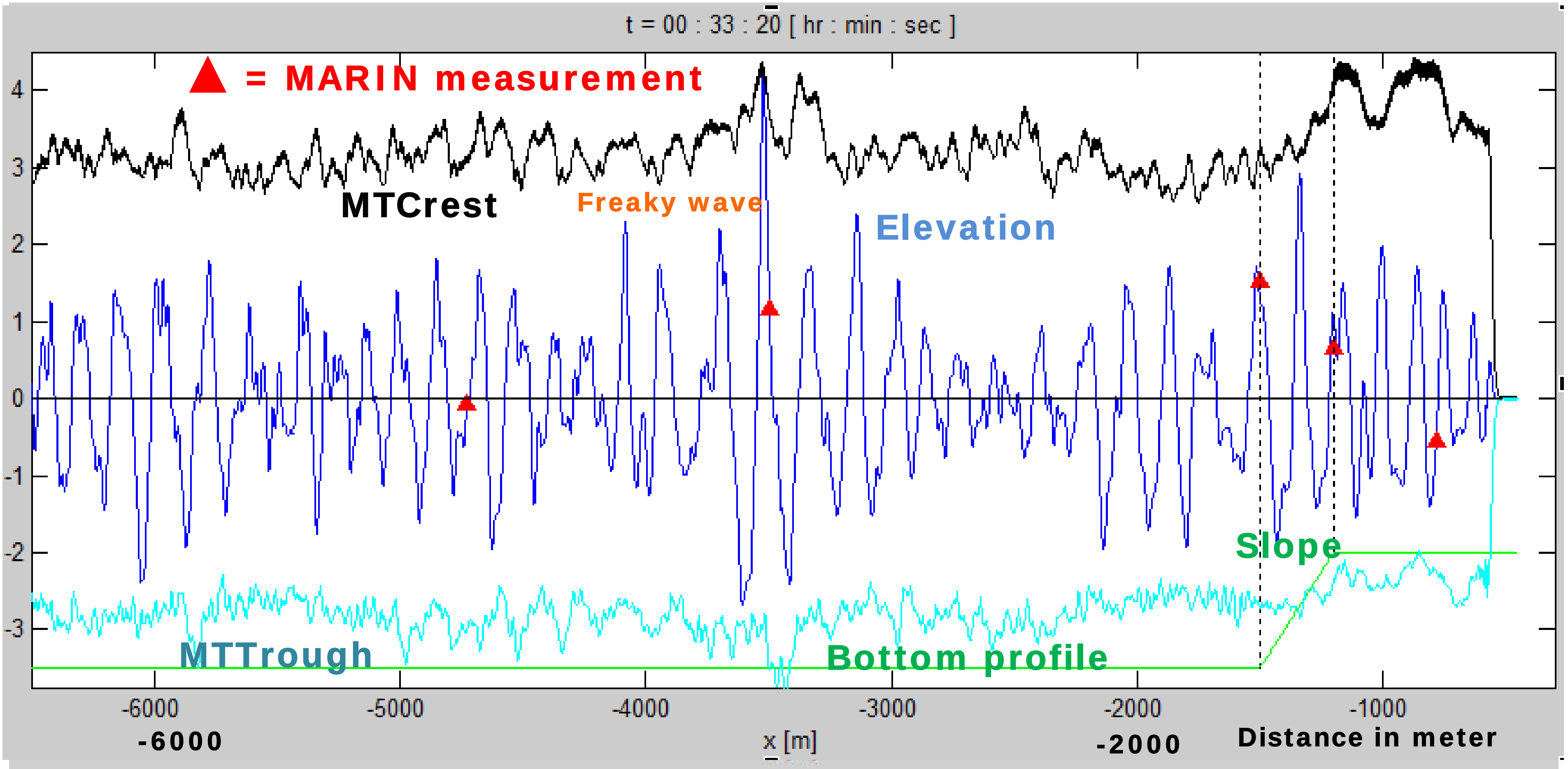
Irregular waves, MARIN Bench 103001

FREAK WAVES

- 3hrs time signal, approx. 1000 waves
- Period: 12s, Hs= 3m

Comparison Exp-Simul at W2, W9, W12, W15 and W17



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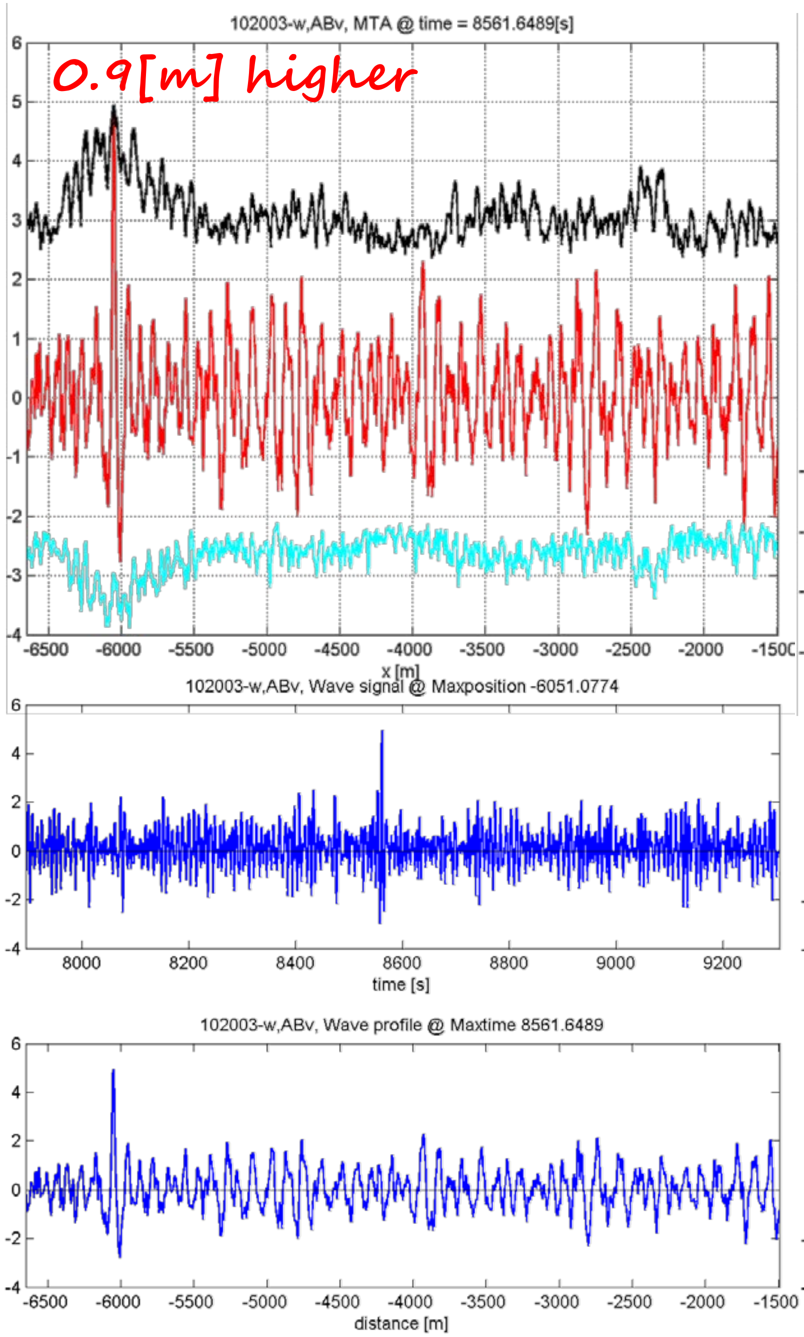
FW-analysis MARIN 102003

date	18-Jun-11	02-Jul-11
wavename	102003_w	102003_w
Depth	30	
PeakPeriod	8.26	
Wavelength	101.55	
HsTot	**3.07**	
DynModel	**NONlin**	**ABv LINEAR**
Freak analysis	--	--
Xfr	**-6051.08**	**-6190.52**
Tfr	**8561.65**	**8542.13**
Crestheight	**4.94**	**4.07**
Troughdepth	**-2.98**	**-2.90**
Waveheight	**7.92**	**6.97**
WH/Hs	**2.58**	**2.27**

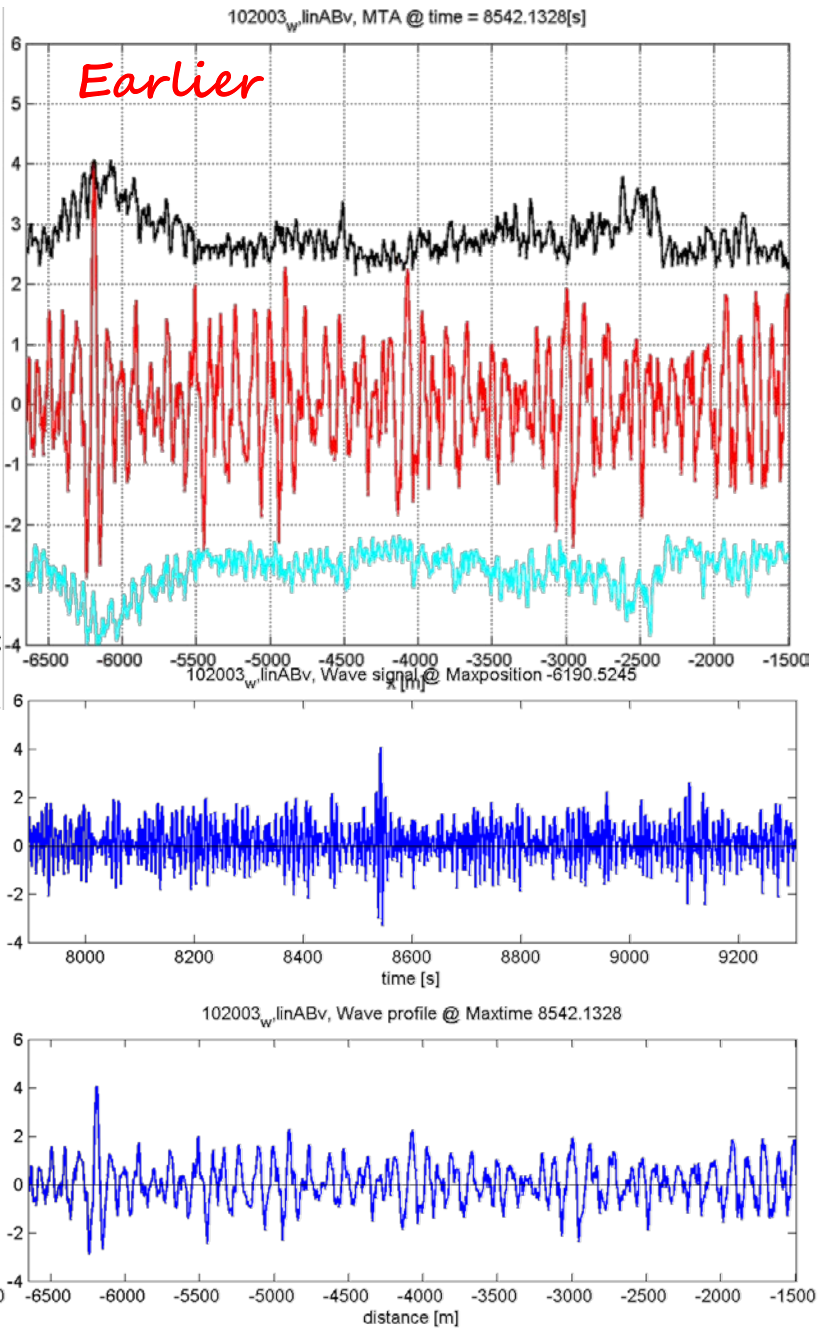
Linear compared to nonlinear:

- earlier in time: 20[s], shorter distance 140[m] (group velocity)
- crest height 0.9m lower, through 0.08 m less deep

NONlin SIMULATIONS



LINEAR SIMULATIONS



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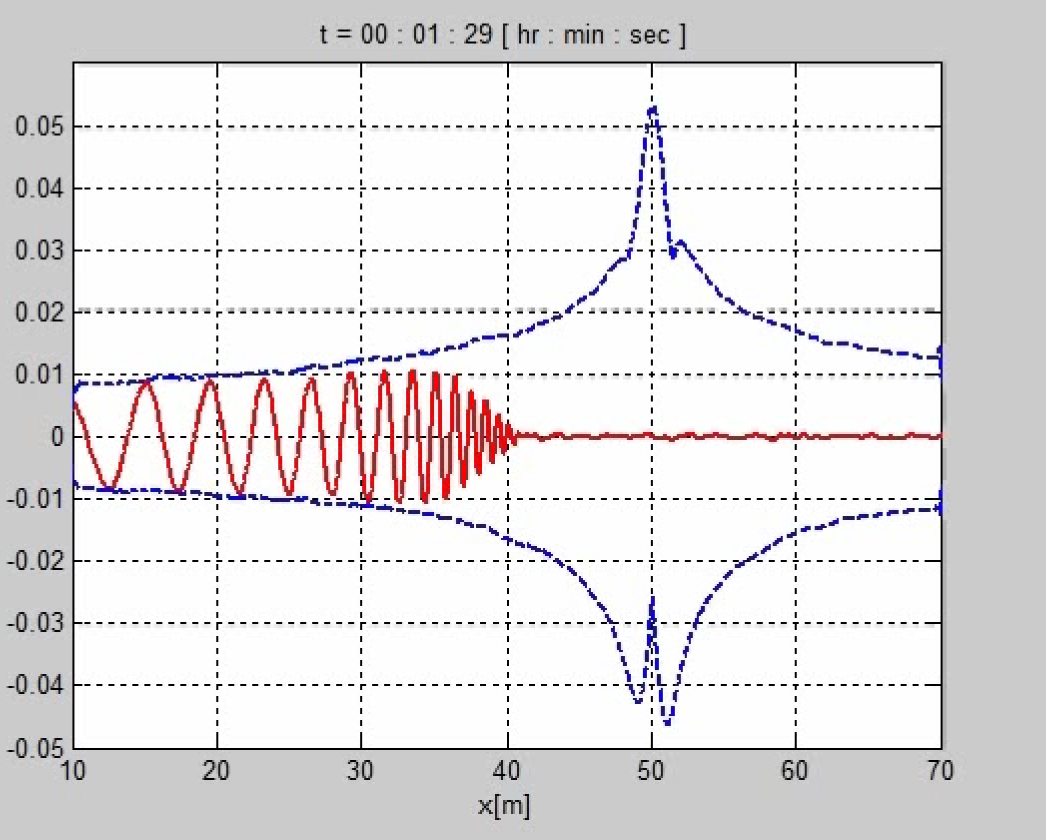
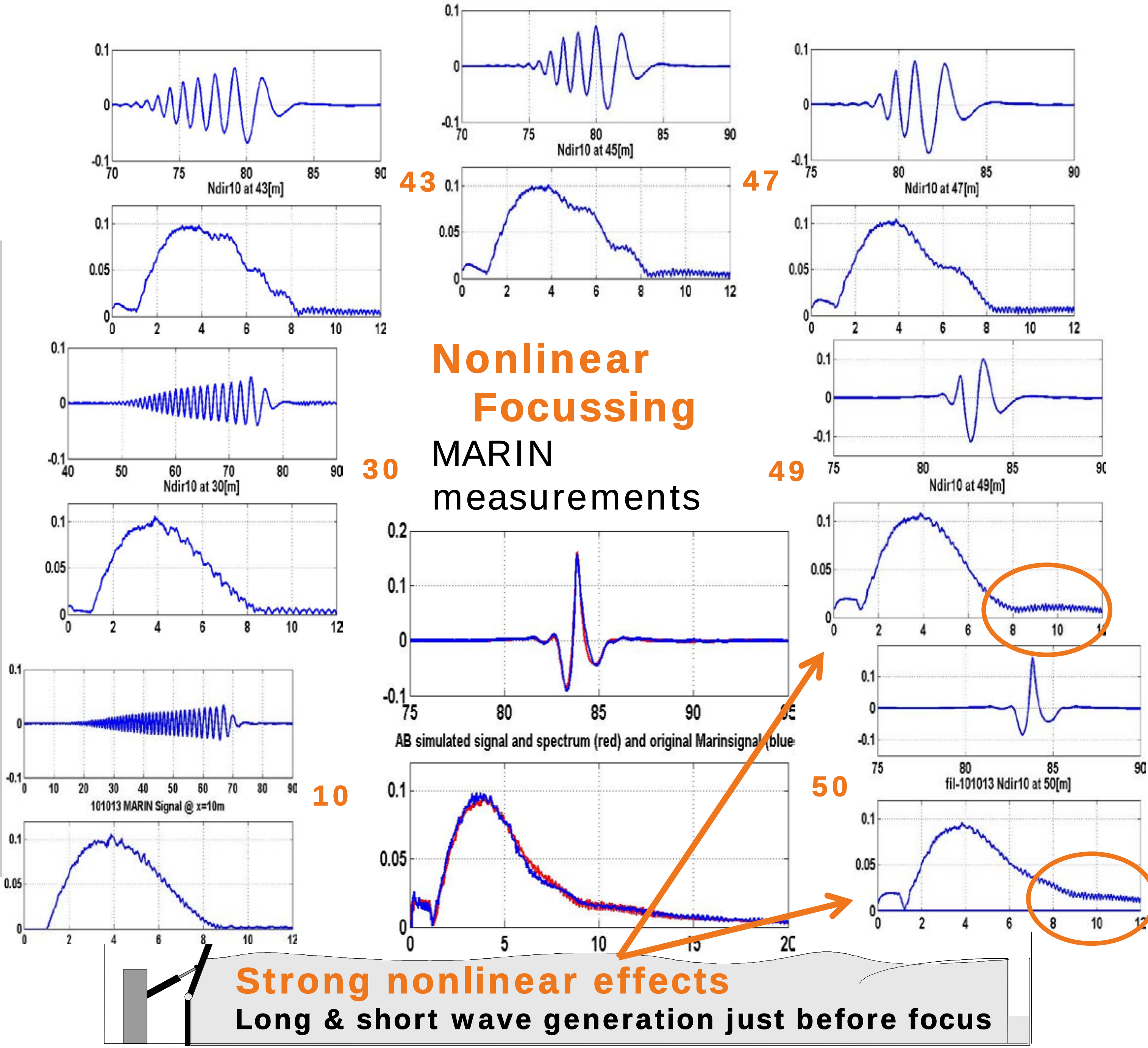
MARIN

Wave Focussing



Nonlinear Focussing

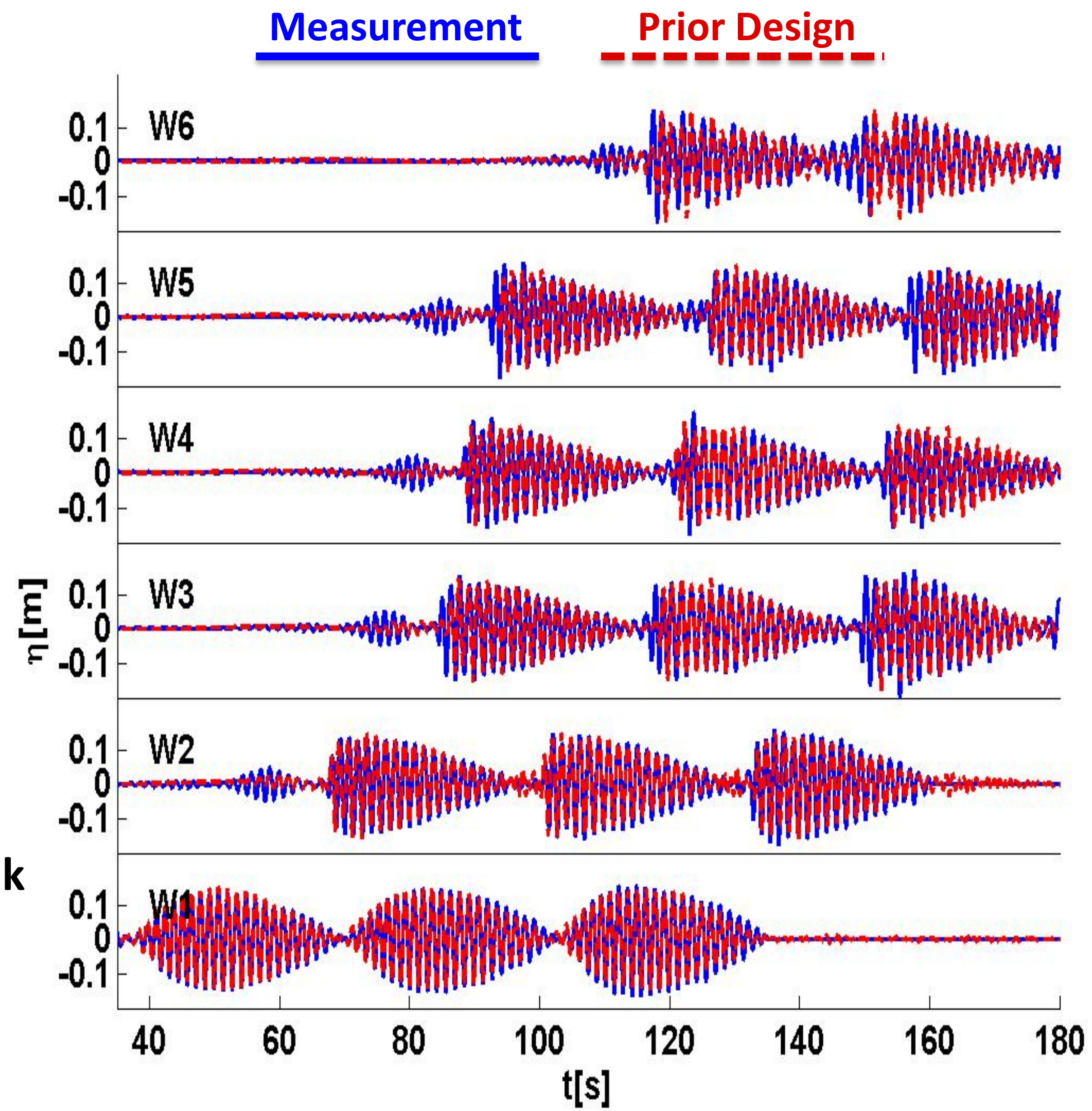
MARIN measurements



Strong nonlinear effects

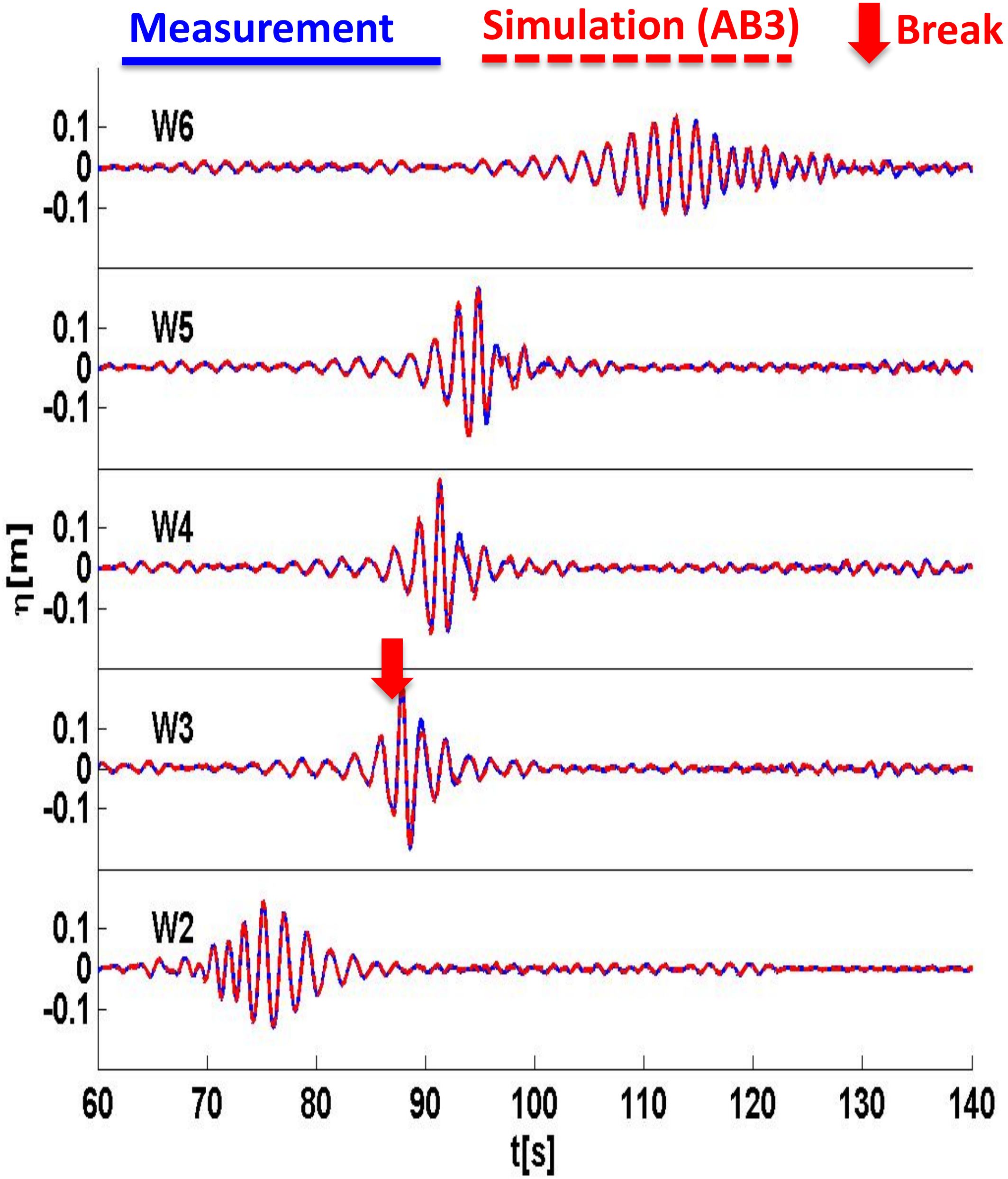
Long & short wave generation just before focus

Design and pre-calculation experiment TUD wave tank



Bichromatic wave breaking, k.a=0.3, at TU-Delft towing tank

Wave breaking



Focussing $k_p.a=0.11$

TUD1403Foc7

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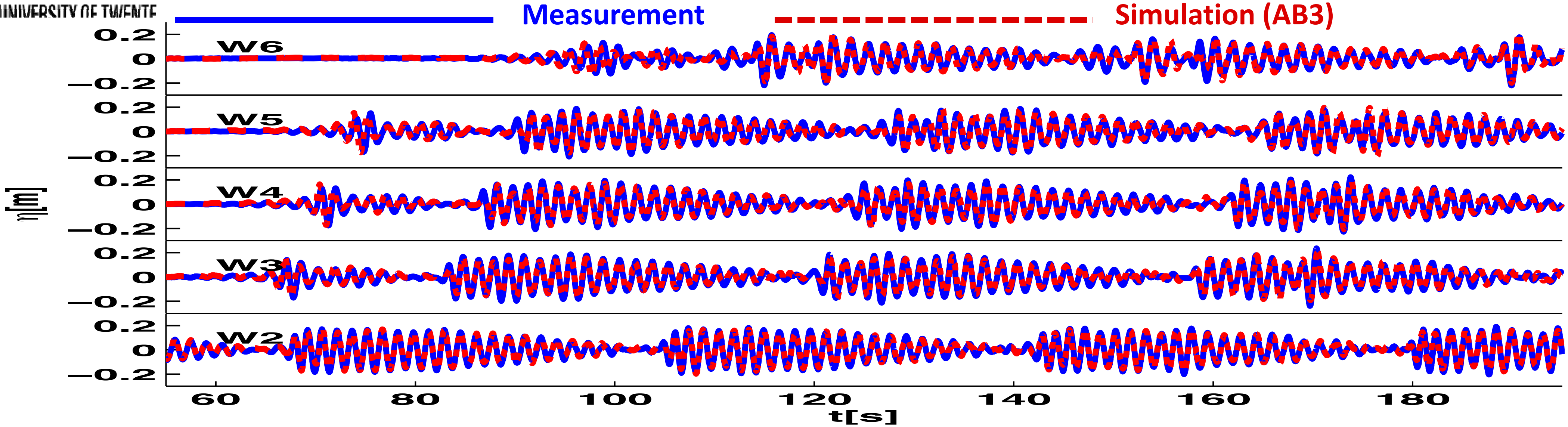
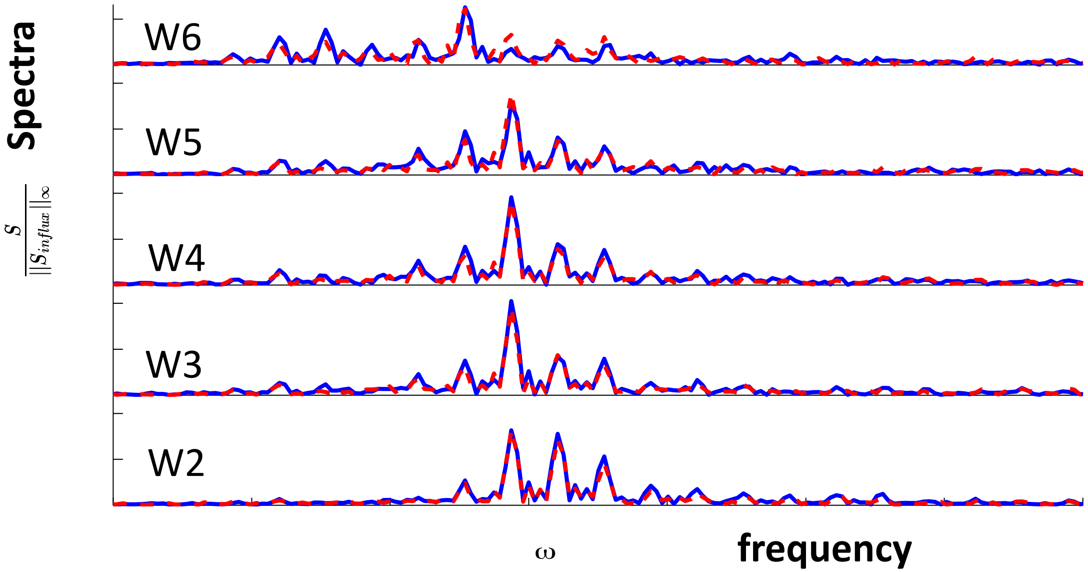
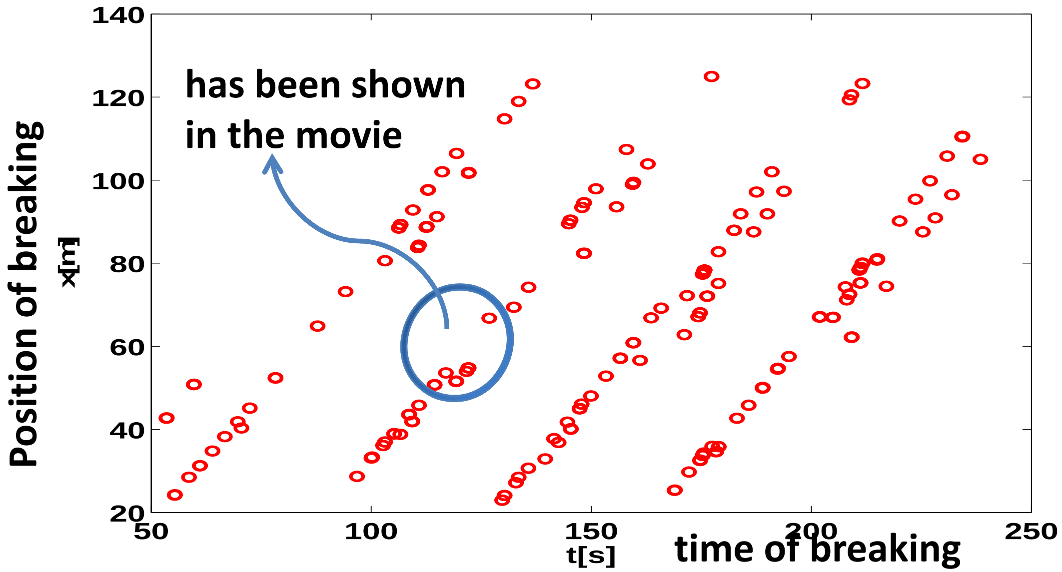
Bichromatic wave $k_p.a=0.37$

Wave breaking







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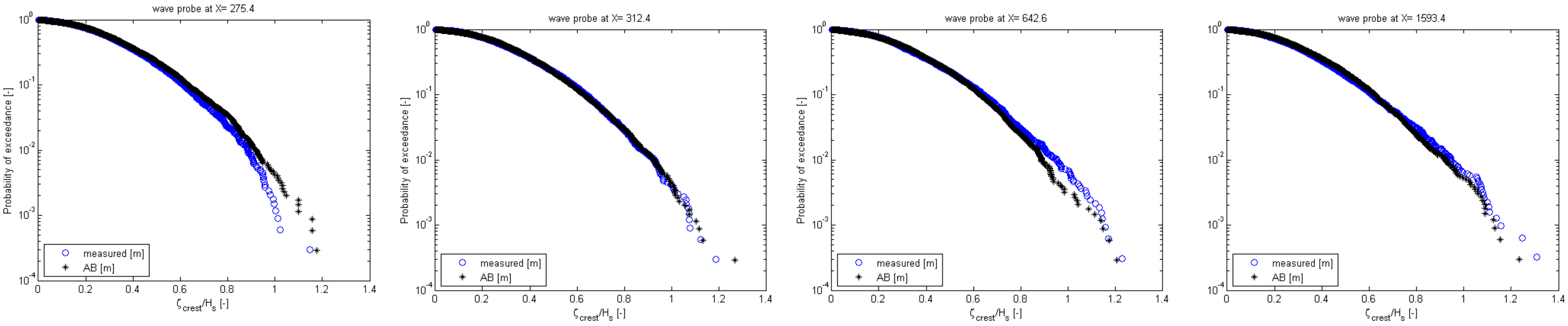
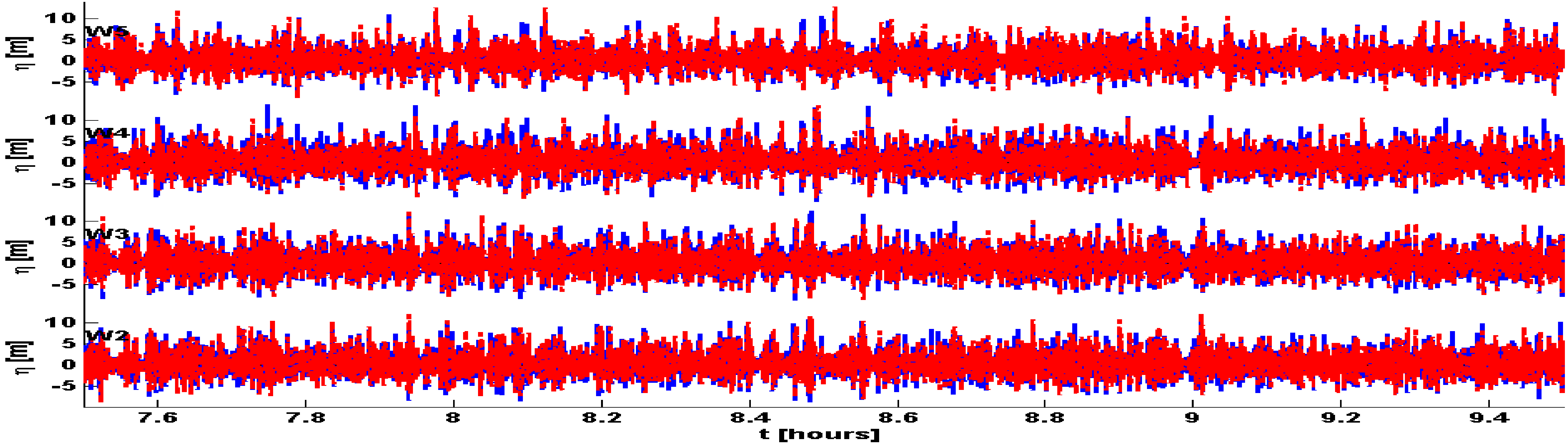
CRESTJIP 223002F (MARIN)
Tp:12 S (Breaking), 9hrs ; Crel≈1.5

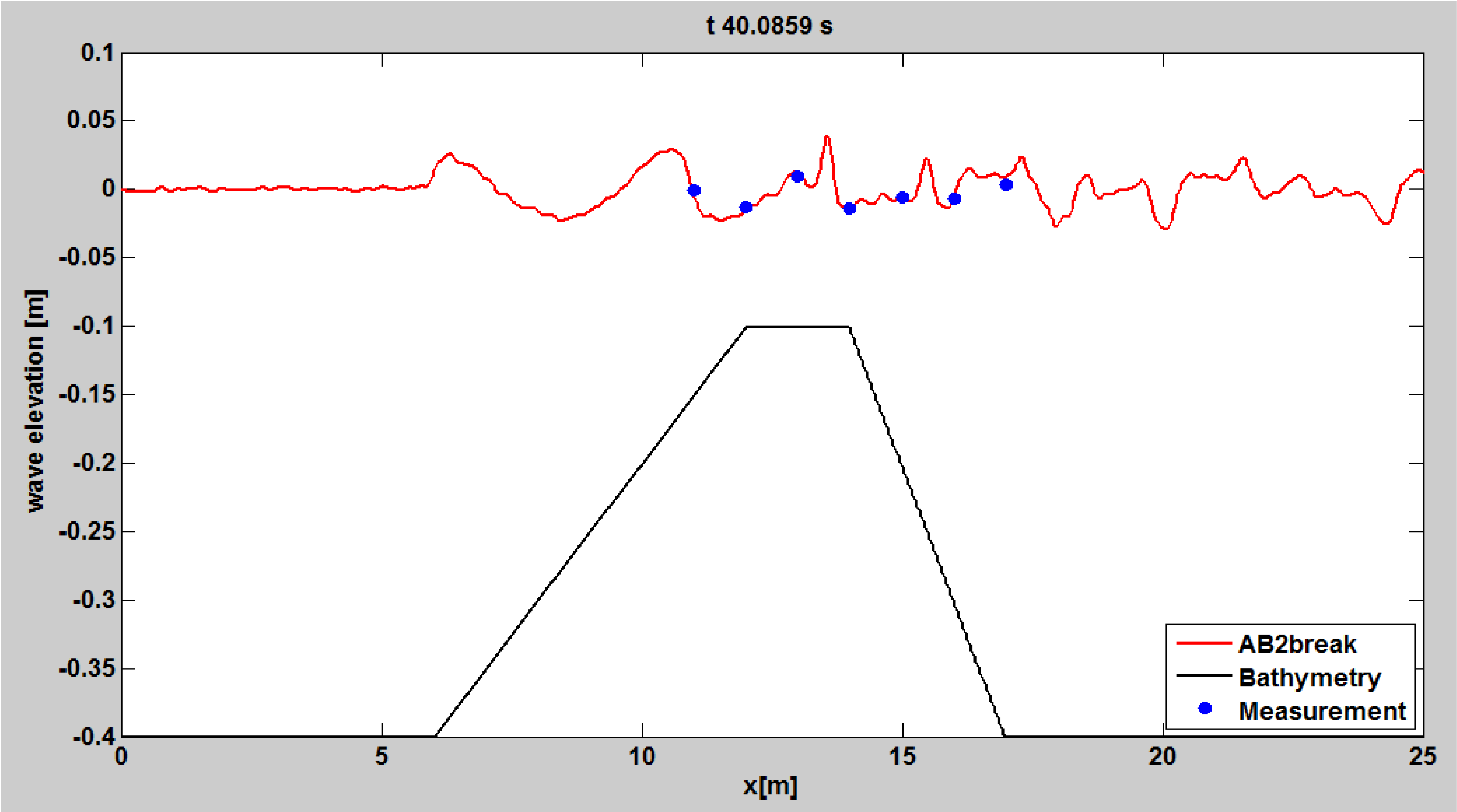
Exceedance plots for breaking waves



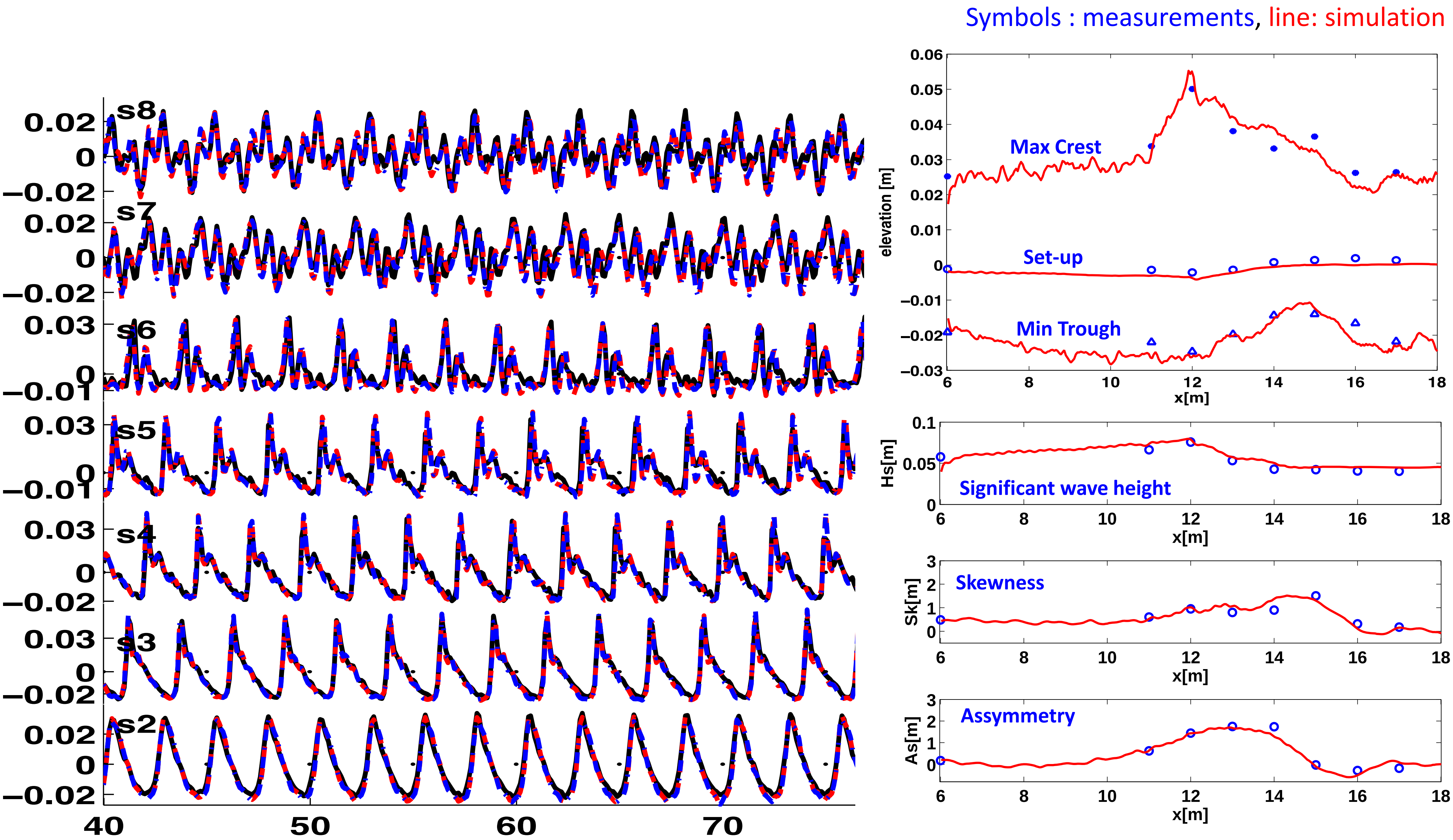


Wave breaking over a trapezoidal bar

Bound Harmonic Generation Phenomenon (Wave Decomposition)

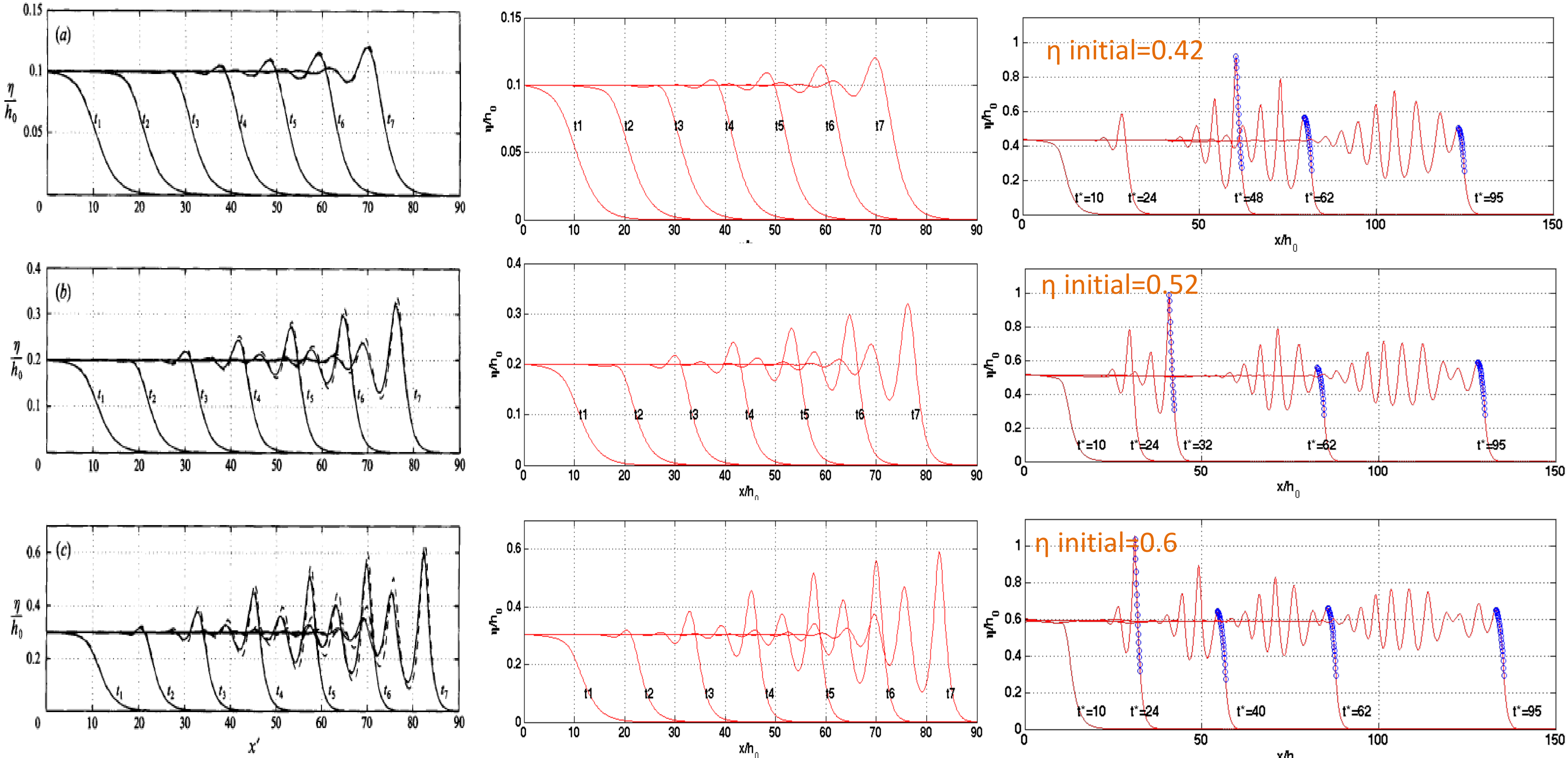


Beji and Battjes Experiment (1993) : Periodic Wave Plunging Breakers case (f=0.4 Hz)



Symbols : measurements, line: simulation
s8
s7
s6
s5
s4
s3
s2
Max Crest
Set-up
Min Trough
elevation [m]
x[m]
Significant wave height
Hs[m]
Skewness
Sk[m]
Assymmetry
As[m]

Transition from undular to purely breaking bore



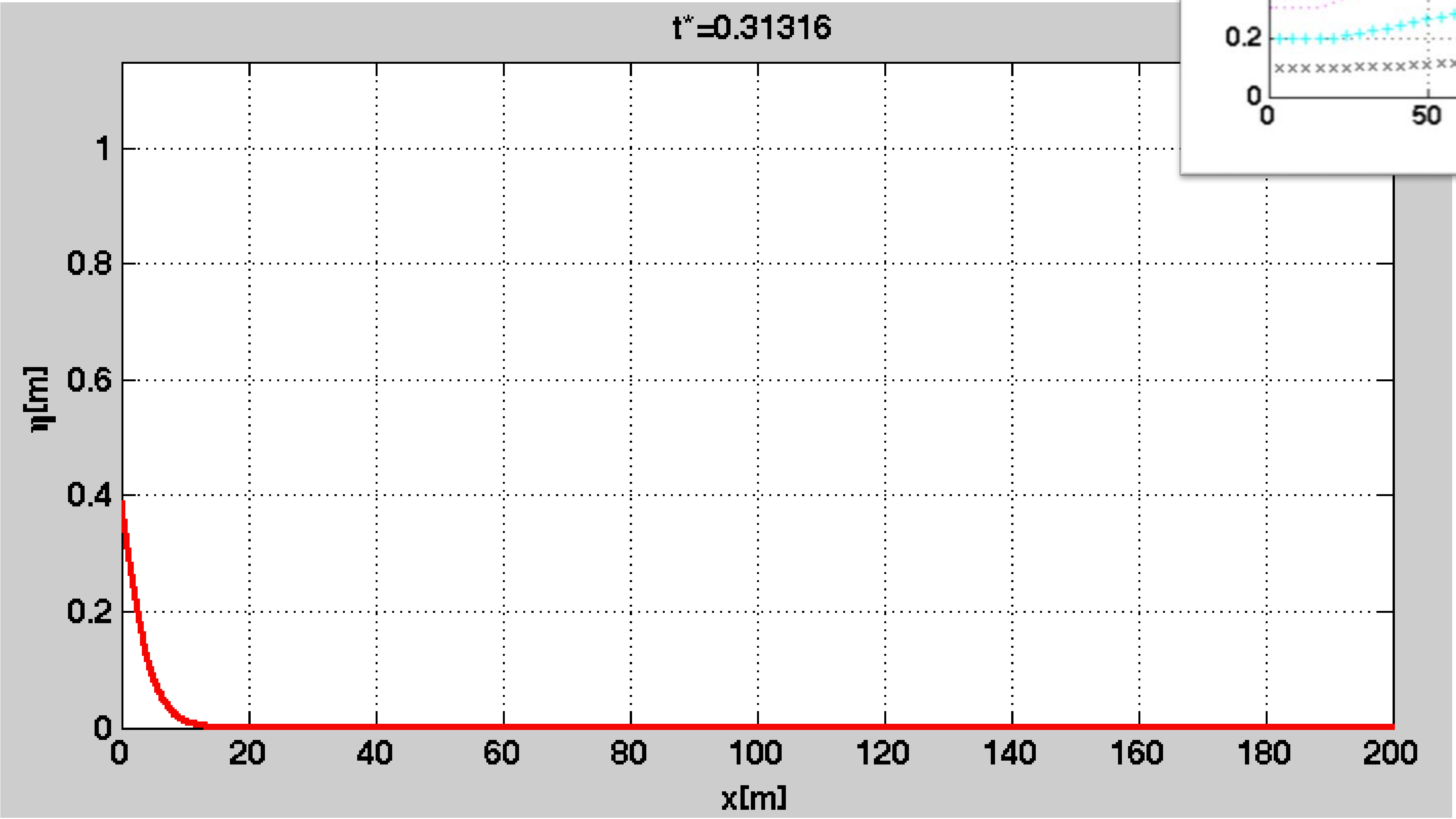
Simulation using fully nonlinear potential flow (Grilli, et al)

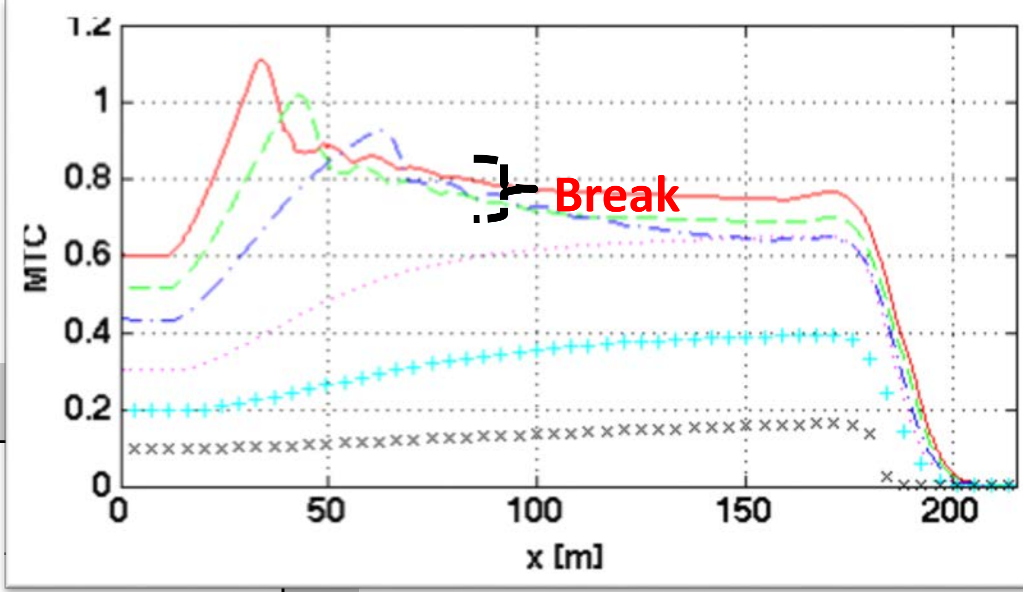
Non breaking case

Simulation using AB

breaking case

η initial=0.52





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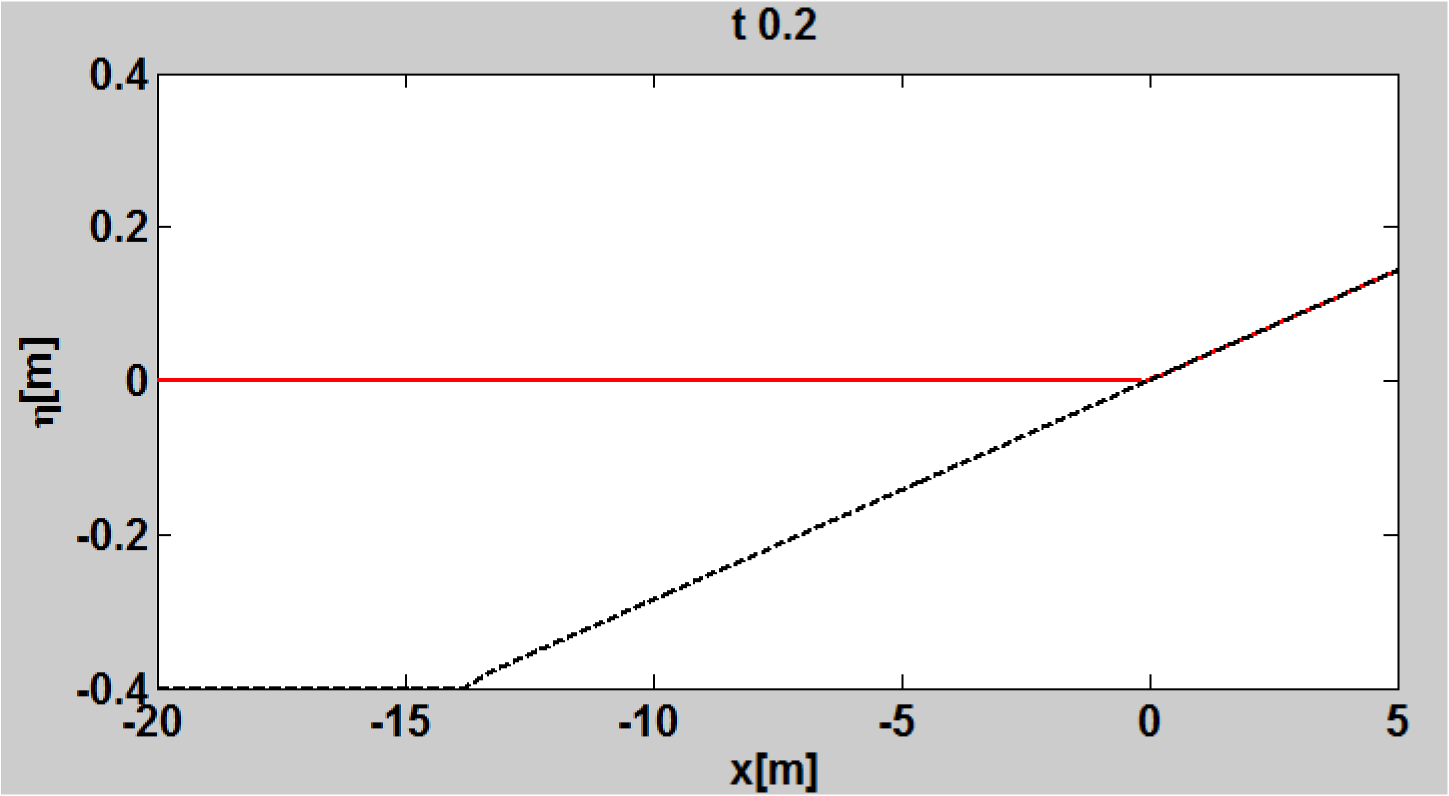
Spilling wave breaking above a slope (Exp. Ting & Kirby 1994)

elevation

Breaking nodes



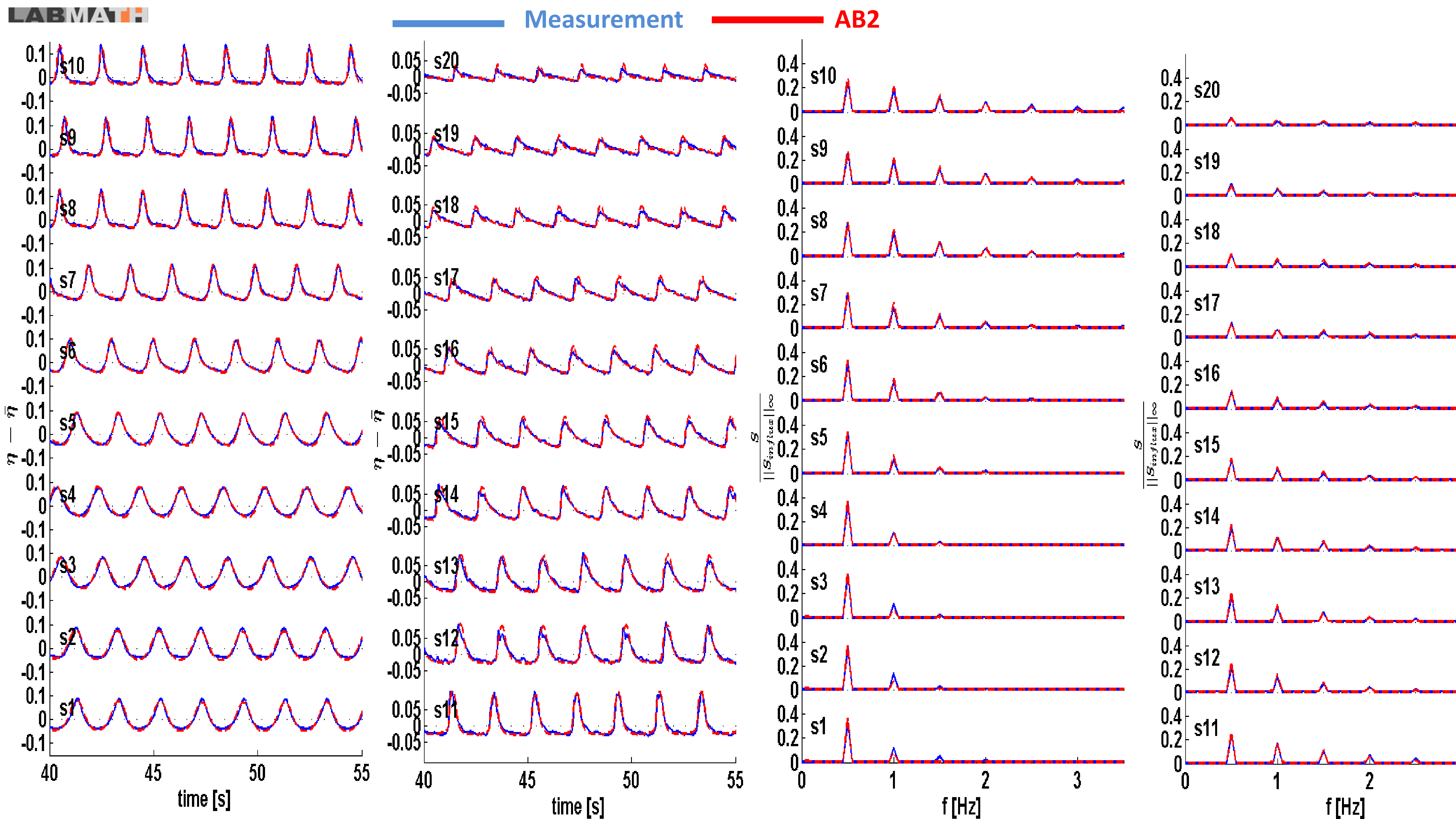
Correlation

s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
0,97	0,97	0,98	0,98	0,99	0,95	0,97	0,98	0,98	0,95

s11	s12	s13	s14	s15	s16	s17	s18	s19	s20
0,96	0,96	0,97	0,97	0,96	0,94	0,94	0,91	0,91	0,84

Crel≈35 → ≈5 for simulation time 60 s :

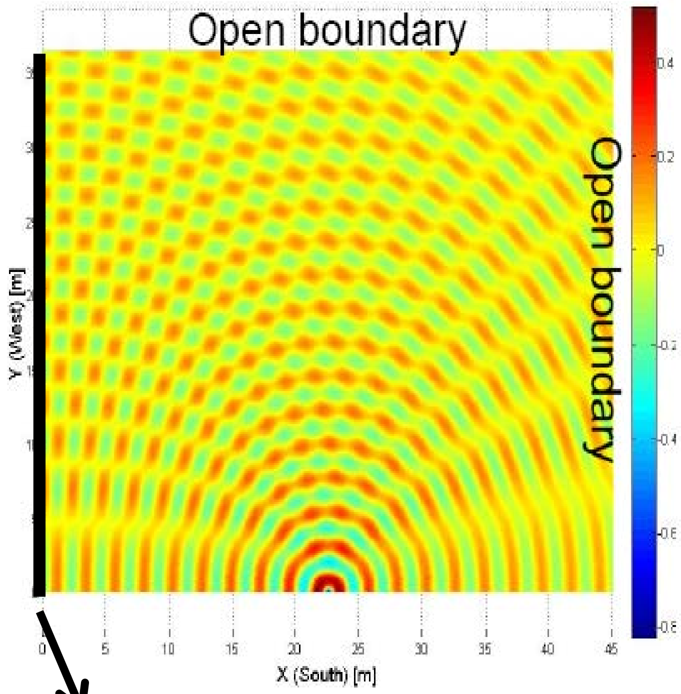
- multiple breaking continue over 5 period.
- small spatial discretization (170 points per wavelength)



LABMATH
Measurement
AB2
s1
s2
s3
s4
s5
s6
s7
s8
s9
s10
s11
s12
s13
s14
s15
s16
s17
s18
s19
s20
$\eta - \bar{\eta}$
time [s]
f [Hz]
$\frac{s}{||s_{influx}||_\infty}$

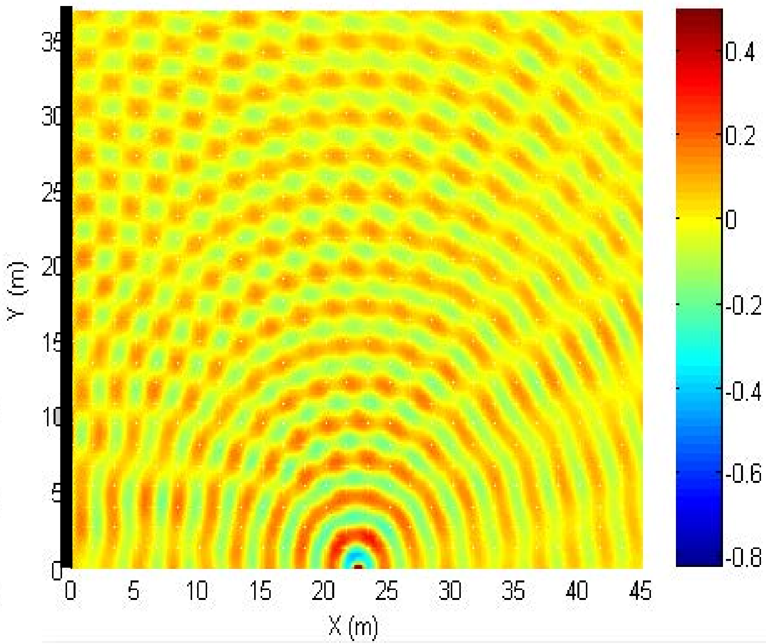
Embedded reflective interfaces 2D

3D "DIFFRAC" code (week)



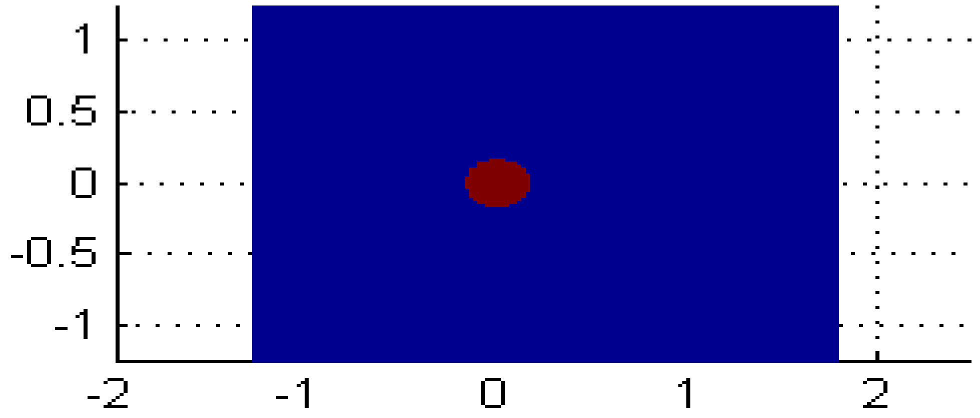
reflective wall

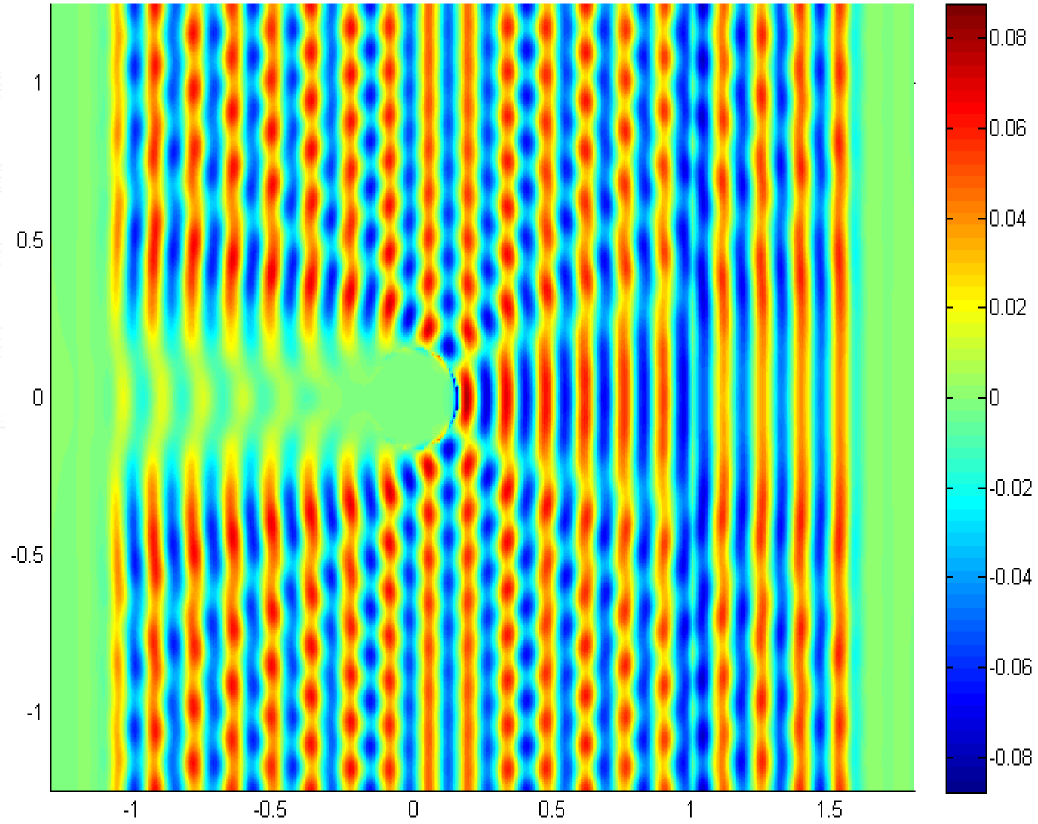
Linear AB (minutes)



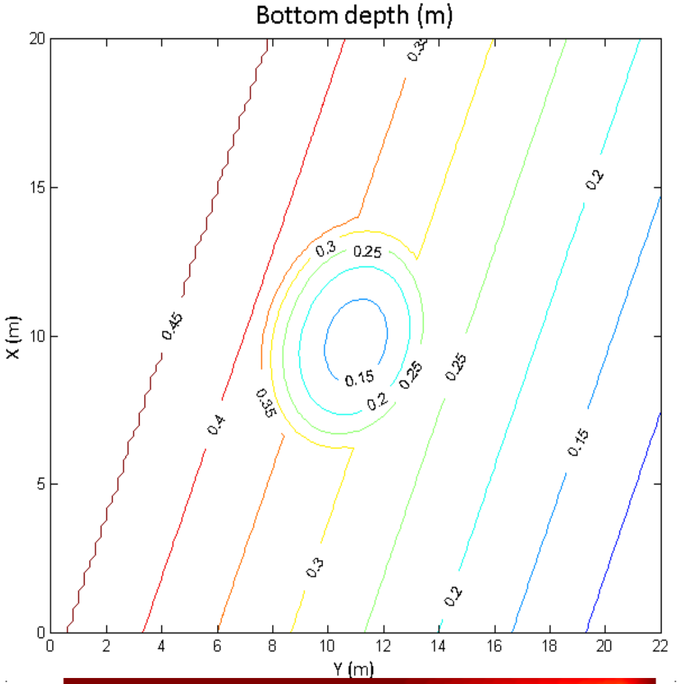
embedded "cylinder"

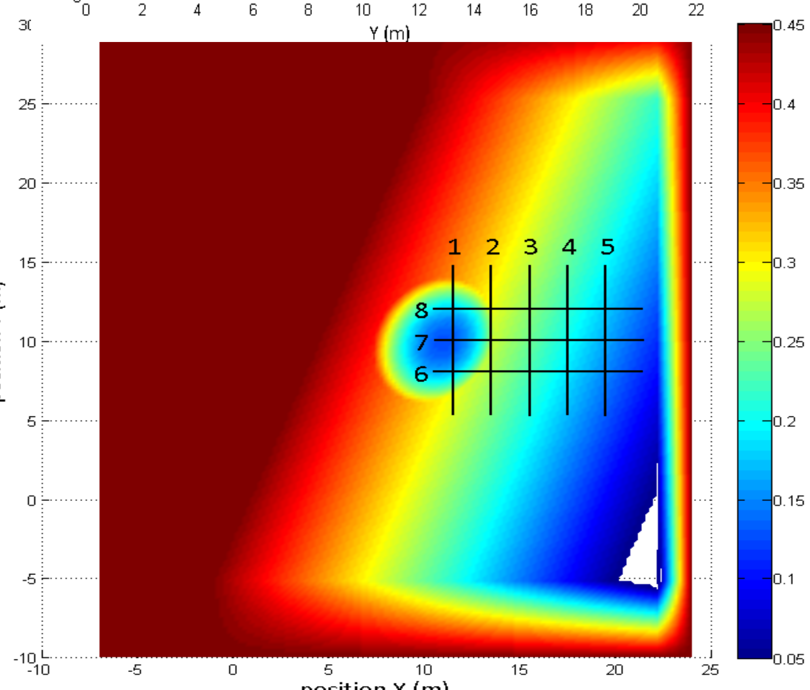
normalized potential wall

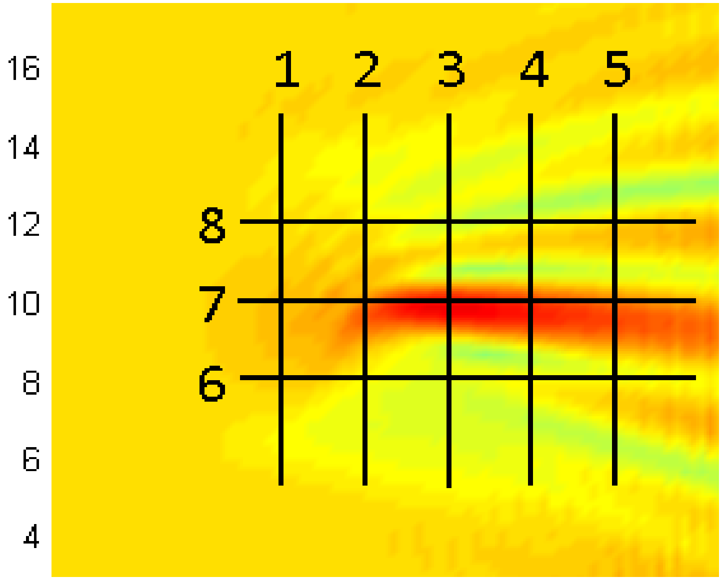


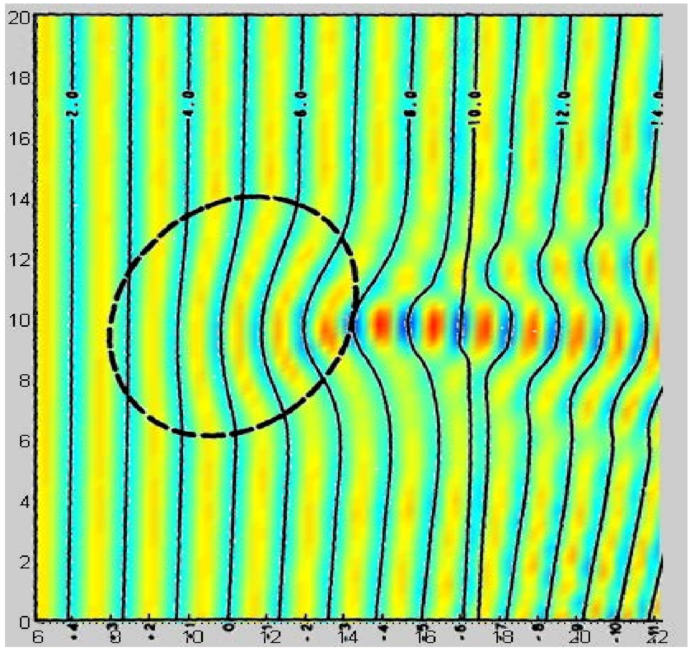


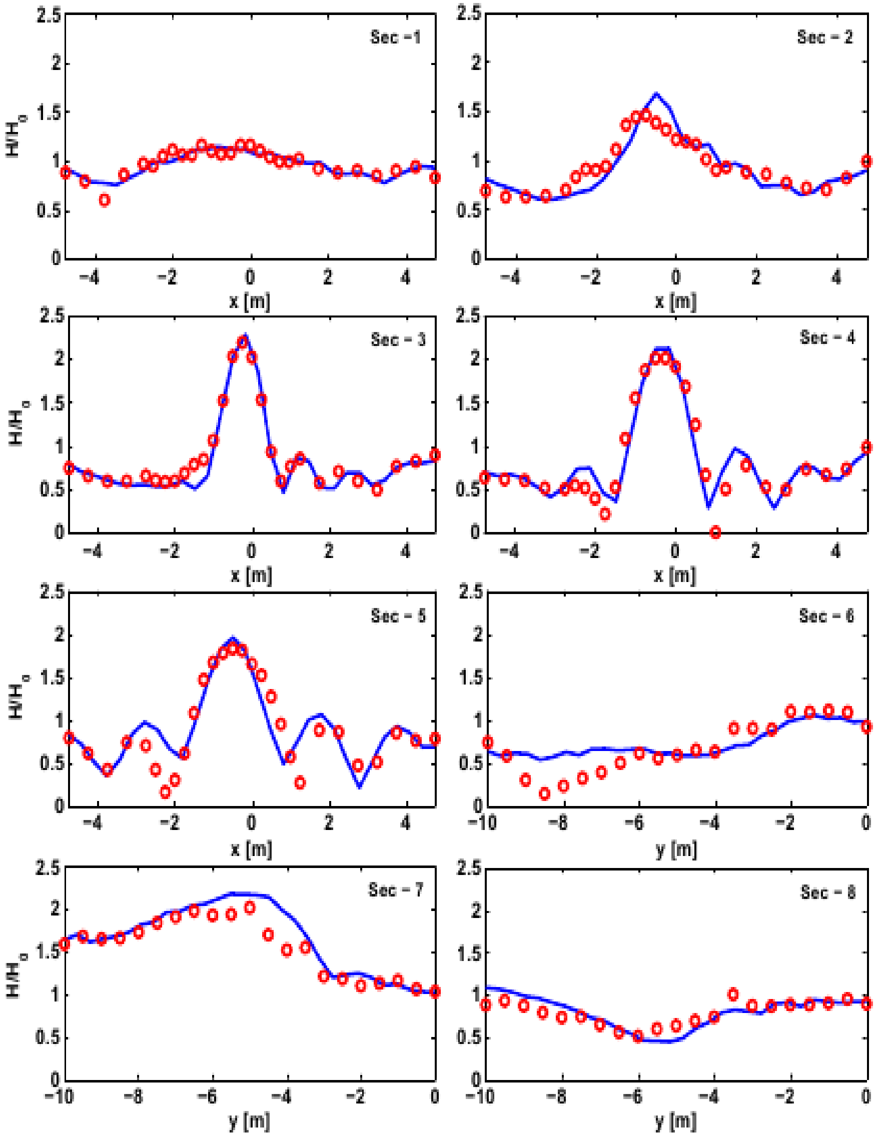
2HD **Refraction & Diffraction** (Berkhoff 1982)











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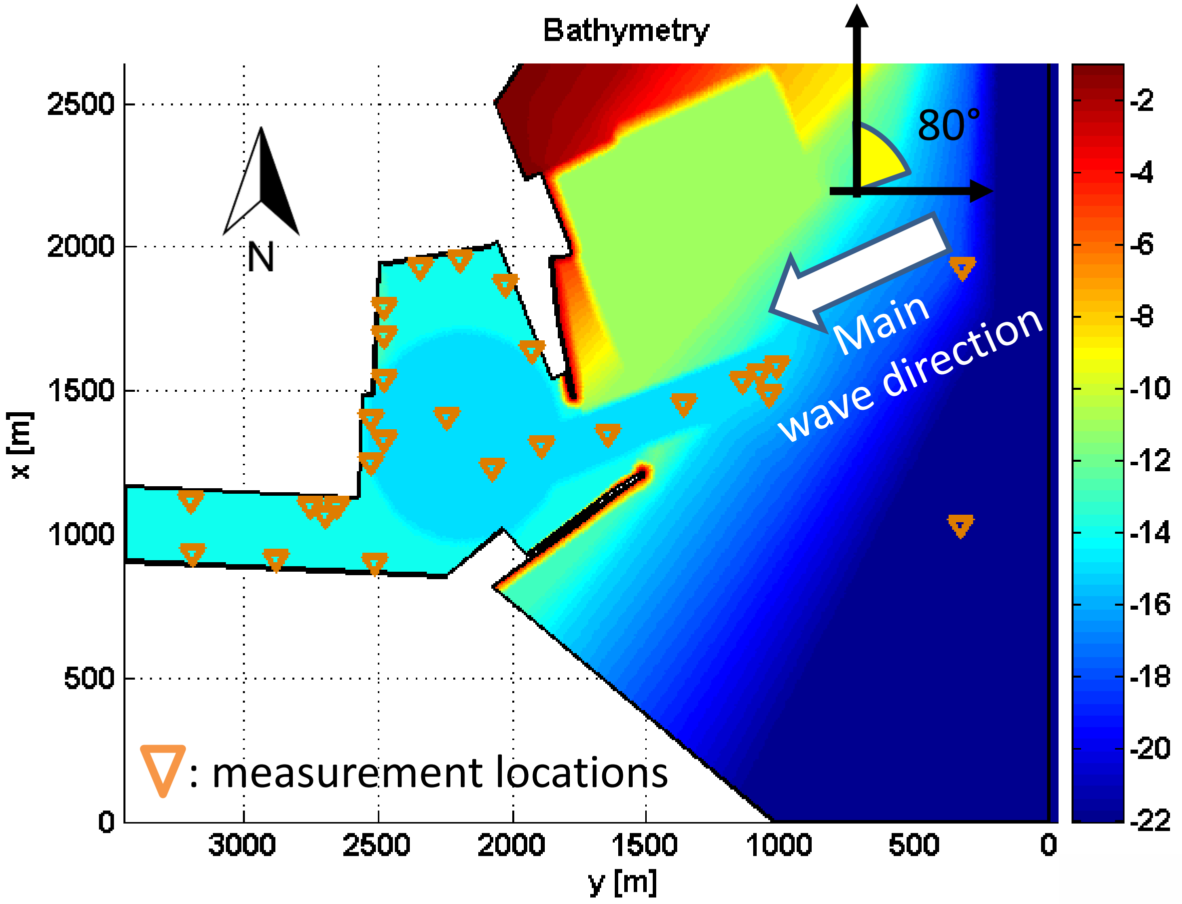
Physical experiment : Harbour of Limassol

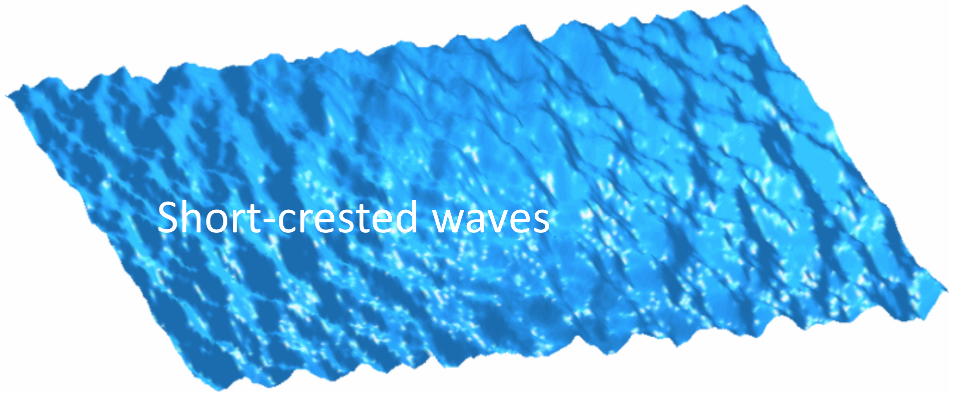


Experiment by **Deltares** 1992 :

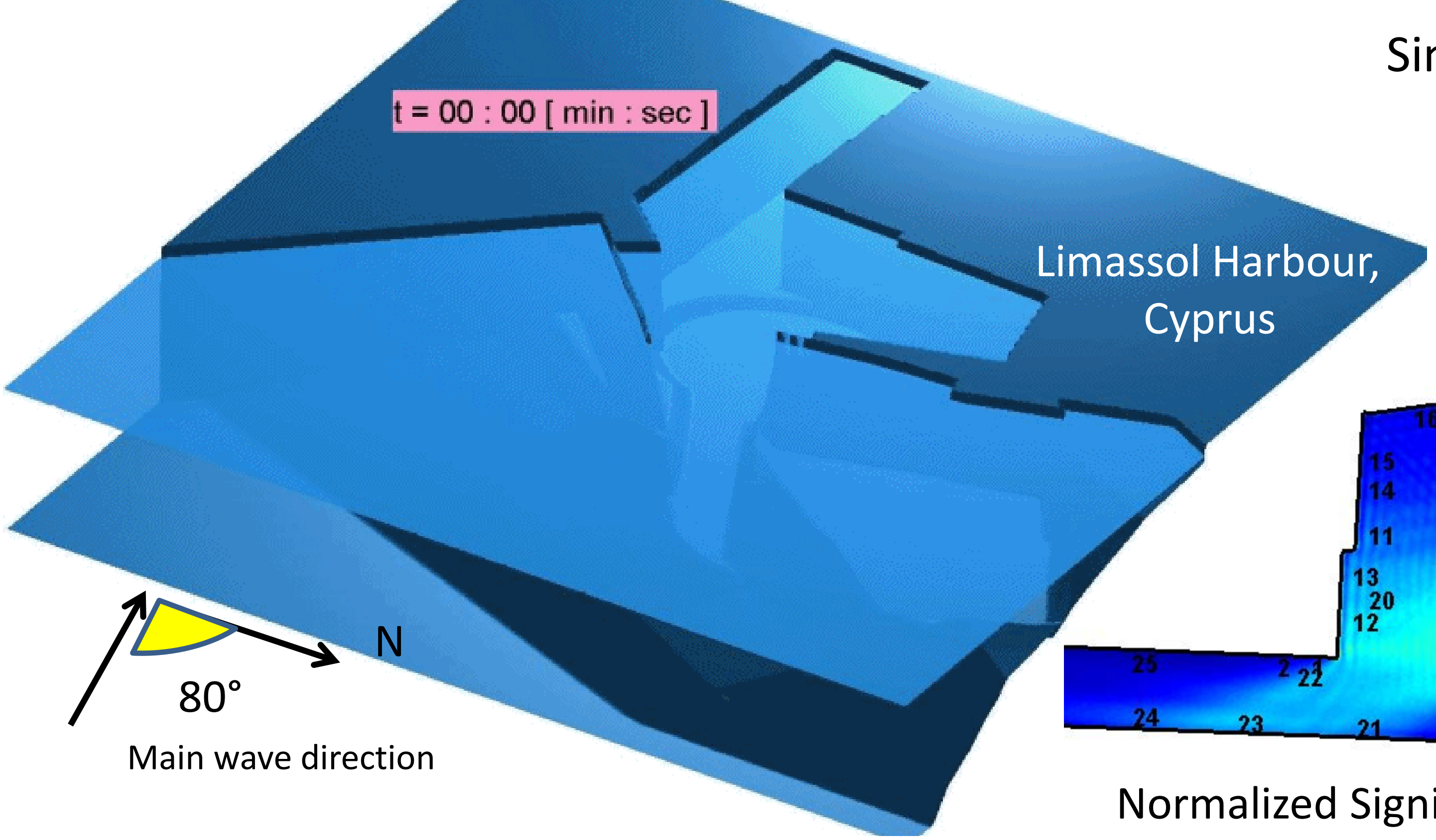
- Complicated bathymetry
- Influx with **short-crested waves** (waves coming from various directions)
- Simulation of accurate harbour entrance

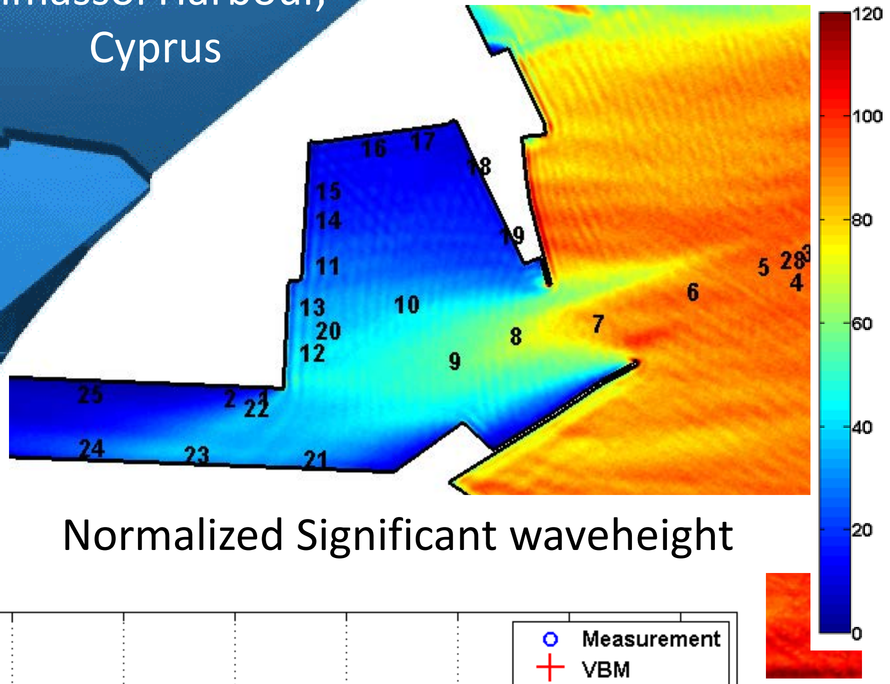
Wind wave – input :

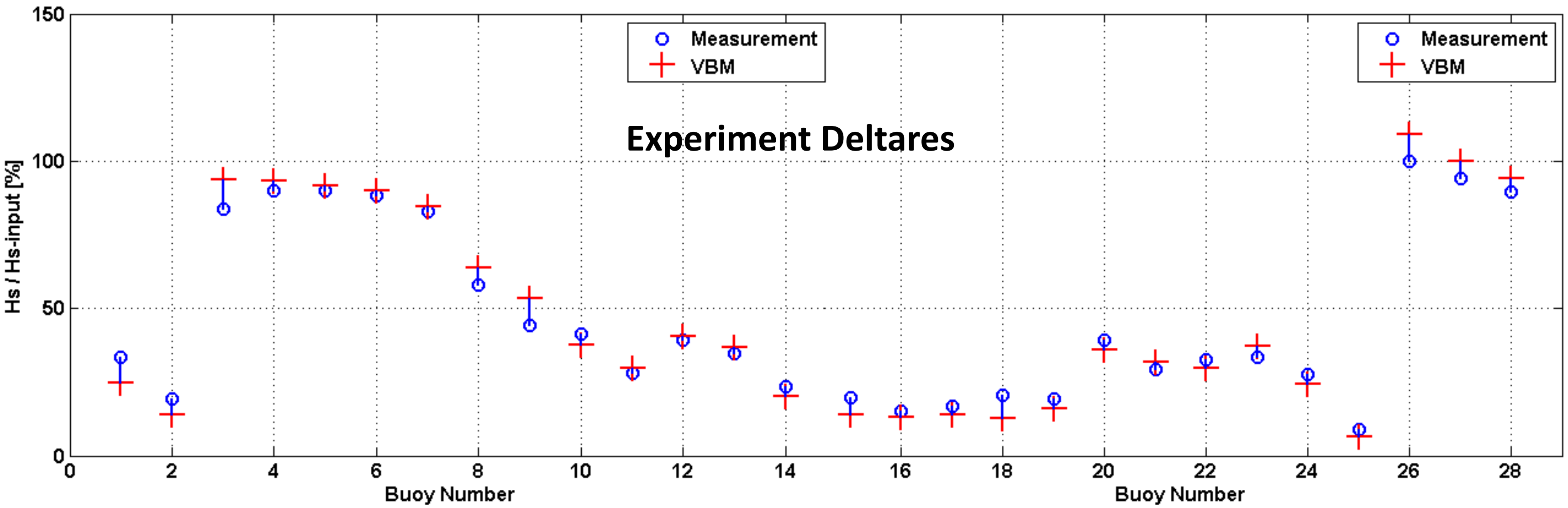
Hs = 2.5 m
Tp = 7.0 s
Direction = 80°
Short-crested waves



Simulations vs Experiments







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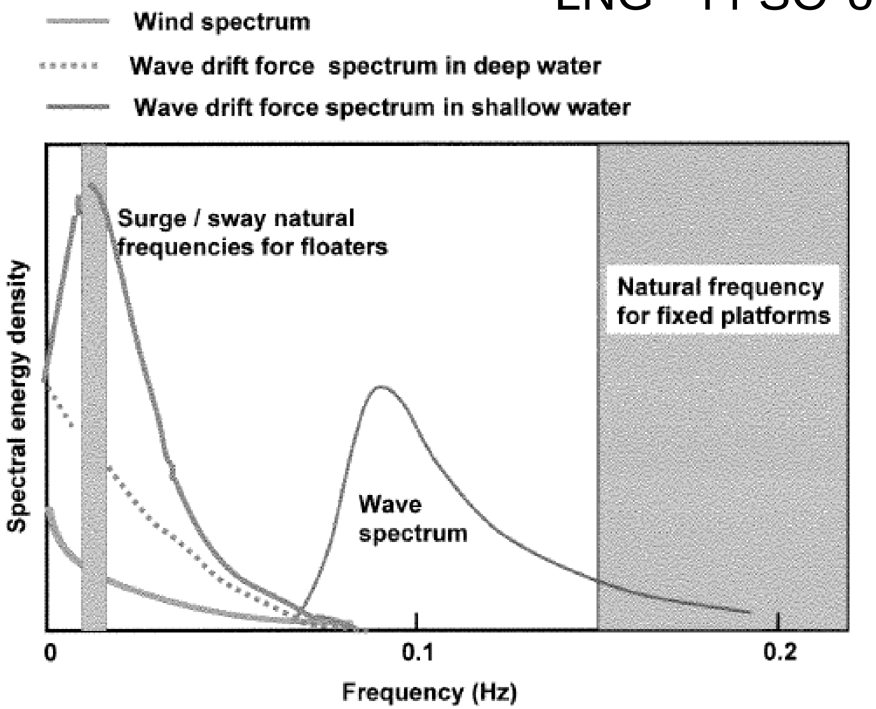
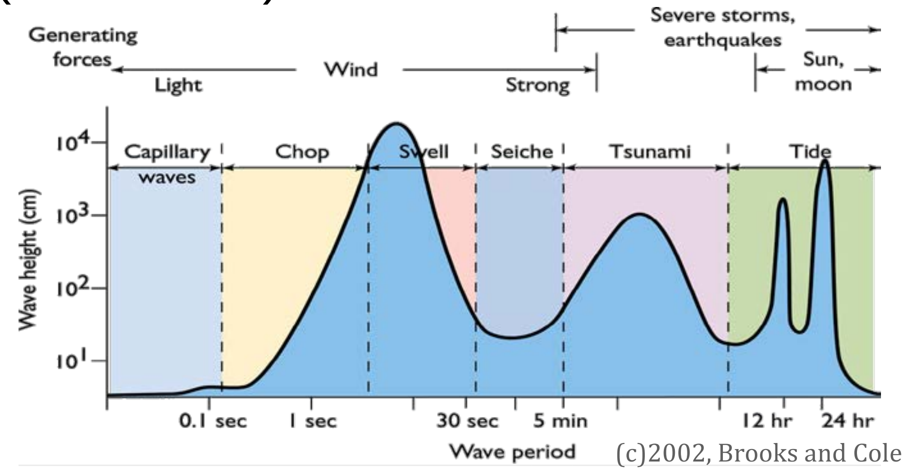
Application

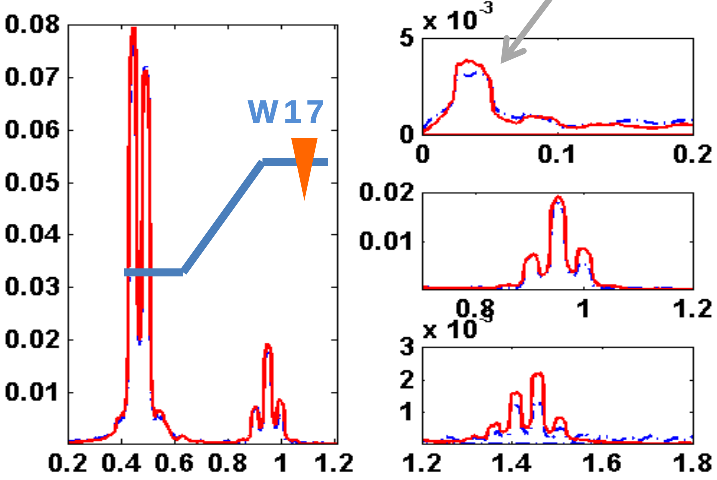
- Infra-Gravity calculation for gas-oil offshore industry, e.g. LNG –FPSO operation sites (resonance)

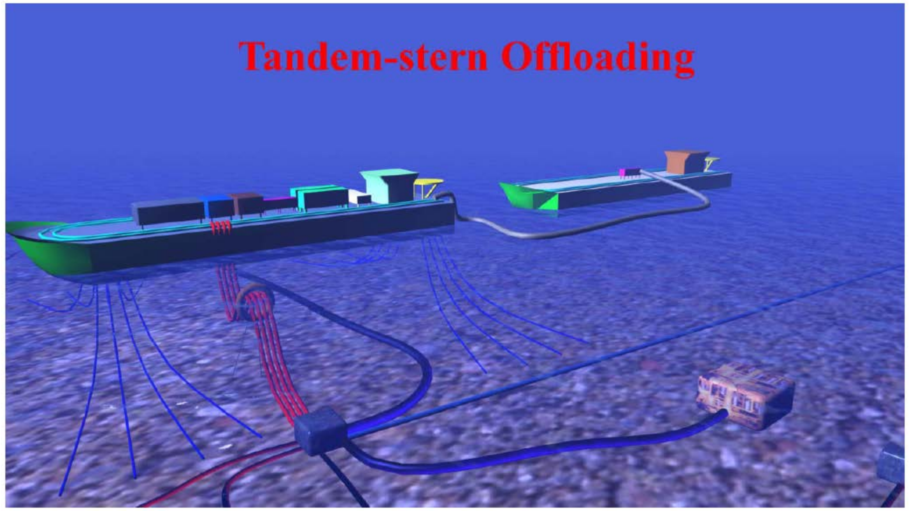




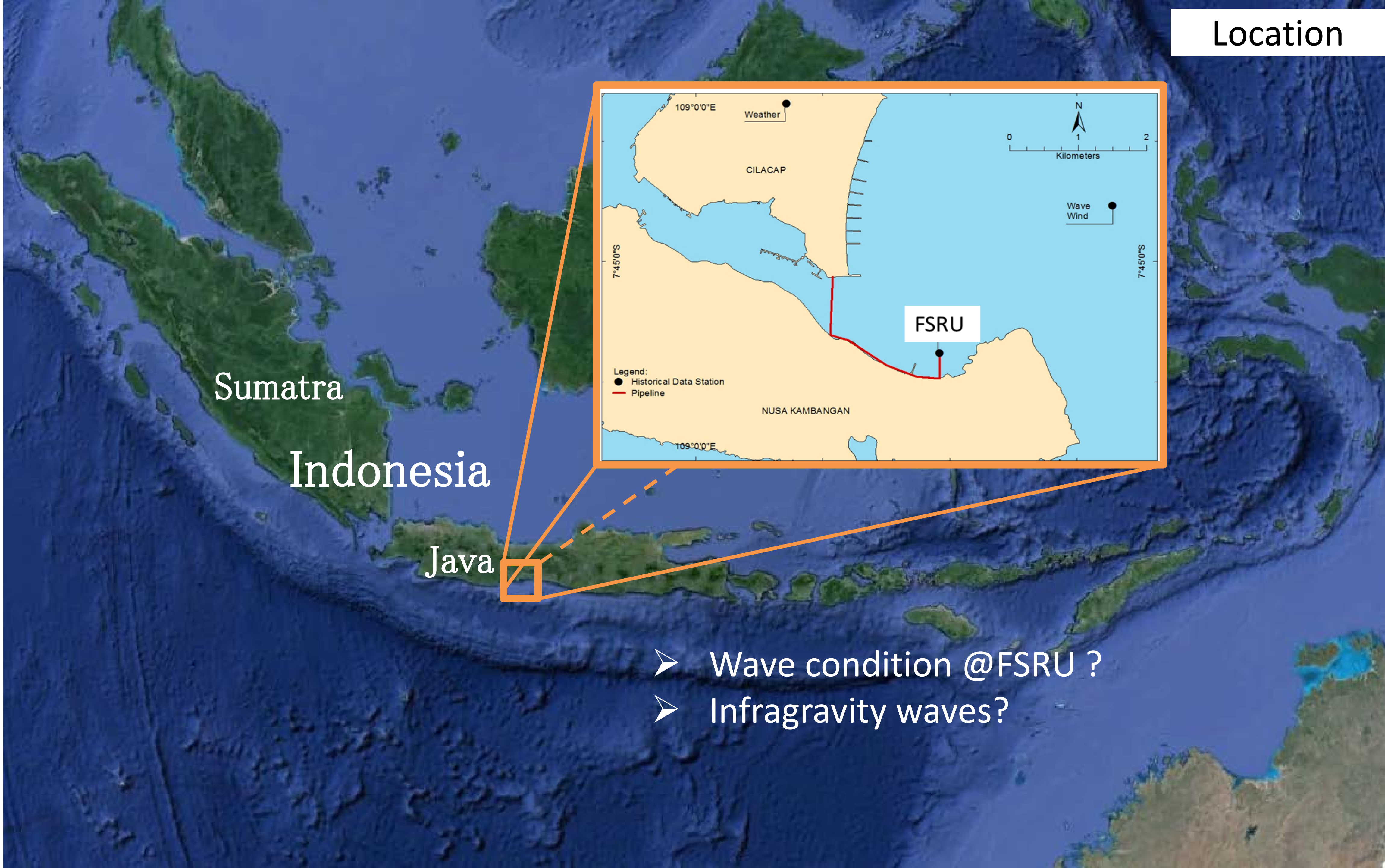
HaWAII bichrom

2 min Long wave





Location



- Wave condition @FSRU ?
- Infragravity waves?

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Simulations for Coastal Engineering applications

Wind field

Phase-averaged wave model

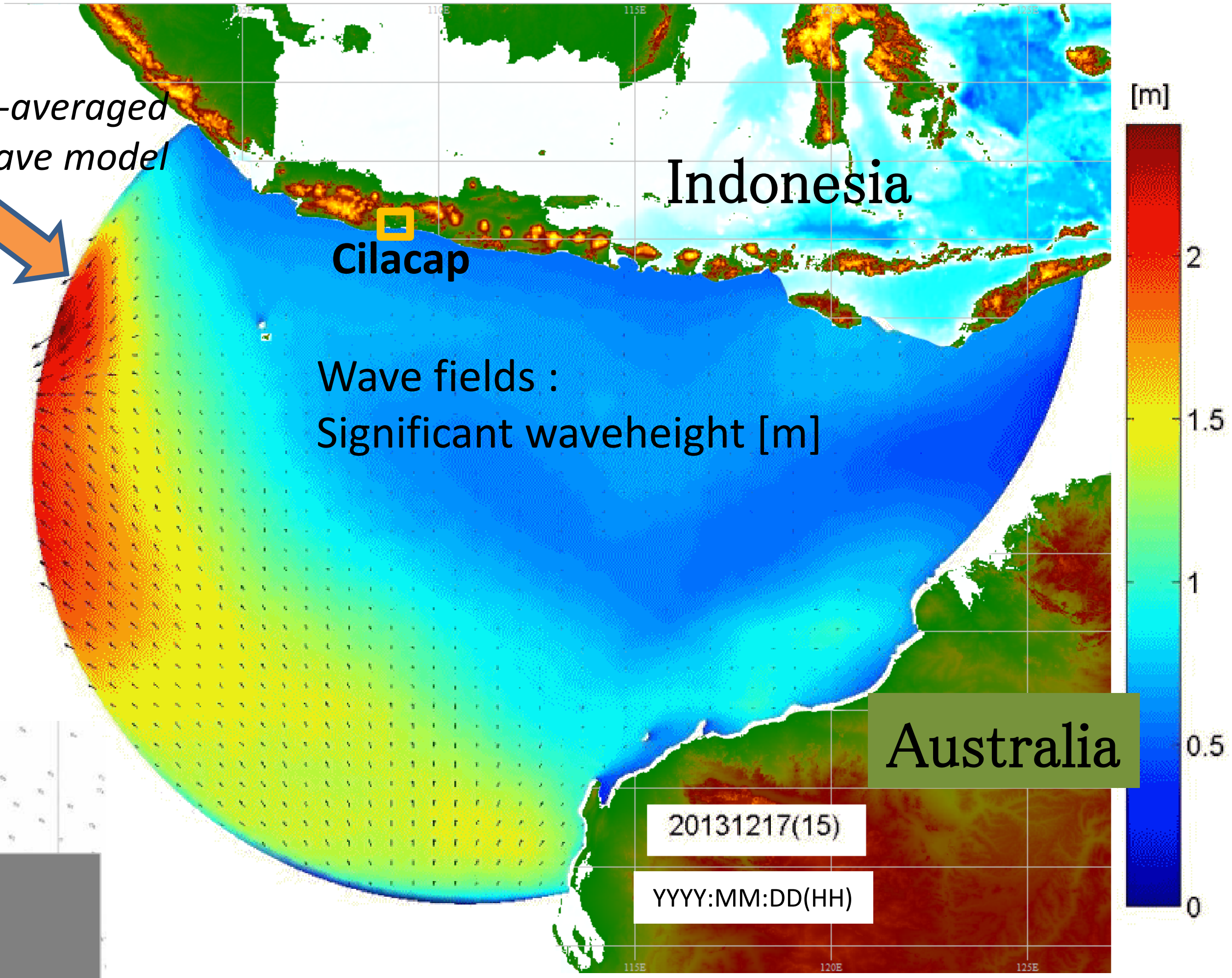
Ocean waves generated by wind

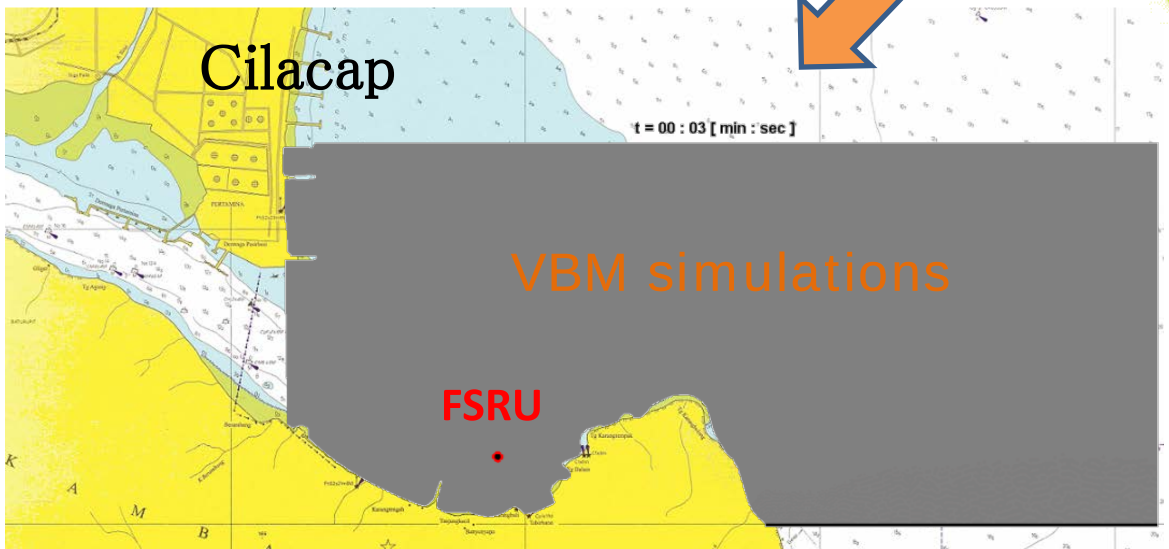
SWAN calculations produce 2D-spectrum
Design time trace of elevation heights at numerical boundary for influx

Simulation area, geometry

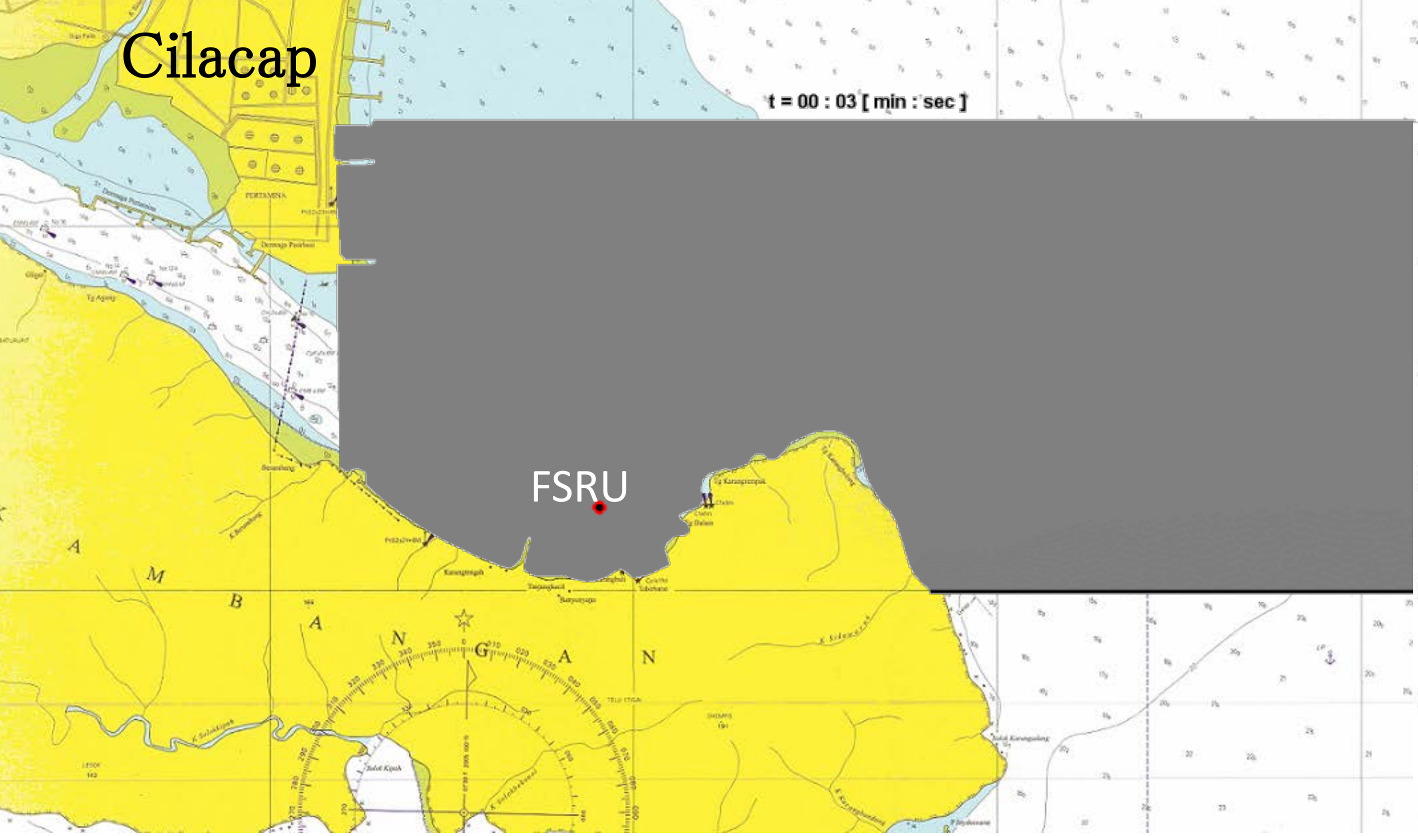
Shallow seas, coastal boundaries, harbour, breakwaters etc

Phase-resolved wave model

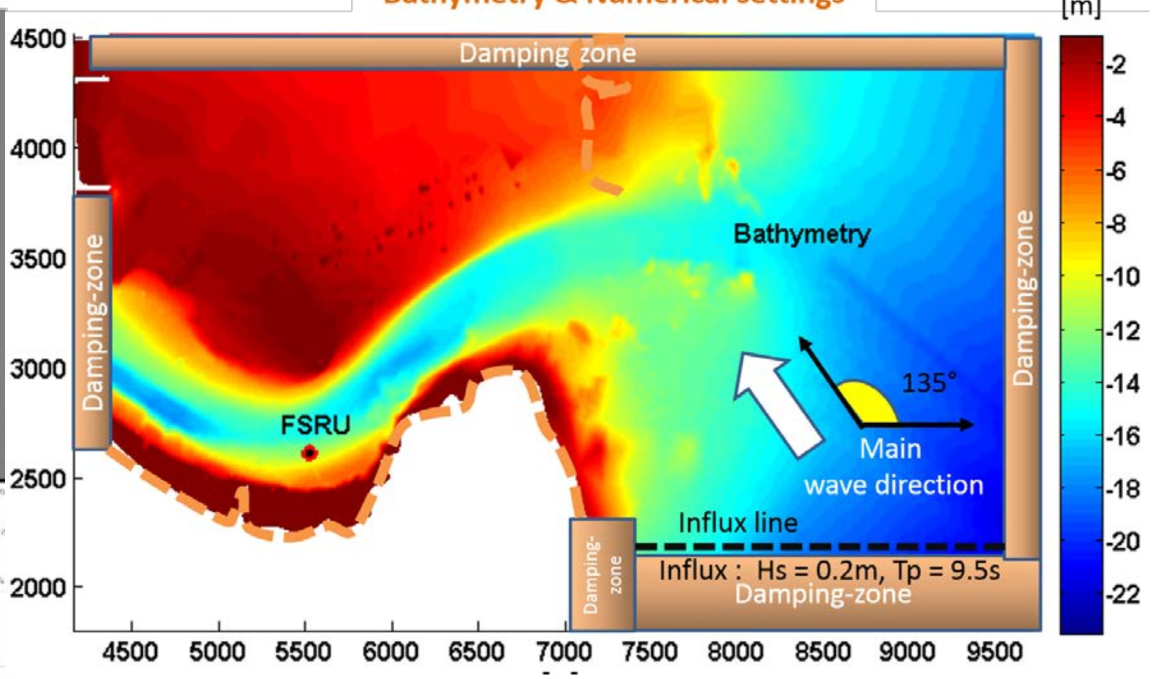


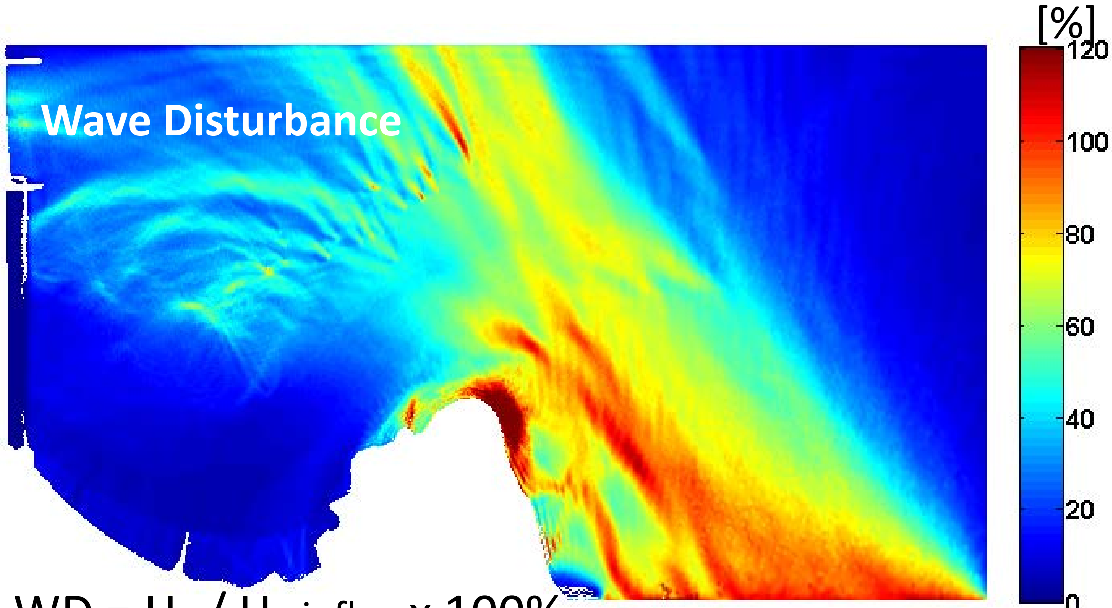


VBM simulations

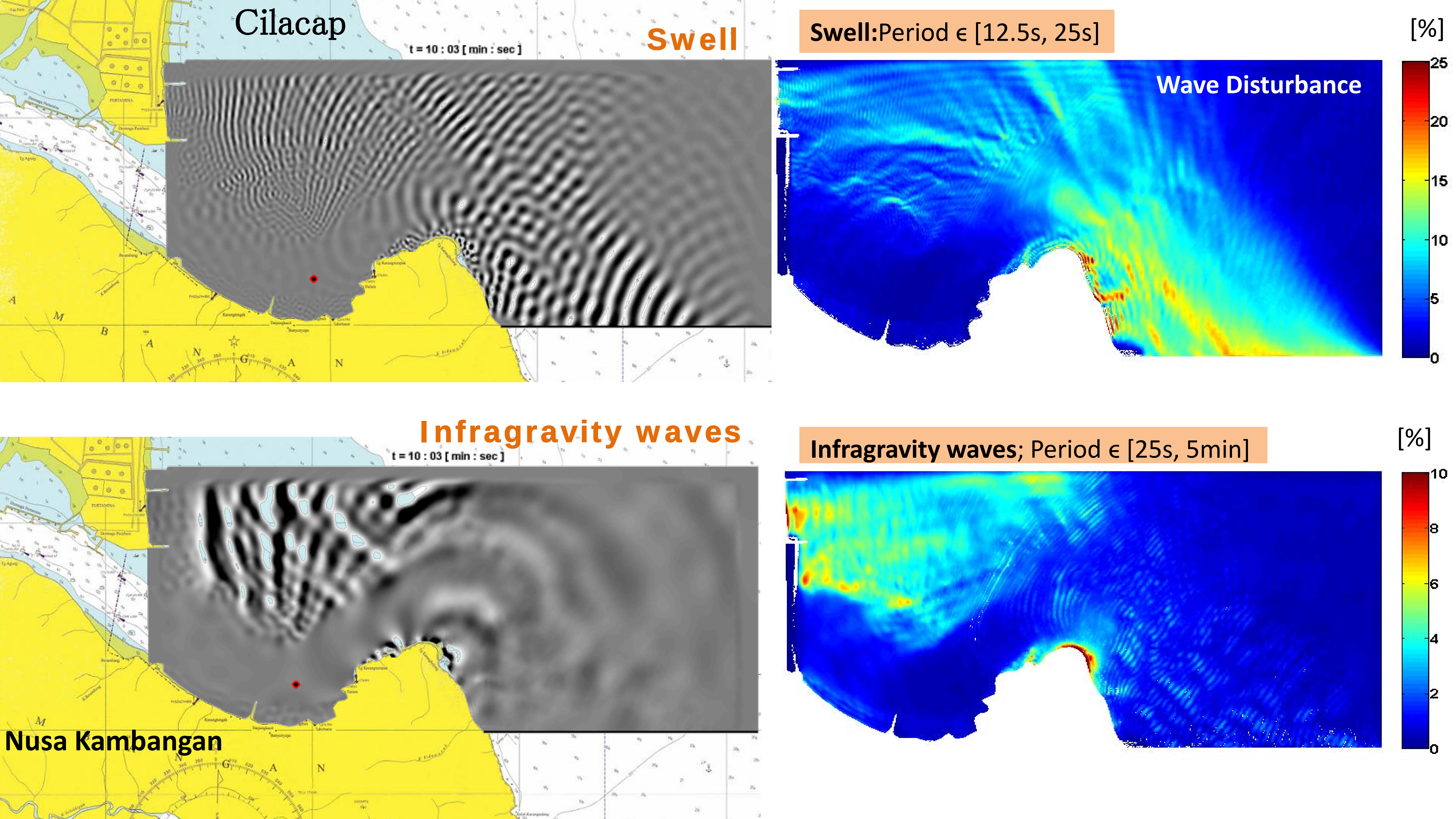


Bathymetry & Numerical settings

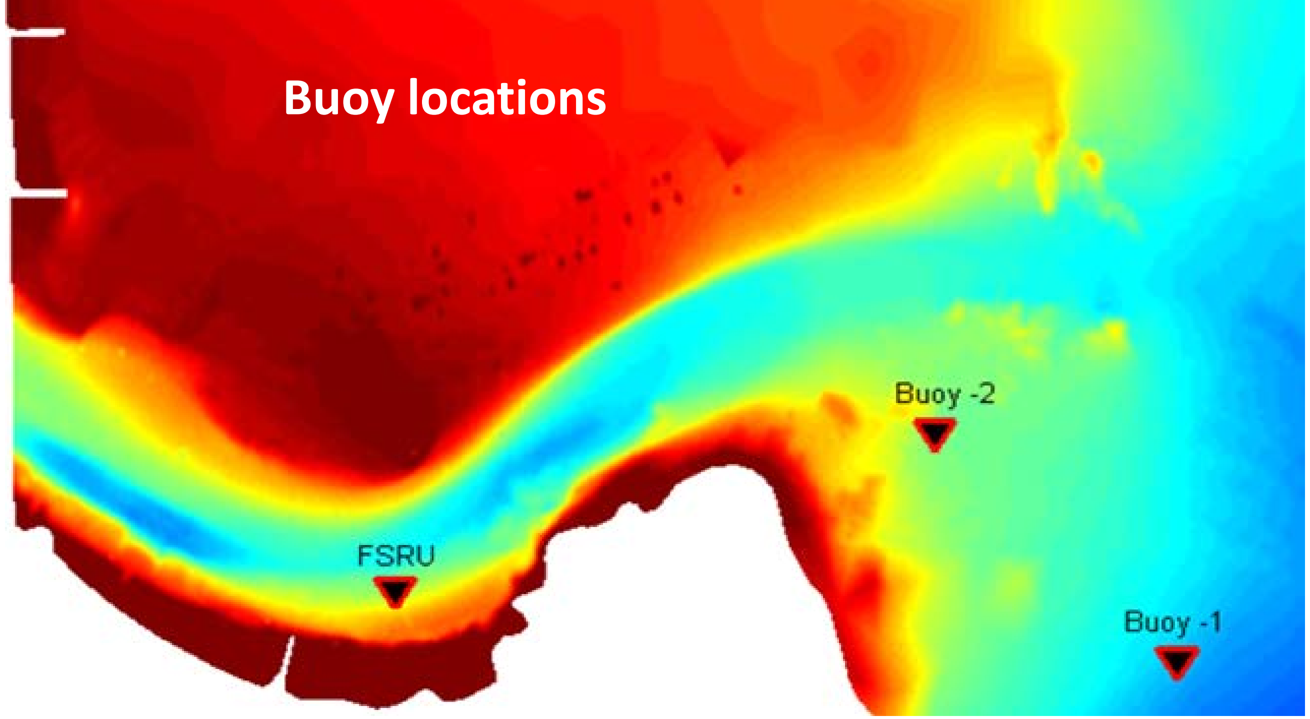




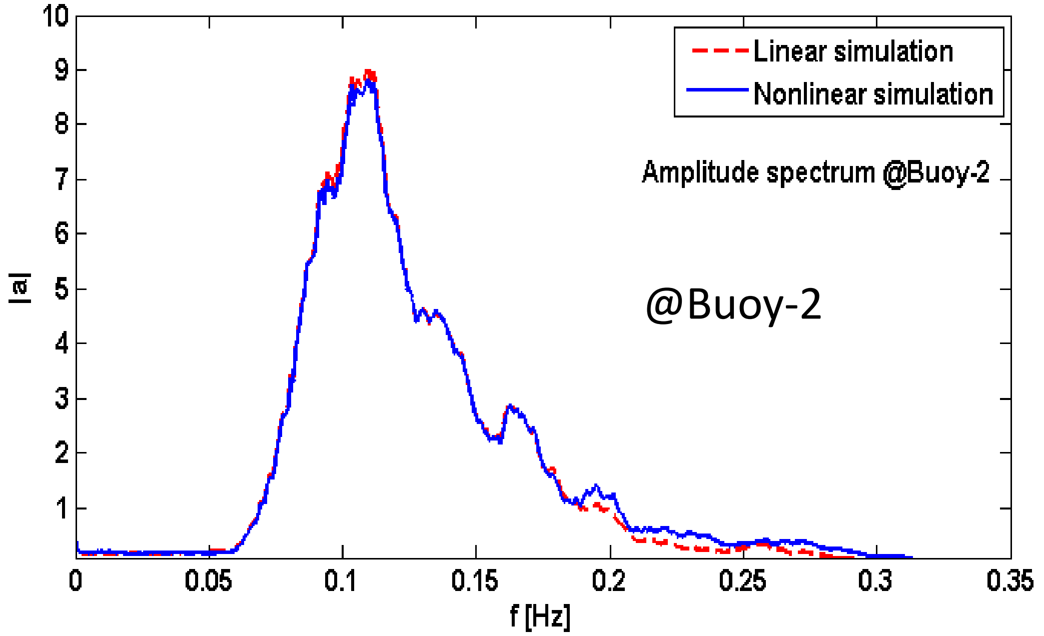
WD = Hs / Hs-influx x 100%



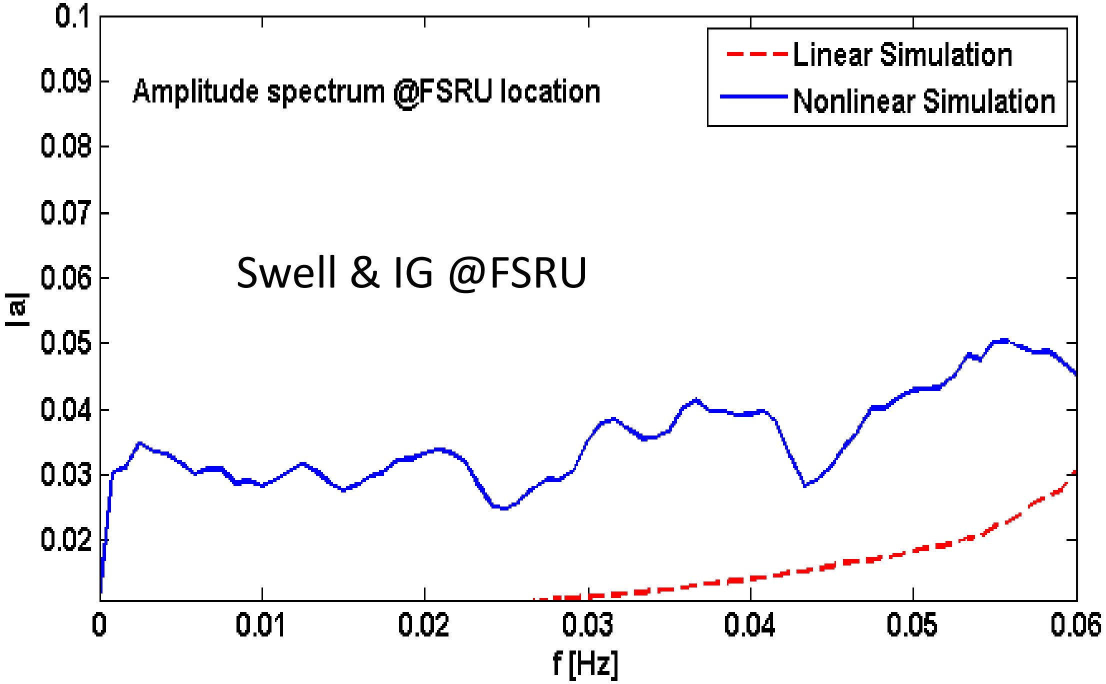
Cilacap
Swell
t = 10 : 03 [min : sec]
Swell:Period ϵ [12.5s, 25s]
[%]
Wave Disturbance
25
20
15
10
5
0
Infragravity waves
t = 10 : 03 [min : sec]
Nusa Kambangan
Infragravity waves; Period ϵ [25s, 5min]
[%]
10
8
6
4
2
0



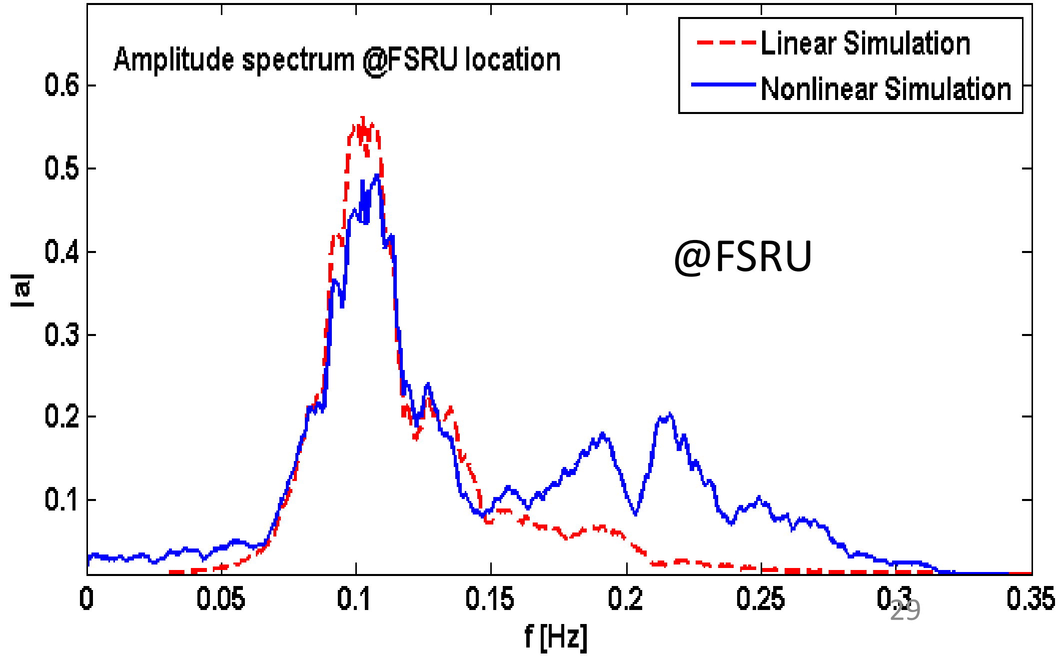
Buoy locations
Buoy -2
FSRU
Buoy -1



Linear simulation
Nonlinear simulation
Amplitude spectrum @Buoy-2
@Buoy-2
|a|
f [Hz]



Amplitude spectrum @FSRU location
Linear Simulation
Nonlinear Simulation
Swell & IG @FSRU
|a|
f [Hz]



Amplitude spectrum @FSRU location
Linear Simulation
Nonlinear Simulation
@FSRU
|a|
f [Hz]

Jakarta, water problem

- Can the wall withstand the tsunami heights and forces of a possible Krakatau eruption?
- What are the wave heights?

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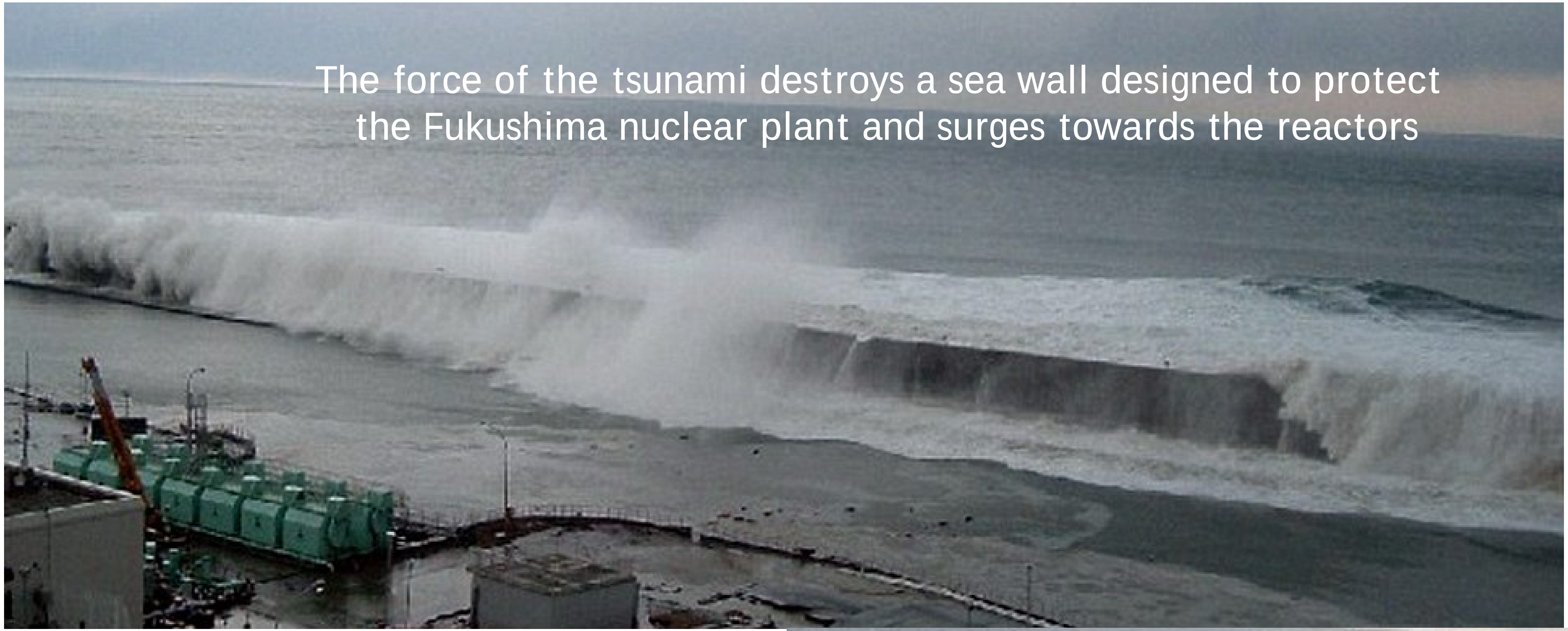
Witteveen+Bos



The force of the tsunami destroys a sea wall designed to protect the Fukushima nuclear plant and surges towards the reactors

Tsunami by 1883 Krakatau explosion

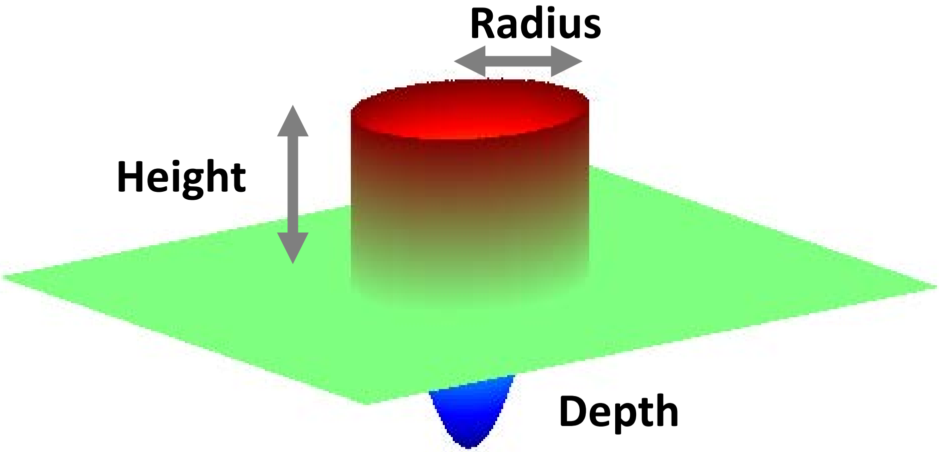
Initial Condition: Inverse Problem

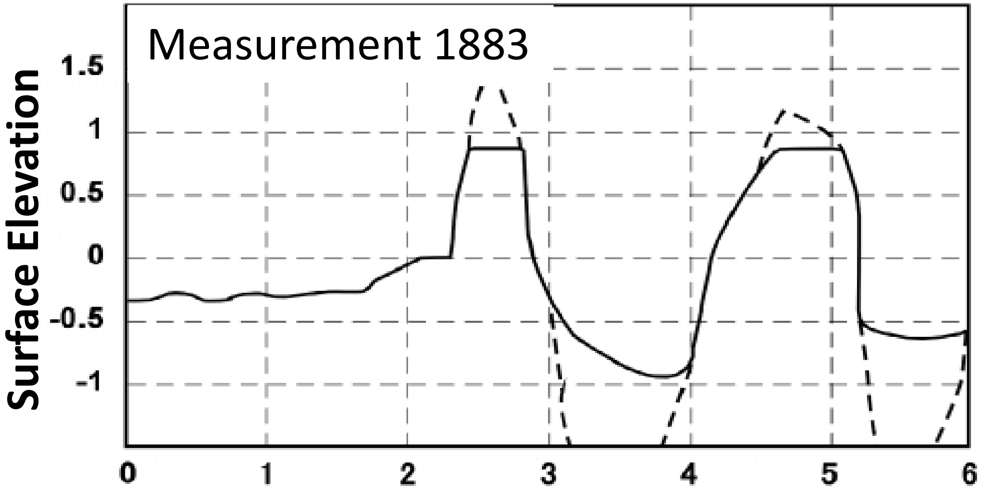
Find generation scenario → **Simulation matches measurements near Batavia**

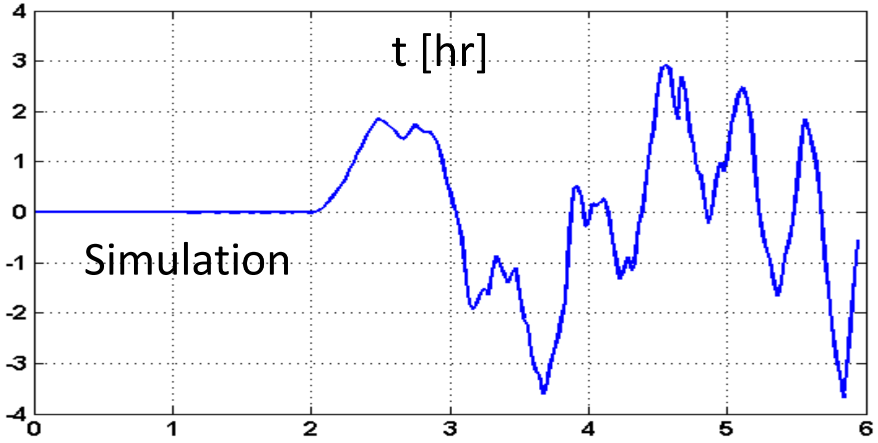
Maeno & Immamura [2011] :

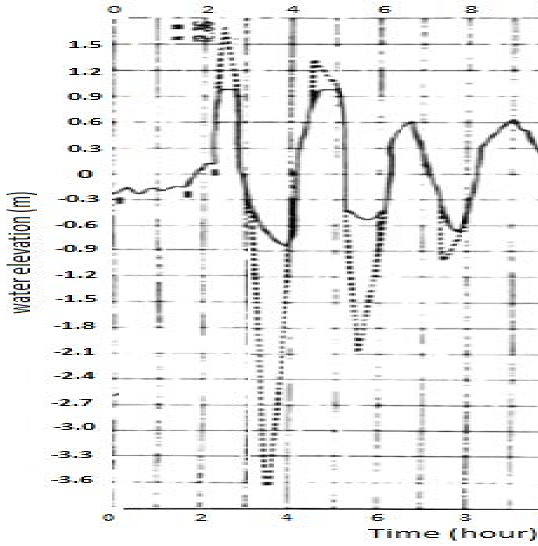
- Use 3 models (for Initial Cond.)
- Pyroclastic flow gives best result

Phreato-magmatic









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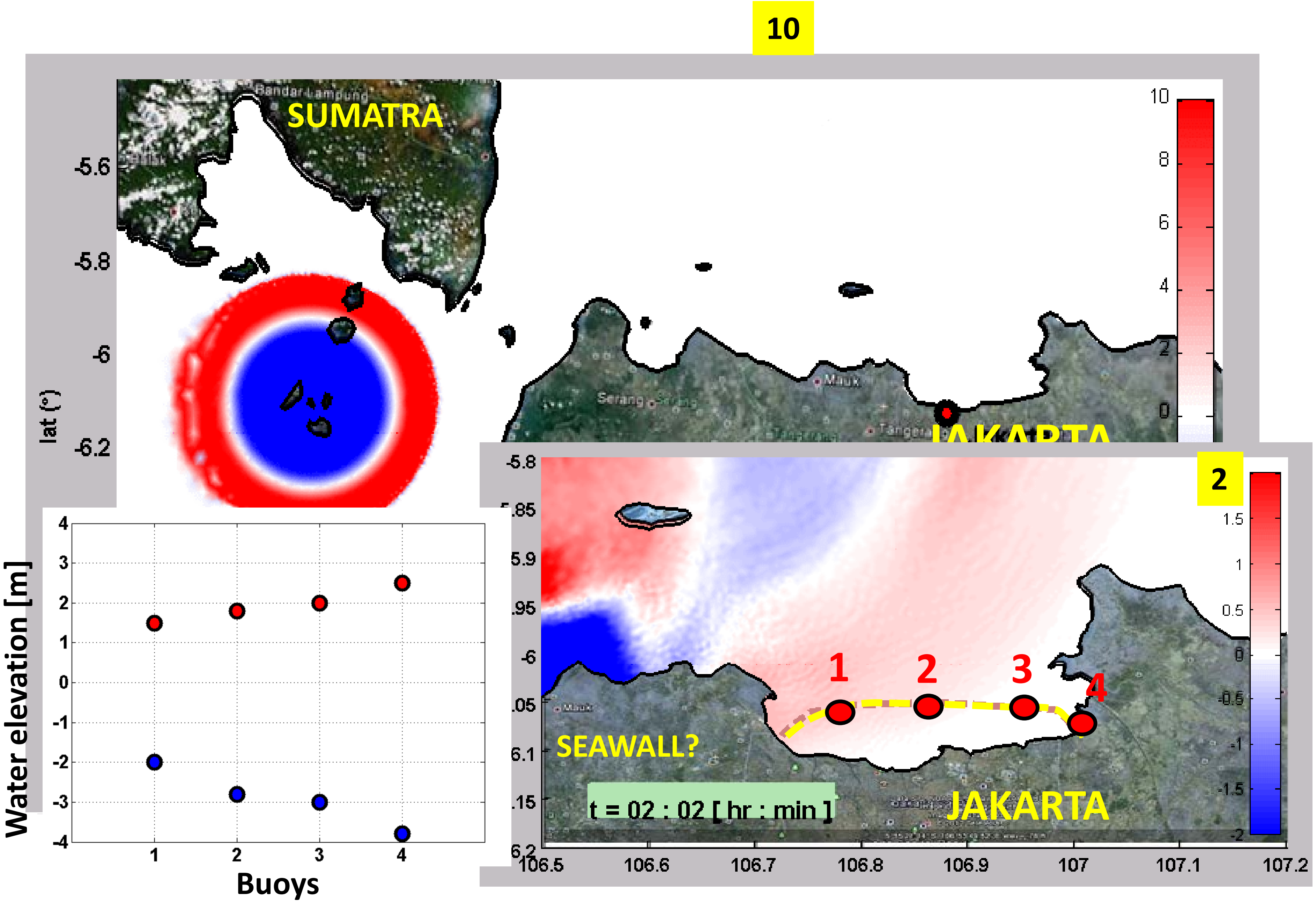
Reconstruction 1883 Krakatau Tsunami



Water Wave Theory

Basic Equations
Fluid Dynamics

17th Newton
18th Euler

Conservations : Mass and momentum
Compressible, incompressible flows

18th Laplace,
Cauchy, Airy

Initial value problem,
Linear wave theory

Theory and Models

19th Stokes, Boussinesq
Korteweg –de Vries (KdV)
Scott Russel

Nonlinear Waves, Spatial reduction (Surface water wave model), uni-directional waves.

Variational theory
Hamiltonian formulation

20th Bateman, Luke, Zakharov
Broer, Miles

Equations on surface,
model interior.
Consistent modelling

Hamiltonian Dynamics of surface waves, BASICS

Bateman, Luke, Zakharov Broer, Miles

Interior

Water is inviscid → No dissipation, 'Conservative'

- Water is incompressible (constant density)
- ASSUME flow is irrotational

$$\left.\begin{aligned}\operatorname{div} U &= 0\\ \operatorname{curl} U &= 0 \Rightarrow U = \nabla\Phi(x,y,z)\end{aligned}\right\} \quad \Delta\Phi(x,y,z)=0$$

Free surface

Assume pressure free atmosphere

- Kinematic cn'd: continuity equation
- Bernoulli equation

$$\partial_t \eta(x,y,t) = U\cdot N = \partial_N \Phi(x,y,\eta(x,t))$$

$$\partial_t \Phi(x,y,\eta(x,t),t) = \ldots\ldots$$

Observation: can be described as system in ClassMechanics, ***in surface variables only***

- Canonical variables

$$\begin{cases}\eta(x,y,t)\\ \phi(x,y,t)=\Phi(x,y,\eta(x,t),t)\end{cases}$$

- Hamiltonian = Total Energy

$$H(\phi,\eta)=K(\phi,\eta)+\frac{1}{2}g\iint \eta^2(x,y)\,dxdy$$

$$\partial_t \eta = \delta_\phi H(\phi,\eta)$$

$$\partial_t \phi = -\delta_\eta H(\phi,\eta)$$

Difficulty KINETIC ENERGY

$$KE = \iint \int_{-D}^{\eta} \tfrac{1}{2}|U|^2\,dzdxdy = ?? = K(\phi,\eta)$$

Approach (do NOT solve Laplace problem)

Consistent modelling through Dirichlet principle

$$K(\phi,\eta) = Min\left\{ \iint \int_{-D}^{\eta} \tfrac{1}{2}|\nabla\Phi|^2\,dzdxdy \,\middle|\, \Phi=\phi \text{ at } z=\eta \right\}$$

Consistent approximation Kinetic Energy

Analysis

Dirichlet's principle (1840)

$$K(\phi,\eta)=Min\left\{\iint\int_{-D}^{\eta}\tfrac{1}{2}\left|\nabla\Phi\right|^{2}dzdxdy\,\middle|\,\Phi=\phi\text{ at }z=\eta\right\}$$

Dirichlet-to-Neumann operator

$$\delta_{\phi}K(\phi,\eta)=\partial_{N}\Phi\text{ at }z=\eta$$

Consistent approximations

$$K(\phi,\eta)=\frac{1}{2g}\int\left(C\partial_{x}\phi\right)^{2}dx \qquad \delta_{\phi}K(\phi)=-\frac{1}{g}\partial_{x}C^{2}\partial_{x}\phi$$

***C* is phase velocity operator**

Approximate:

VBM: low-dim vertical structure, Finite Elements

AB: analytic with FIO (Fourier-Integral Operators), spatial-spectral

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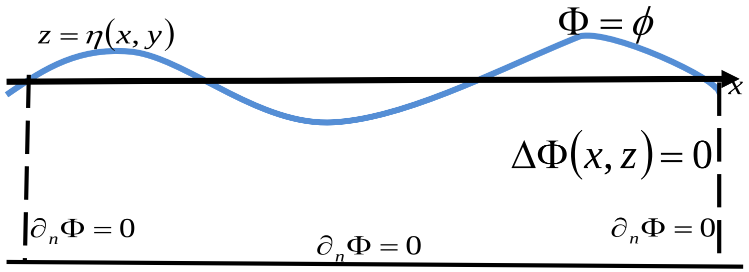
VBM Approximation Kinetic Energy (Avoid calculation of potentials in interior)



$$D(\Phi)=\iint\int_{-D}^{\eta}\tfrac{1}{2}|\nabla\Phi|^2\,dz\,dx\,dy \qquad K(\phi,\eta)=Min\{D(\Phi)|\Phi=\phi \text{ at } z=\eta\}$$

Consistent **VBM**-approximation: restrict minimizing set of functions

- Use as Ansatz $\Phi(x,z)=\phi(x)+F(z)\psi(x)$, with $F(\eta)=0$; then $\Phi(x,\eta)=\phi(x)$
- Take *F(z)* an Airy function $F(z)=1-\dfrac{\cosh(\kappa(z+D))}{\cosh(\kappa D)}$ with parameter κ
- Inserted in *K* leads to $K=K(\phi,\psi,\eta,\kappa)$
- Then $\delta_\psi K(\phi,\psi,\eta,\kappa)=0$, elliptic eqn $\Rightarrow \psi=\psi(\phi)$

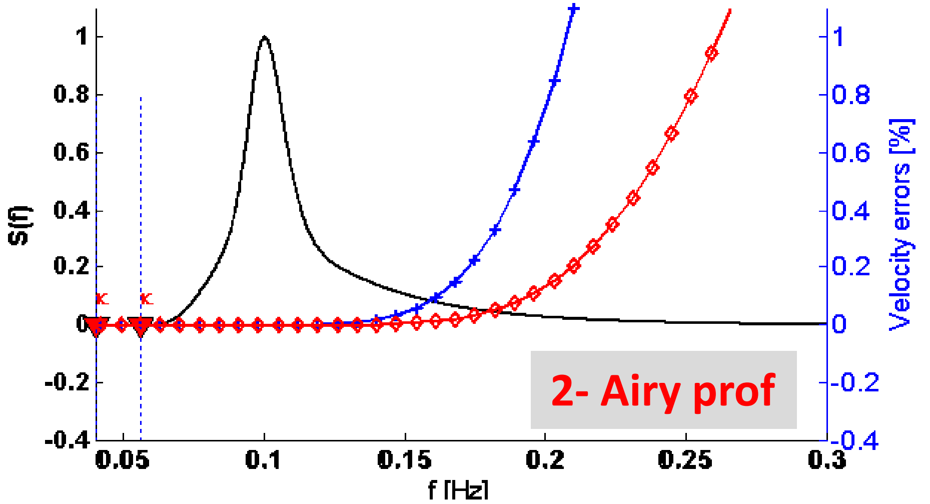
  $K_{VBM}=K(\phi,\psi(\phi),\eta,\kappa)$
- Optimize parameter κ depending on initial spectrum ! $\kappa\rightarrow K(\ldots,\kappa)=\frac{g}{2}\int V_{VBM}(k(\omega),\kappa)S_0(\omega)d\omega$
- Combination of Airy functions possible to improve dispersion

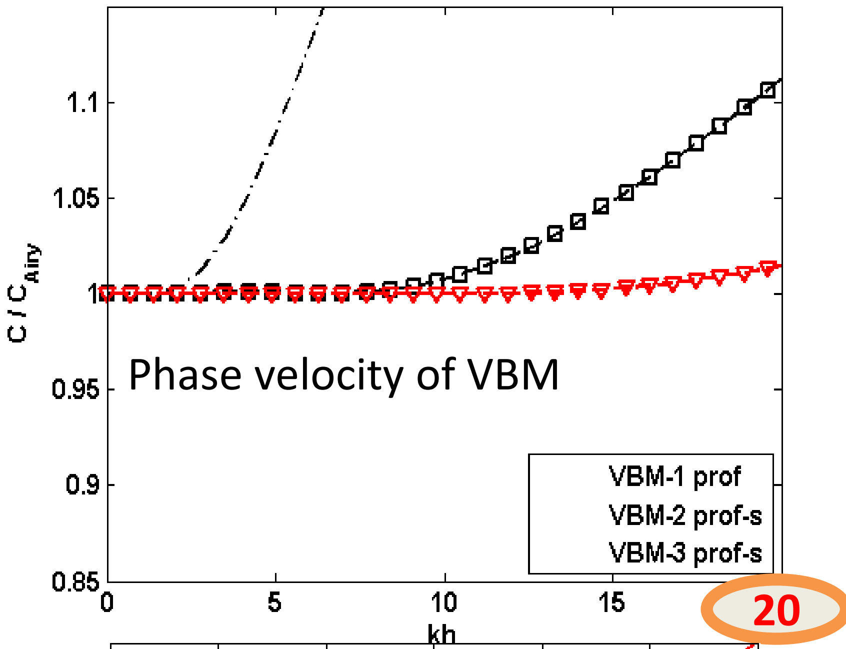
Dispersive properties of Optimized VBM

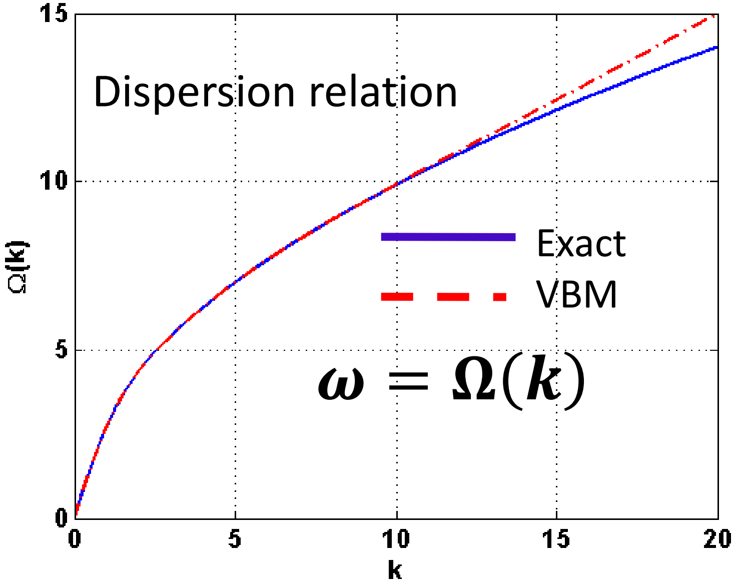
$$K_{vbm} = \min_{\kappa} \min_{\psi} \left\{ \frac{1}{2} \iint_{-h}^{\eta} |\nabla \Phi|^2 \, dz d\underline{x} \quad \middle| \Phi = \phi + A(\kappa, z) \cdot \psi(\underline{x}) \right\}$$

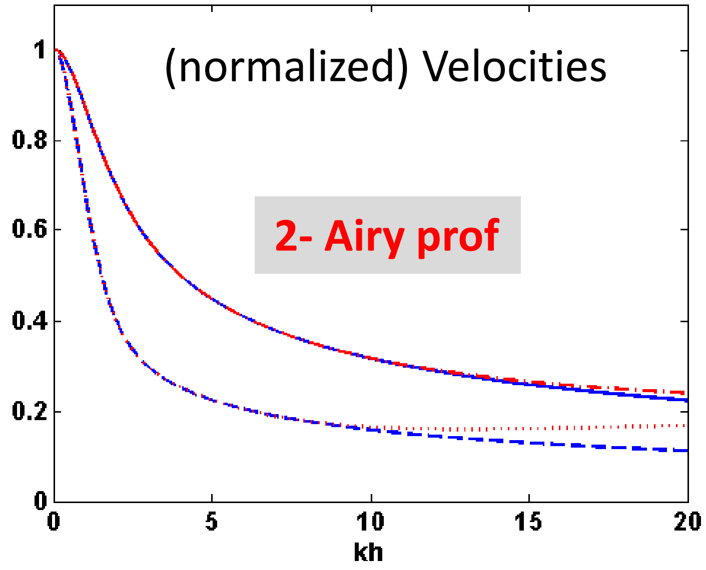
$$A_m = \frac{\cosh(\kappa_m (z+h))}{\cosh(\kappa_m h)} - 1$$

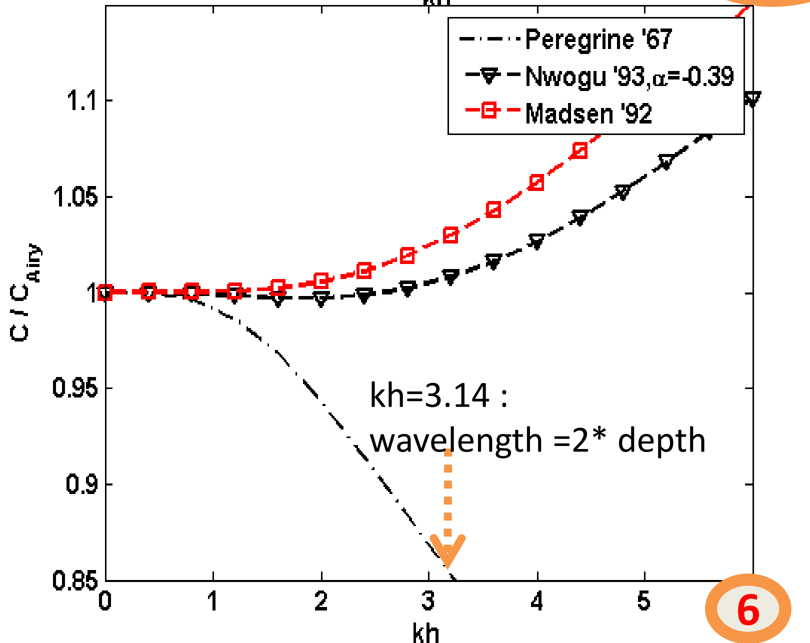
Tailor-made dispersion-relation depending on wave spectrum



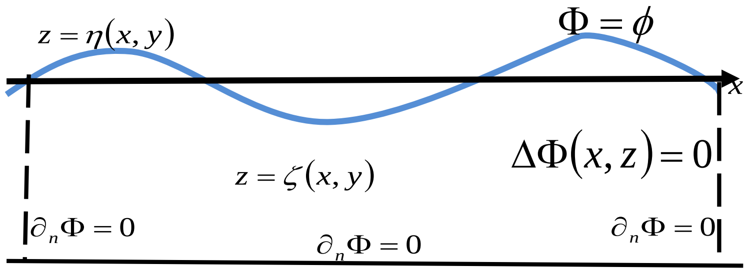








AB- Approximation Kinetic Energy
(Avoid calculation of potentials in interior)



$$D(\Phi)=\iint\int_{-D}^{\eta}\tfrac{1}{2}\left|\nabla\Phi\right|^2 dz\,dx\,dy \qquad K(\phi,\eta)=Min\left\{D(\Phi)\middle|\Phi=\phi \text{ at } z=\eta\right\}$$

$$K(\phi,\eta)=\frac{1}{2g}\int\left(C\partial_x\phi\right)^2 dx$$

C is phase velocity operator

$$\delta_\phi K(\phi)=-\frac{1}{g}\partial_x C^2\partial_x\phi$$

Consistent **AB**-approximation (spatial-spectral)

- Linear Airy theory: exact (dispersion) in strip

$$C^2 \hat{=}\, g\tanh(kD)/k \qquad \delta_\phi K(\phi)\,\hat{=}\, k\tanh(kD)\hat{\phi}(k)$$ **Pseudo-Diff-Operator**

- Shallow water $\quad C^2=g\left(D(x)+\eta(x,t)\right) \qquad \delta_\phi K(\phi)=-\partial_x(D+\eta)\partial_x\phi$

- 2[nd] order above *D(x)* $\quad C^2\,\hat{=}\left[g\tanh(kH)/k\right]_{\text{symm}} \text{ with } H=D(x)+\eta(x,t)$ **Fourier-Int-Operator**

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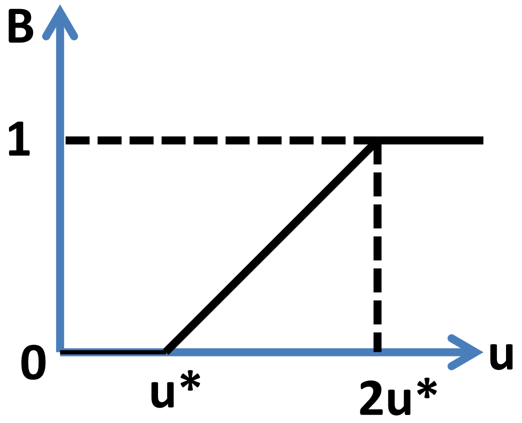
Wave Breaking

fully dispersive!

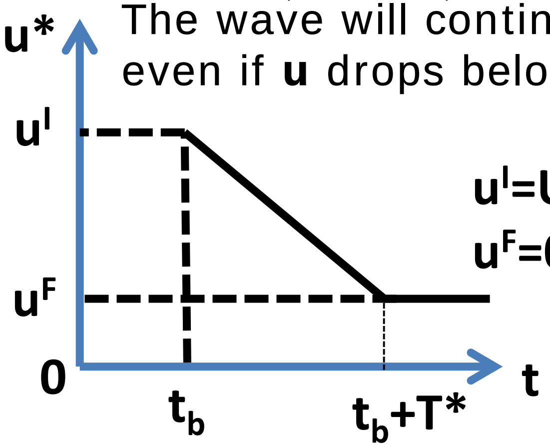
Eddy viscosity model $\partial_t u = \cdots + R$ $\quad R = \frac{1}{H}\partial_x F; \quad F = -\upsilon N; \quad \upsilon = B(u)\delta_B^2 H.N; \quad \mathrm{N} = \partial_t \eta; \quad H = D + \eta;$

υ : eddy viscosity localized at front of breaking wave

δ_B : mixing length coefficient; $\delta_B \in (0.9, 1.5)$

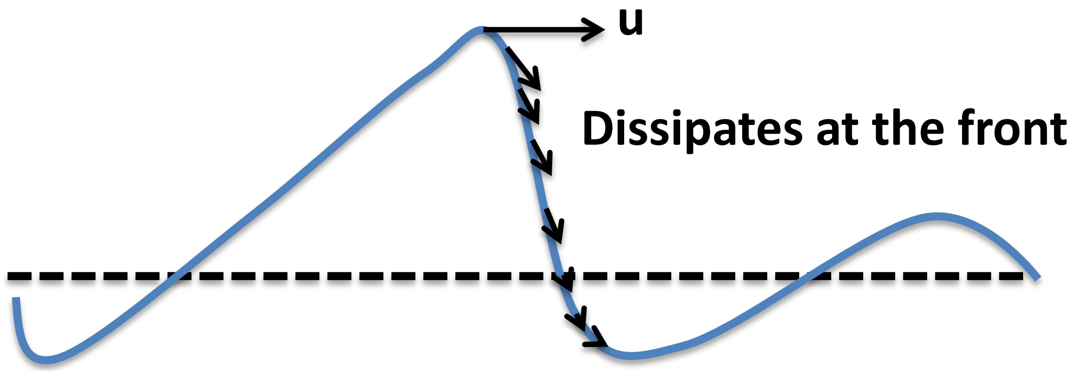


The wave will continue to break even if **u** drops below **u**^{I} .



u^I=U at t$_b$

u^F=0.2u^I



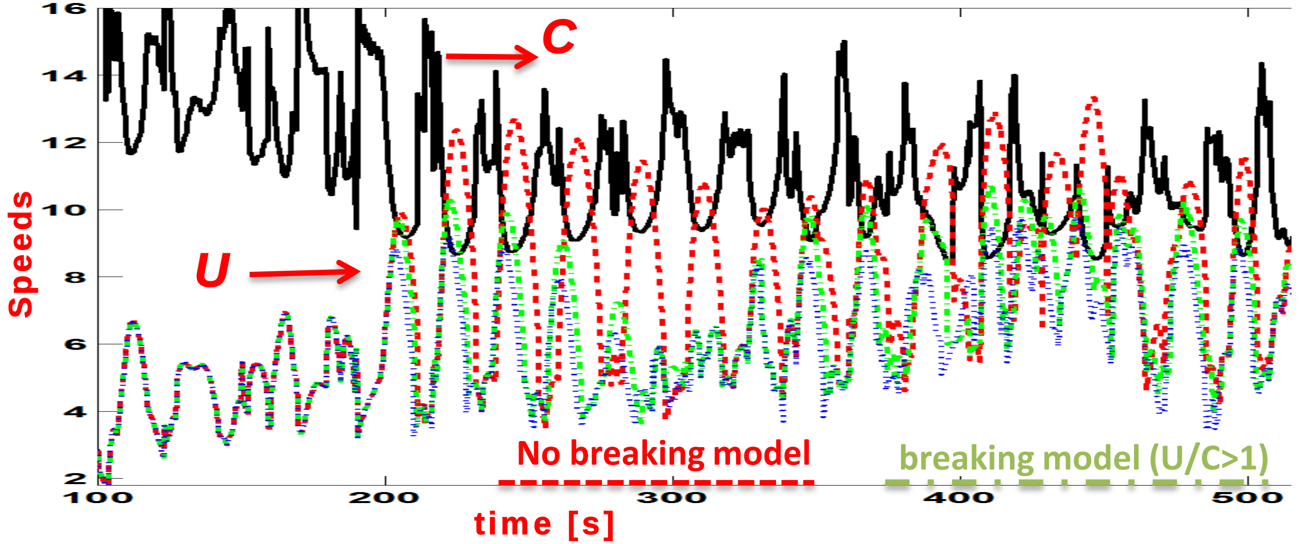
Kinematic breaking criterion:

particle velocity at crest (U) > Crest speed

Crest speed $C(x_c,t) = \sqrt{g\tanh(k(x_c,t)D)/k(x_c,t)}$

with $k(x,t) = \frac{\partial}{\partial x}\theta(x,t)$

Plot of max (U) and C for ABHS4 simulation of irregular wave (MARIN 223002F)



Conclusions

- AB and VBM in horizontal variables only (Boussinesq reduction)
  - Practical use of Dirichlet principle by consistent approximation:
    → *all symmetry properties are retained, robust*
  - AB: FIO's are 'expensive' but efficient approximation by *interpolation* techniques
  - VBM: optimized dispersion, more profiles more expensive

- Performance is satisfying/good compared to experiments;
  at present:
  - AB most suitable for wave tank simulations ('fast')
  - VBM for coastal applications

- Extension to wave-ship interaction in progress

Announcement: **HaWaSI VBM and AB will become available in 2015**
(advanced options for tailor-made license)

We like to hear your coastal eng problems and are interested to collaborate

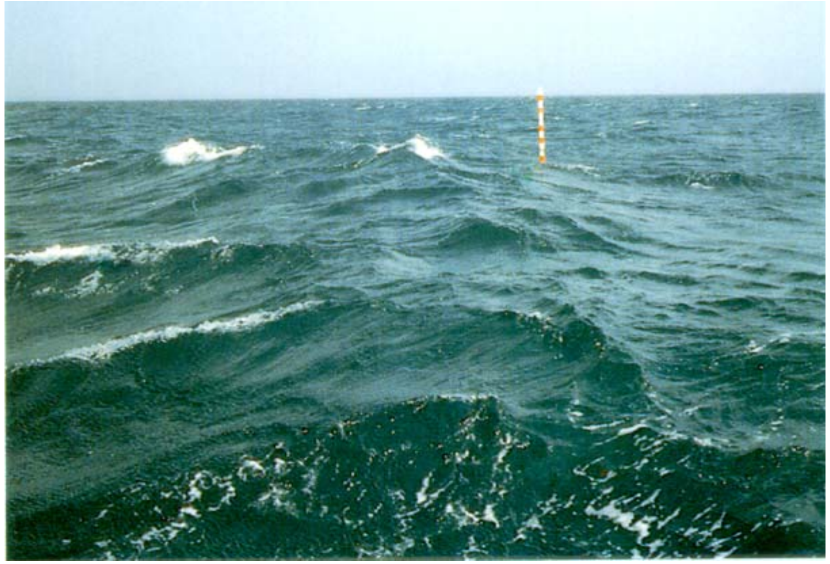
Marine science in Netherlands: MARIN and Delft (TUD and Deltares)
Math-contribution at universities decreases rapidly (←→ SRO water)

The advancement of Mathematics has profited tremendously from study of Fluid Mechanics / waves

MathProfits

- Asymptotics:
  - bdy-layers → (matched) asymptotic expansions
  - WKB asymptotics
  - characteristics (Hamilton-Jacobi)
- Infinite dimensionality → Hilbert (Courant & Hilbert)
  - functionals (var principles Maupertuis, Euler/Dirichlet)
  - gen solutions pde: shock relations
- Dyn. System theory & pde
  - complete integrability (‘65 KdV)
  - Nonlinearity: Fermi Pasti-Ulam
  - Topological study of nonlin problems (Poincare, Lax)
- Numerics:
  - fem (static → dynamic),
  - vof (balance laws),
  - Kruskal & Zabusky ‘67
- Modelling:
  - balance (conservation) laws
  - optimization formulations
  - Ham-consistent modelling & *numerics*

Acknowledgements



Recent Publications

R. Kurnia & EvG, MARHY 2014, Chennai

Lie S Liam, D. Adytia & EvG, *Ocean Eng.* 2014

R. Kurnia & EvG, *Coastal Eng.* 2014

D. Adytia & EvG, *J. Coastal Eng.* 2012

EvG & Andonowati, *Wave Motion* 2011

A.L. Latifah & EvG, *Nonlin. Processes Geophys* 2012

EvG & I. van der Kroon, *Wave Motion* 2012

I. Lakhturov & EvG, *Wave Motion* 2011

G. Klopman, EvG, M.Dingemans, *J. Fluid Mech* 2010

L. She Liam & EvG, *Physics Letters A* 2010

N. Karjanto & EvG, *J. Hydro-environment Research* 2010

EvG, Andonowati, L. She Liam & I. Lakhturov, *J. Comp. and Appl. Math* 2010

D. Adytia & EvG, APAC2009 World Scientific 2010, Vol. 1

N. Karjanto & EvG, *Handbook of Solitons*, Nova Science 2009

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Acknowledgements

KNAW