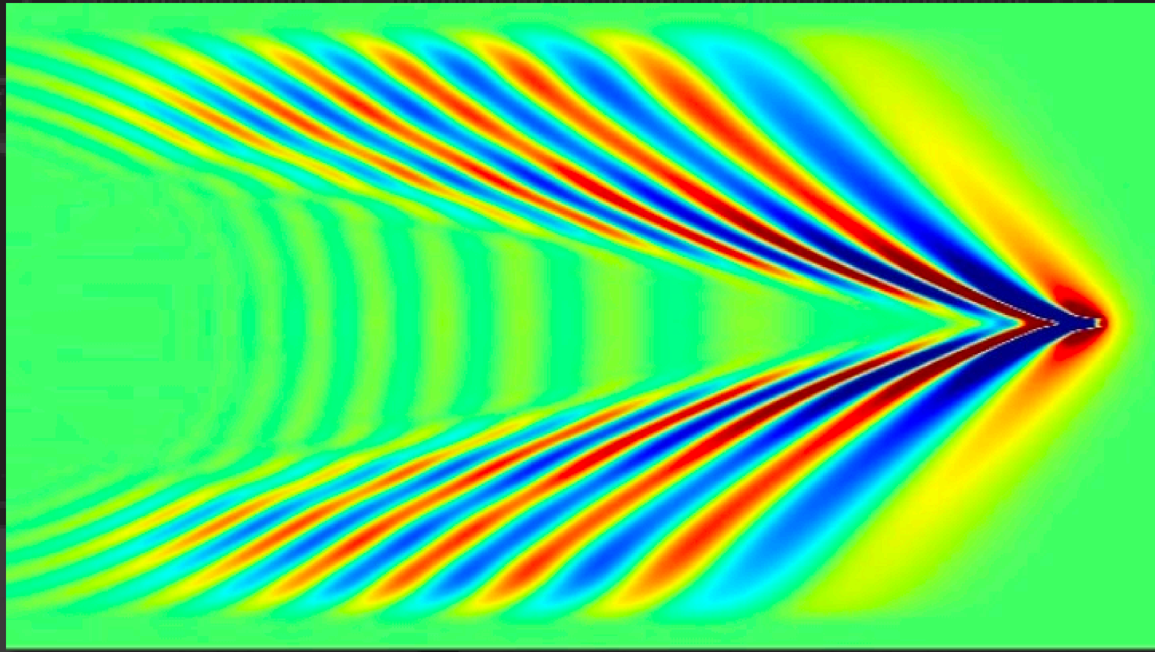
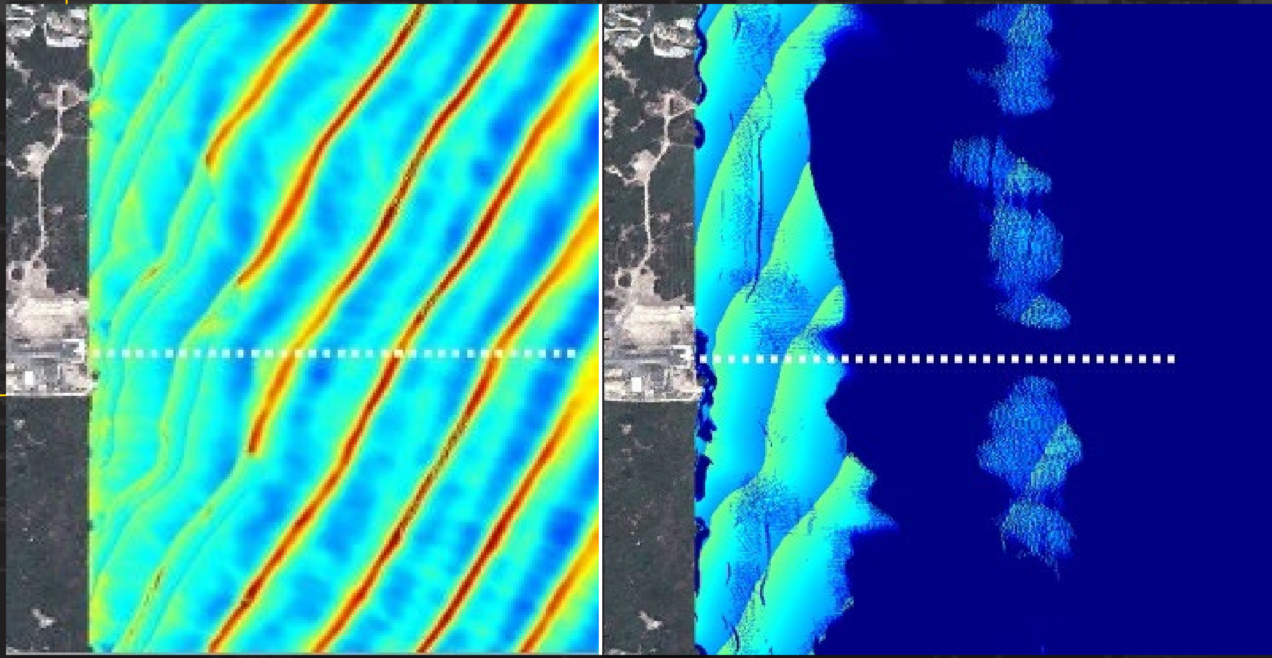
FUNWAVE DEVELOPMENT FINALIZATION: DEEP WATER MODULE



Michael-Angelo Y. Lam
Matt Malej
Gabriela Salgado-Dominquez
Marissa J. Torres

10 June 2025

SoN NAV-21-1694 & 1687
(FUNWAVE Dev in deep water/inlet-basins)



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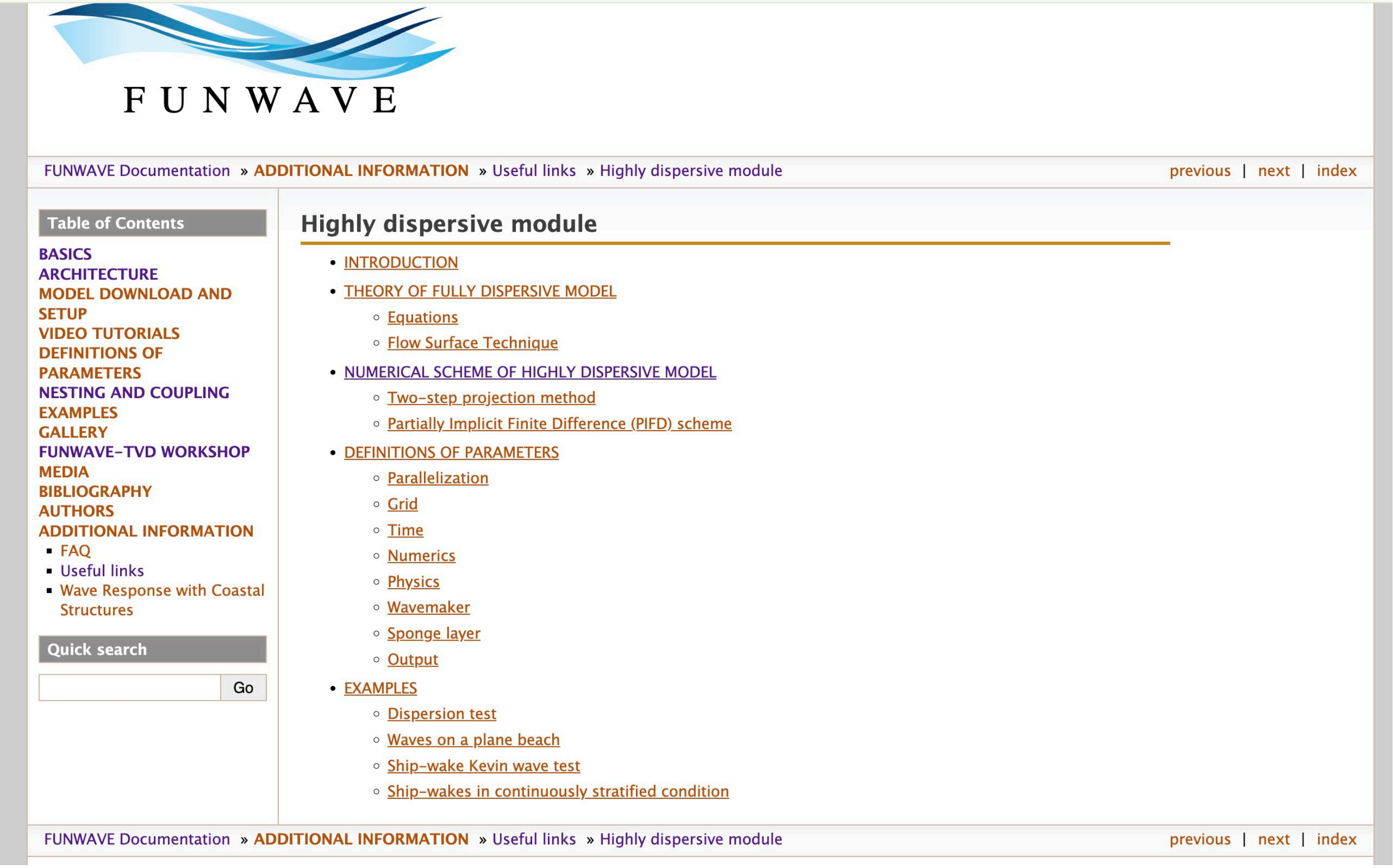
HIGHLY DISPERSIVE MODEL DEVELOPMENT

- Theory
- Numerical scheme
- Preliminary tests

WIKI page:

https://fengyanshi.github.io/build/html/highly_dispersive_model.html



FUNWAVE

FUNWAVE Documentation » ADDITIONAL INFORMATION » Useful links » Highly dispersive module — previous | next | index

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Highly dispersive module

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THEORY

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Conservative Form of 3D Navier–Stokes Equations

$$\frac{\partial \boldsymbol{\Psi}}{\partial t} + \nabla \cdot \boldsymbol{\Theta}(\boldsymbol{\Psi}) = \mathbf{S}$$

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \boxed{\frac{\partial}{\partial \sigma}}\right)$$

New spatial derivative with $\boldsymbol{\sigma}$, surface flow, instead of z

$$\boldsymbol{\Psi} = \begin{pmatrix} D \\ Du \\ Dv \\ \boxed{D\omega} \end{pmatrix}$$

$$\boldsymbol{\Theta} = \begin{pmatrix} Du\mathbf{i} + Dv\mathbf{j} + \boxed{\omega\mathbf{k}} \\ (Duu + (\frac{1}{2}g\eta^2 + gh\eta))\mathbf{i} + Duv\mathbf{j} + \boxed{u\omega\mathbf{k}} \\ Duv\mathbf{i} + (Dvv + (\frac{1}{2}g\eta^2 + gh\eta))\mathbf{j} + \boxed{v\omega\mathbf{k}} \\ \boxed{Du\omega\mathbf{i} + Dv\omega\mathbf{j} + \omega\omega\mathbf{k}} \end{pmatrix}$$

New terms and fourth equation for conservation of momentum in $\boldsymbol{\sigma}$ direction

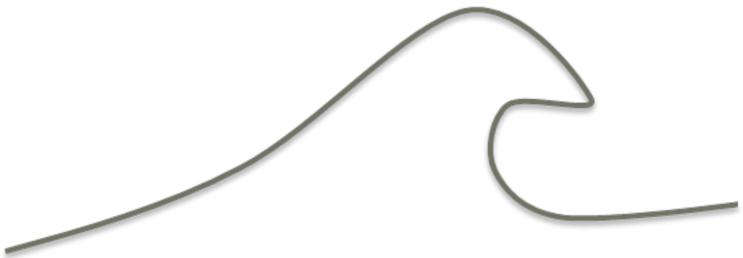
SURFACE FLOW TECHNIQUE

Depth-Integrated Mass Conservation Equation

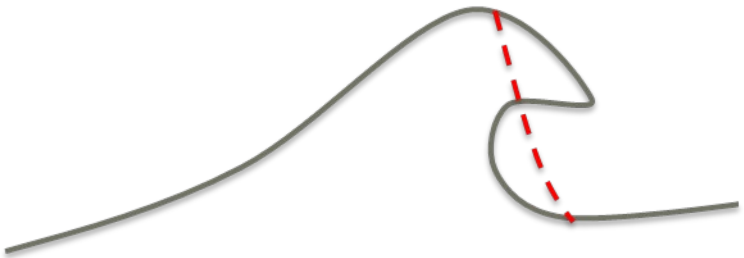
$$\frac{\partial D}{\partial t} + \frac{\partial}{\partial x}\left(D \int_0^1 u\,\boxed{d\sigma}\right) + \frac{\partial}{\partial y}\left(D \int_0^1 v\,\boxed{d\sigma}\right) = 0$$

Integrals with respect z replace with $\boldsymbol{\sigma}$, surface flow

Navier-Stokes solver with VOF



Surface wave model

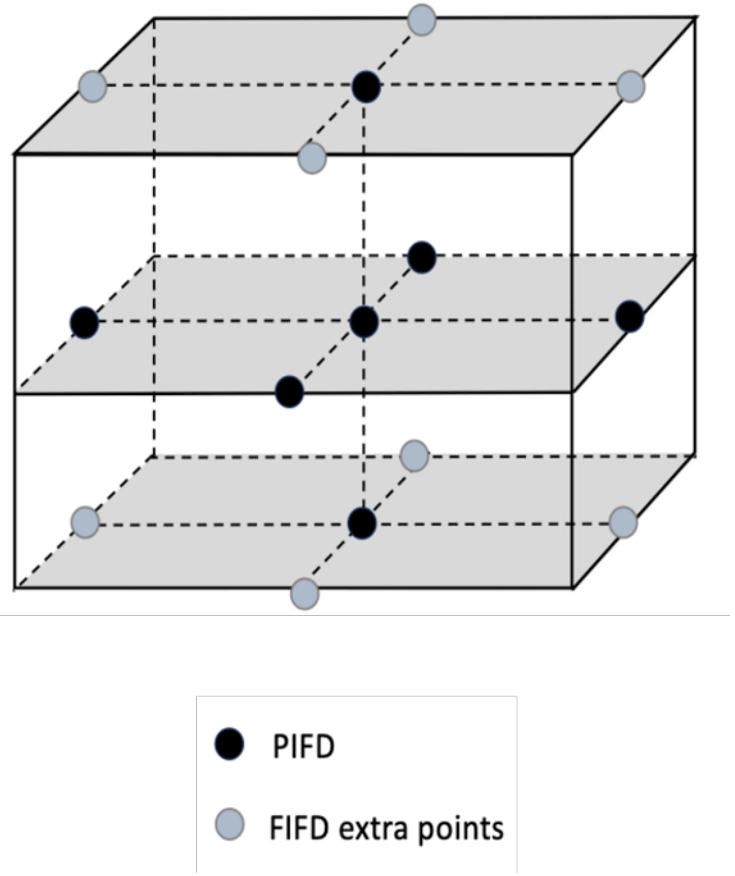


NUMERICAL SCHEME

- Two-step projection method:
  - Hydrostatic predictor phase (analogous to original FUNWAVE)
  - New non-hydrostatic corrector phase (Poisson Equation)

$$\frac{\partial}{\partial x}\left[\frac{\partial p}{\partial x}+\frac{\partial p}{\partial \sigma}\frac{\partial \sigma}{\partial x^*}\right]+\frac{\partial}{\partial y}\left[\frac{\partial p}{\partial y}+\frac{\partial p}{\partial \sigma}\frac{\partial \sigma}{\partial y^*}\right]+\frac{\partial}{\partial \sigma}\left(\frac{\partial p}{\partial x}\right)\frac{\partial \sigma}{\partial x^*}+$$
$$\frac{\partial}{\partial \sigma}\left(\frac{\partial p}{\partial y}\right)\frac{\partial \sigma}{\partial y^*}+\left[\left(\frac{\partial \sigma}{\partial x^*}\right)^2+\left(\frac{\partial \sigma}{\partial y^*}\right)^2+\frac{1}{D^2}\right]\frac{\partial}{\partial \sigma}\left(\frac{\partial p}{\partial \sigma}\right)=$$
$$\frac{\rho}{\Delta t}\left(\frac{\partial u^*}{\partial x}+\frac{\partial u^*}{\partial \sigma}\frac{\partial \sigma}{\partial x^*}+\frac{\partial v^*}{\partial y}+\frac{\partial v^*}{\partial \sigma}\frac{\partial \sigma}{\partial y^*}+\frac{1}{D}\frac{\partial w^*}{\partial \sigma}\right)$$

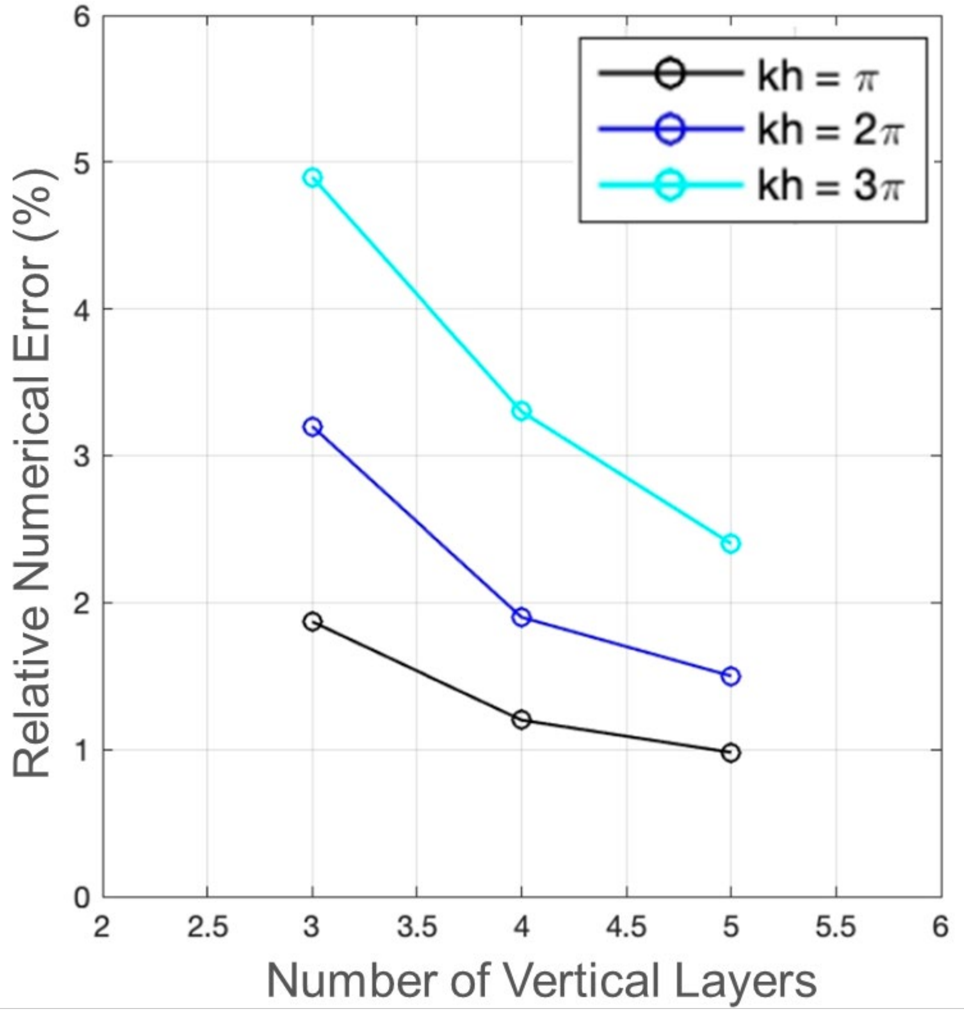
* variables are values from the predictor phase



- 15-point Fully Implicit Finite Difference (FIFD) replaced with 7-point Partially Implicit Finite Difference (PIFD)
- Point reduction increases efficiency by 50%

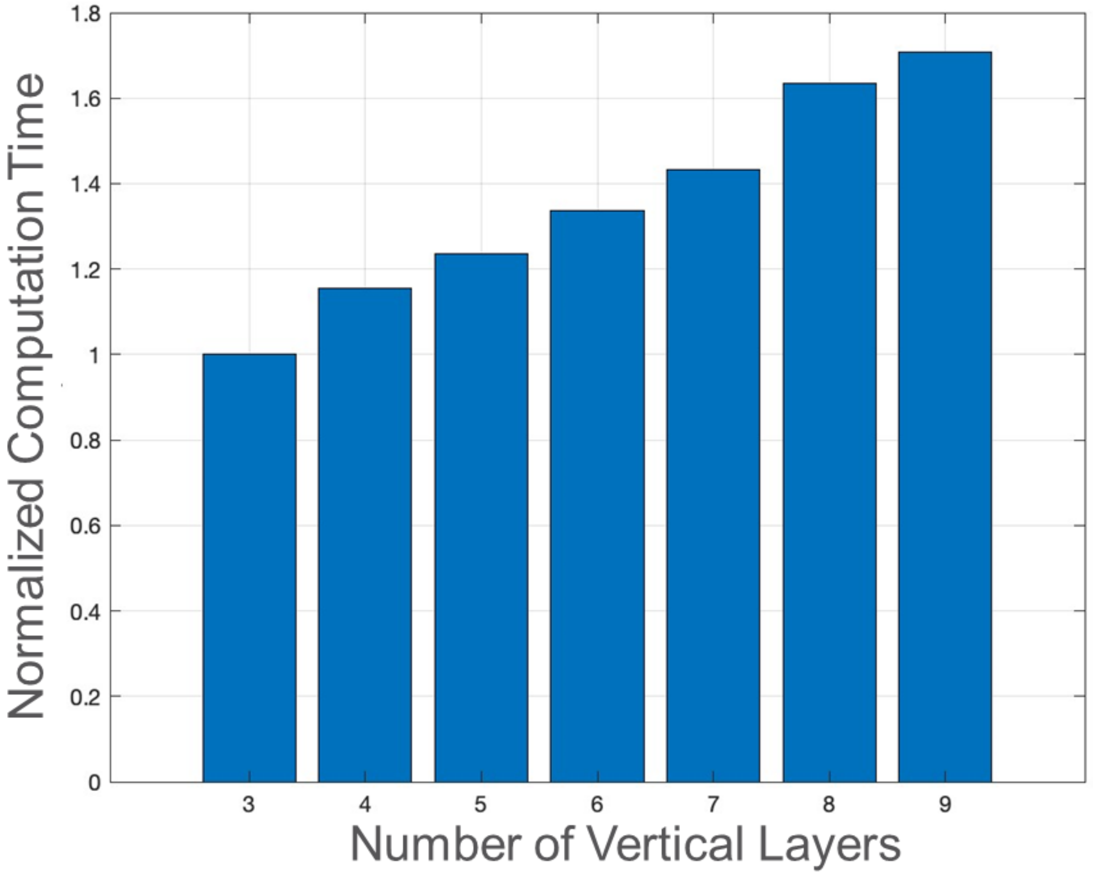
DISPERSION TESTS

- Standing wave experiments with different kh
- Current FUNWAVE version limited to $kh < \pi$
- 4-layer performs well (~2% error) for $kh = 2\pi$



EFFICIENCY

- Increasing the number of layers does not drastically increase computation time.
- Less than double the computation time when tripling the number of layers from 3.
- Unfortunately, the 3-layer model is about 8 times slower than the original FUNWAVE version.

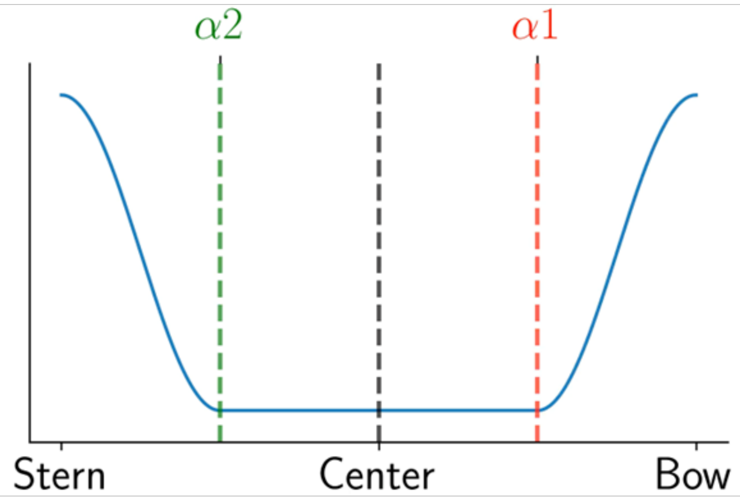


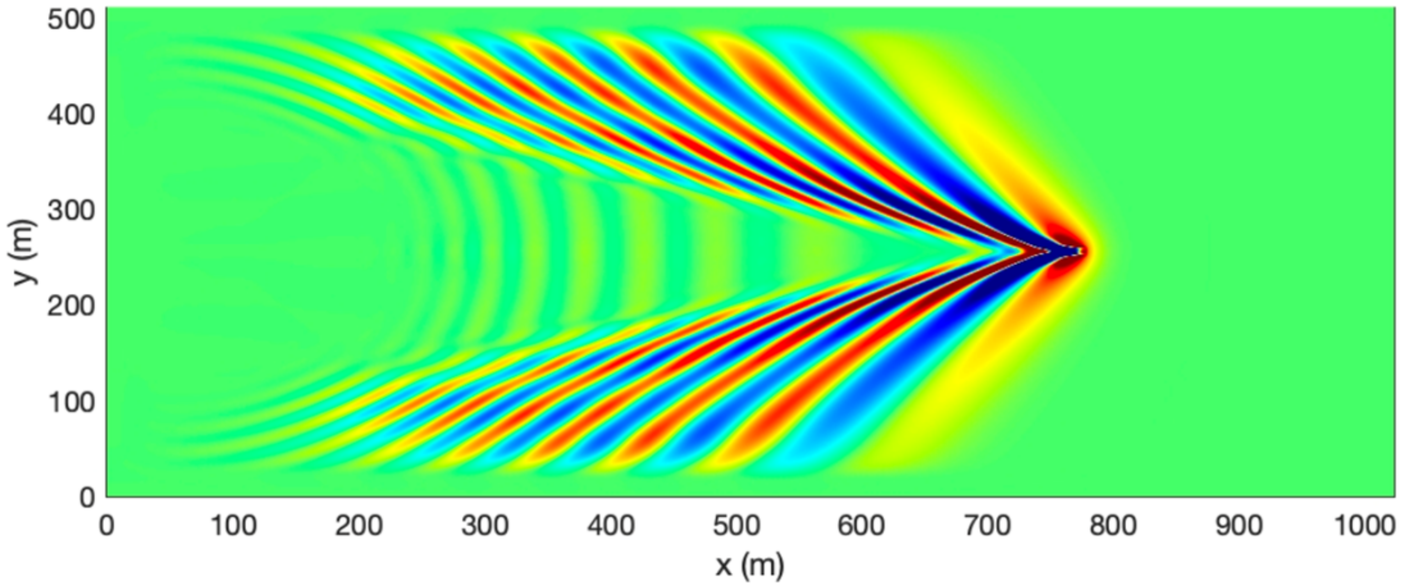
SHIPWAKES

$$p_a(\tilde{x},\tilde{y},t) = Pf(\tilde{x},t)q(\tilde{y},t),$$

$$f(\tilde{x},t) = \begin{cases} \cos^2\left[\frac{\pi(\tilde{x}-x^*(t)-\frac{1}{2}\alpha_1 L)}{(1-\alpha_1)L}\right], & \frac{1}{2}\alpha_1 L < \tilde{x}-x^*(t) \le \frac{1}{2}L \\ \cos^2\left[\frac{\pi(x^*(t)-\tilde{x}-\frac{1}{2}\alpha_2 L)}{(1-\alpha_2)L}\right], & -\frac{1}{2}L \le \tilde{x}-x^*(t) < -\frac{1}{2}\alpha_2 L \\ 1, & -\frac{1}{2}\alpha_2 L \le \tilde{x}-x^*(t) \le \frac{1}{2}\alpha_1 L \end{cases}$$

$$q(\tilde{y},t) = \begin{cases} \cos^2\left[\frac{\pi(|\tilde{y}-y^*(t)|-\frac{1}{2}\beta W)}{(1-\beta)W}\right], & \frac{1}{2}\beta W < |\tilde{y}-y^*(t)| \le \frac{1}{2}W \\ 1, & |\tilde{y}-y^*(t)| \le \frac{1}{2}\beta W \end{cases}$$

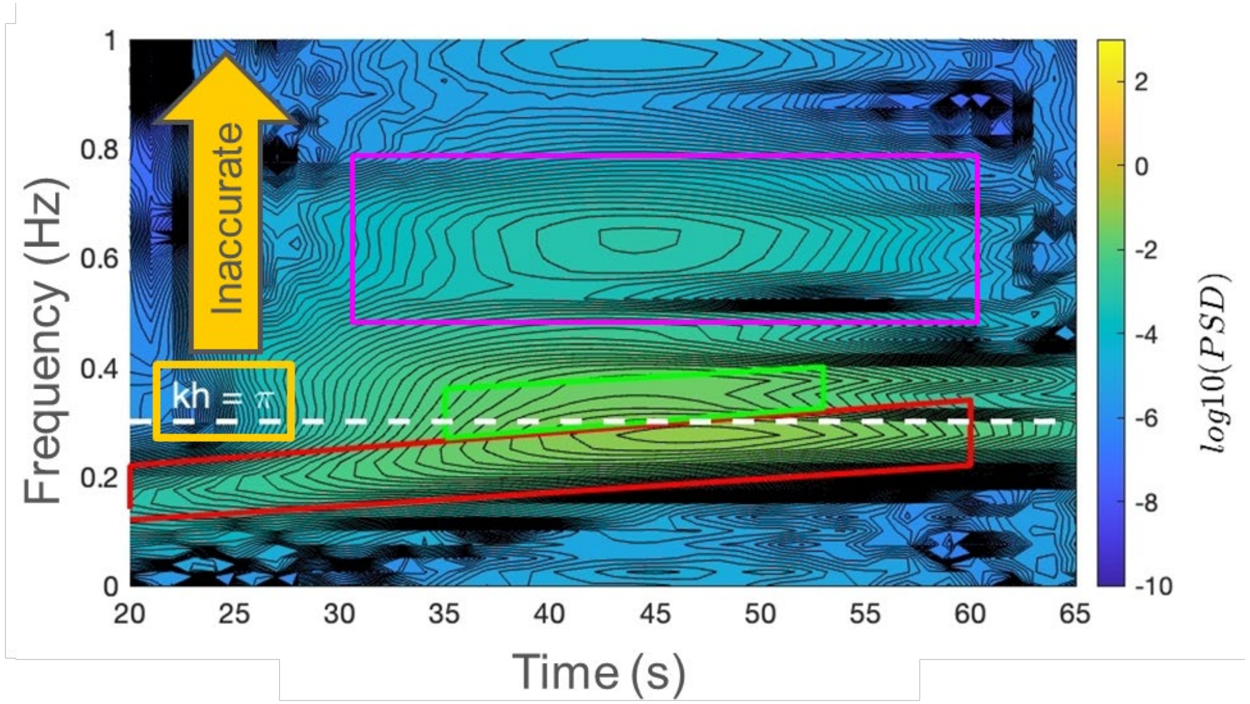


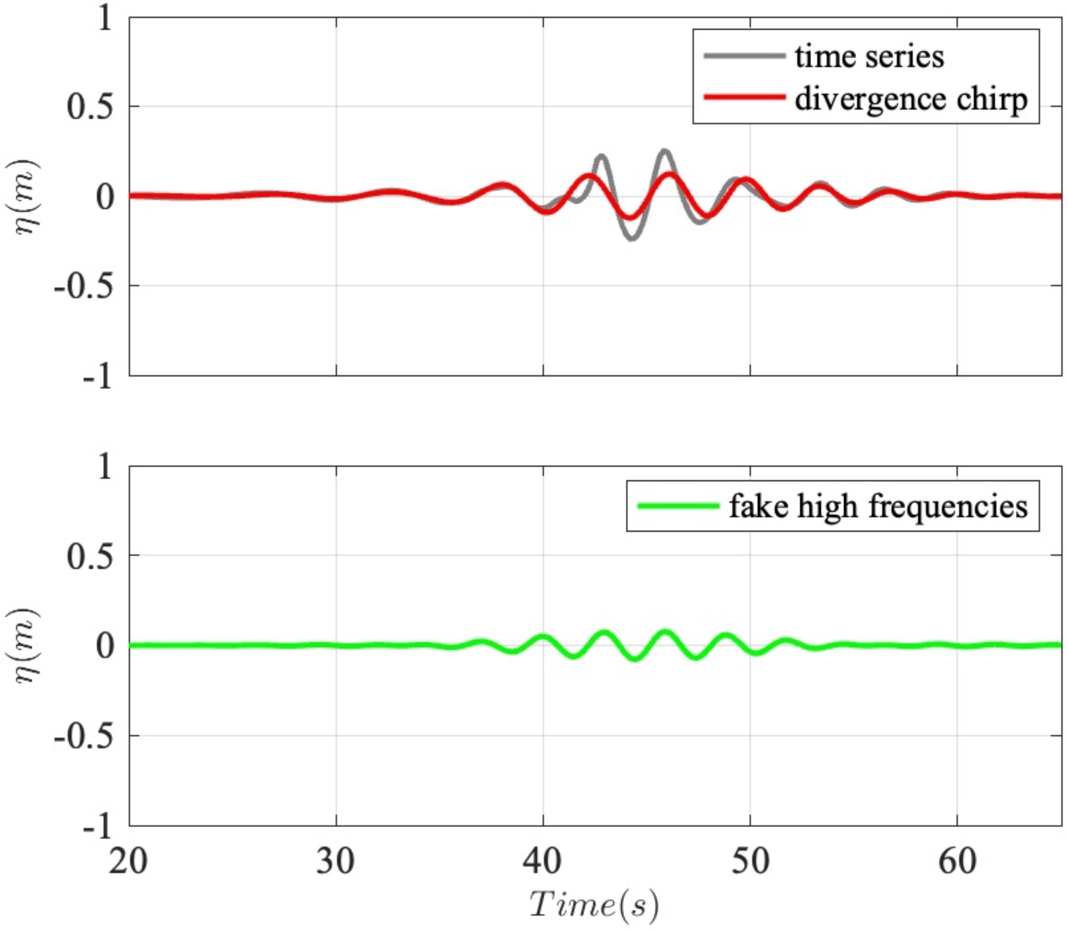


Same pressure source configuration as original FUNWAVE

SHIPWAKES: DEFICIENCIES

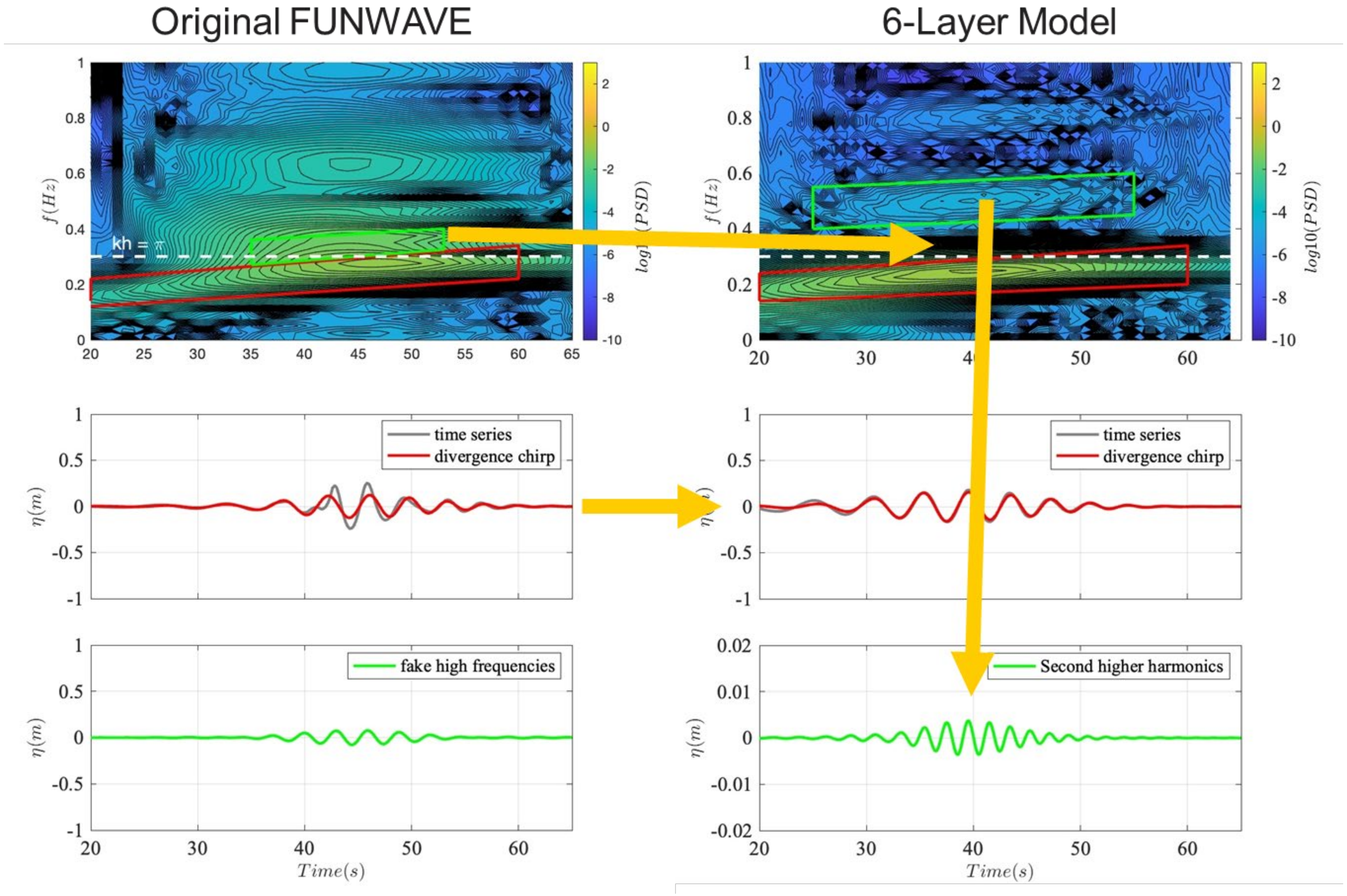
- Bulk energy is the main divergence chirp
- Fake higher-frequency energy is due to modeling errors for $\mathrm{kh} > \pi$
- Higher harmonics, $f > 0.6$, are not accurate, as the chirp frequency is 0.25





SHIPWAKES: IMPROVEMENTS

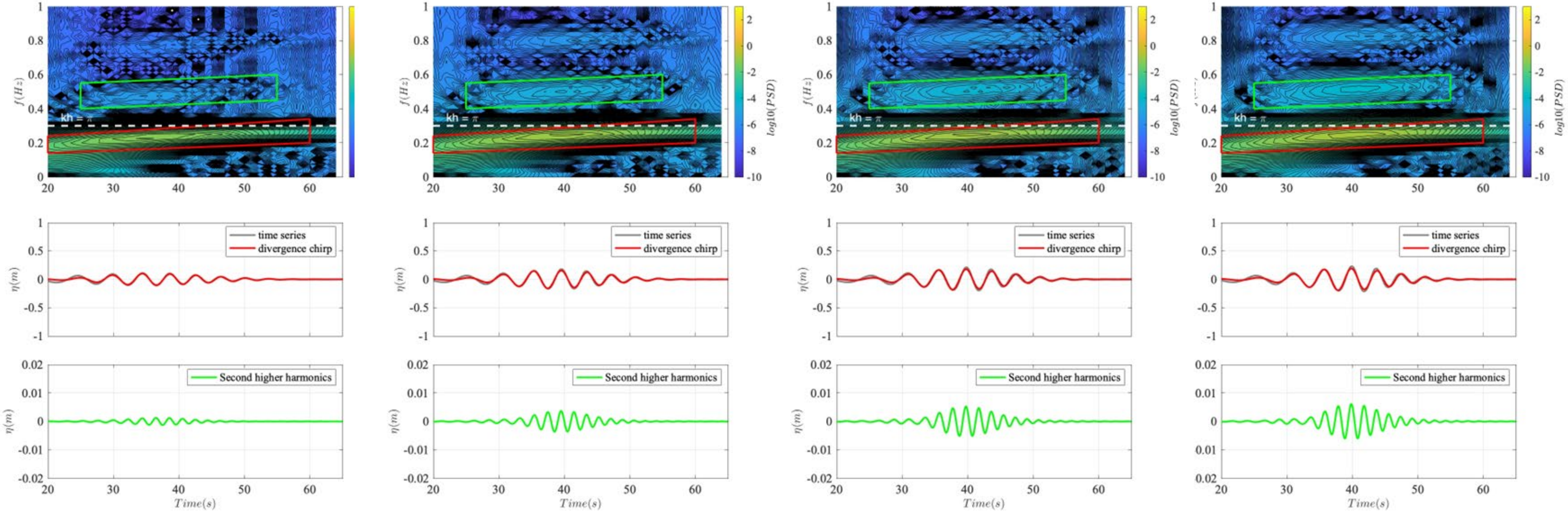
- No fake higher-order energy
- Less distortion of the main divergence chirp
- Higher harmonics more accurate, $f = 0.5$, of divergence chirp, $f = 0.25$



SHIPWAKES: IMPACT OF LAYERS

Second harmonic energy increasing

3 layers | 6 layers | 9 layers | 12 layers



The 3-layer model is more accurate than FUNWAVE.

Minor difference between the second-order harmonics of the 9-layer and 12-layer models

TIDE AND SURGE MODULE DEVELOPMENT

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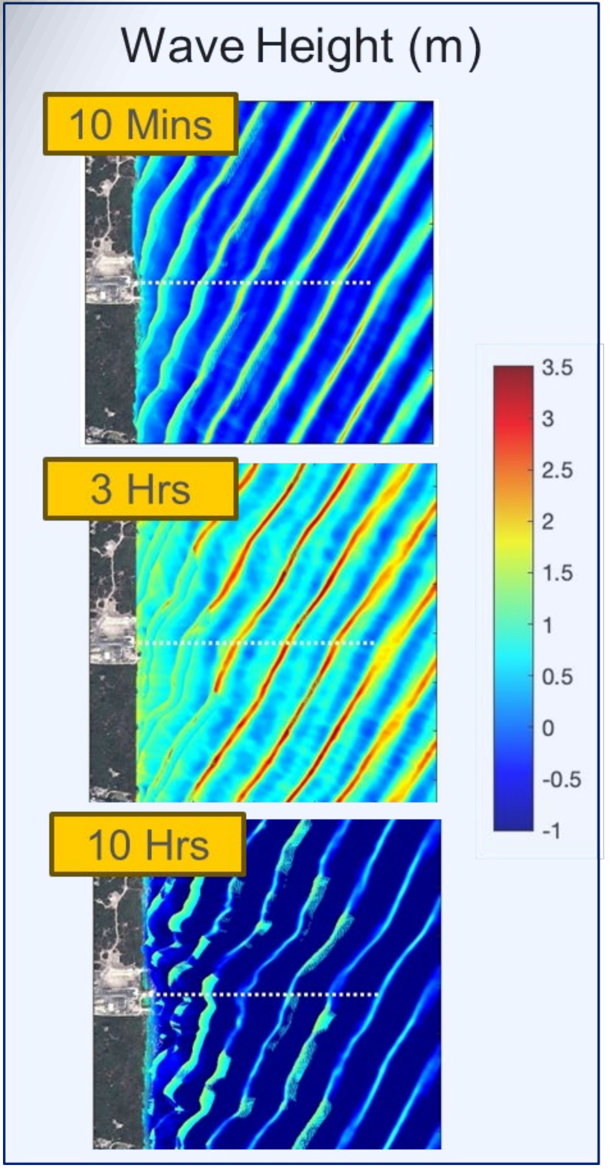
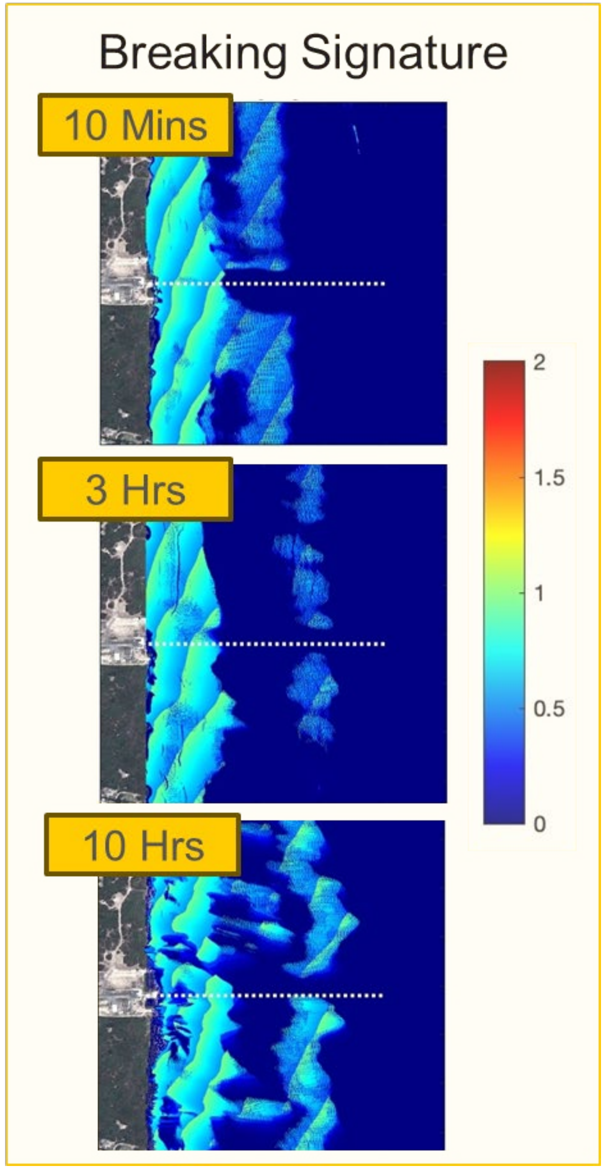
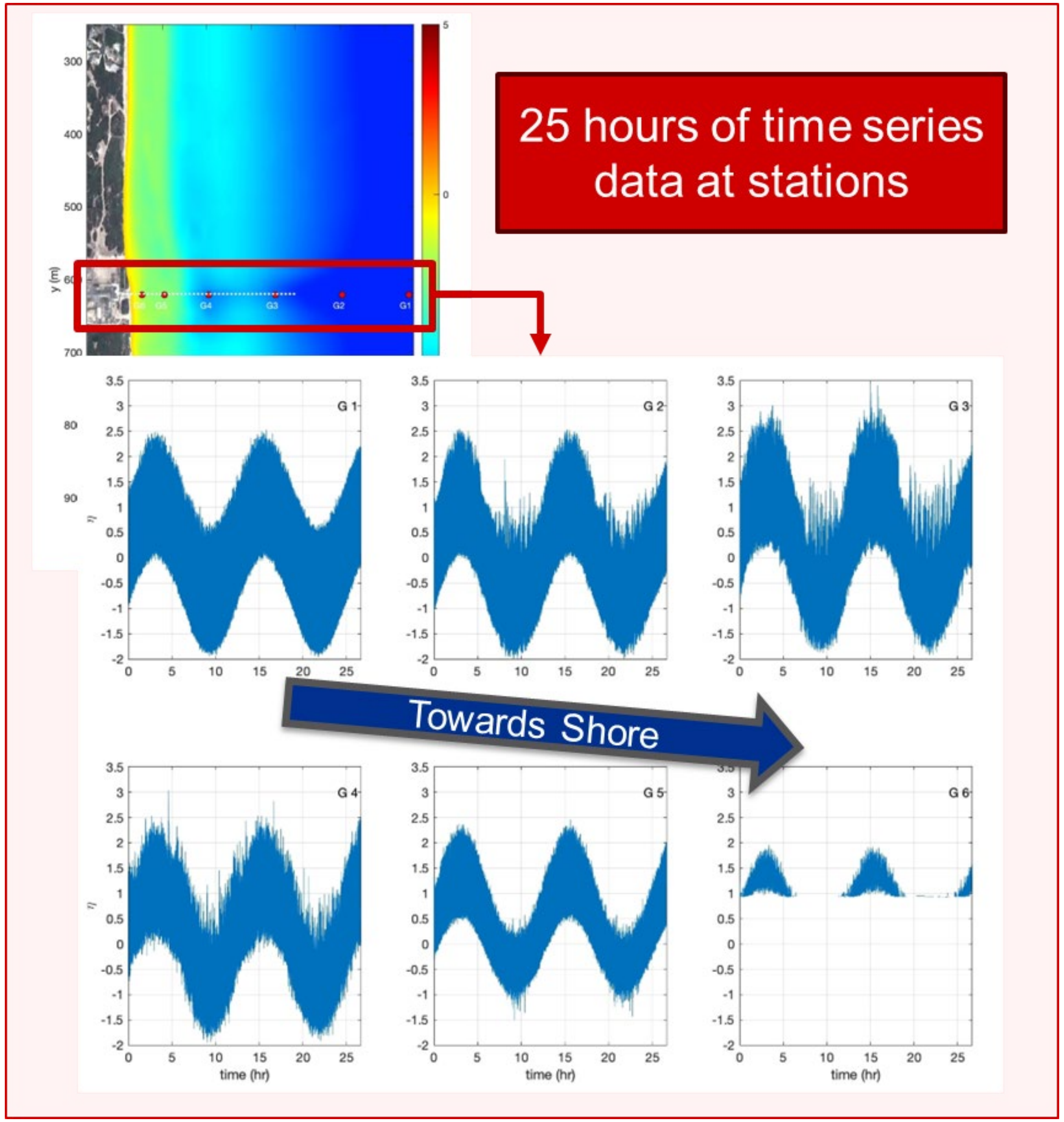
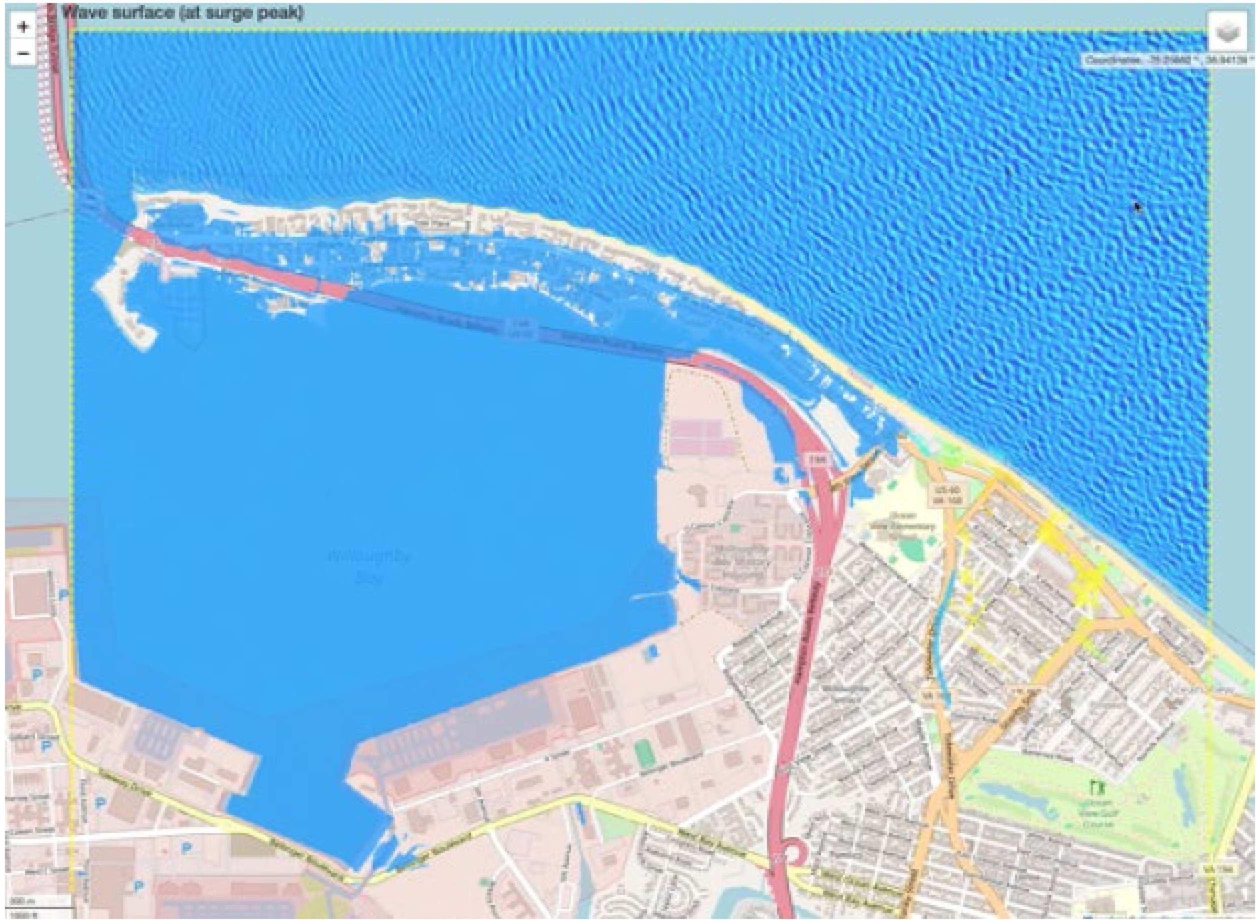






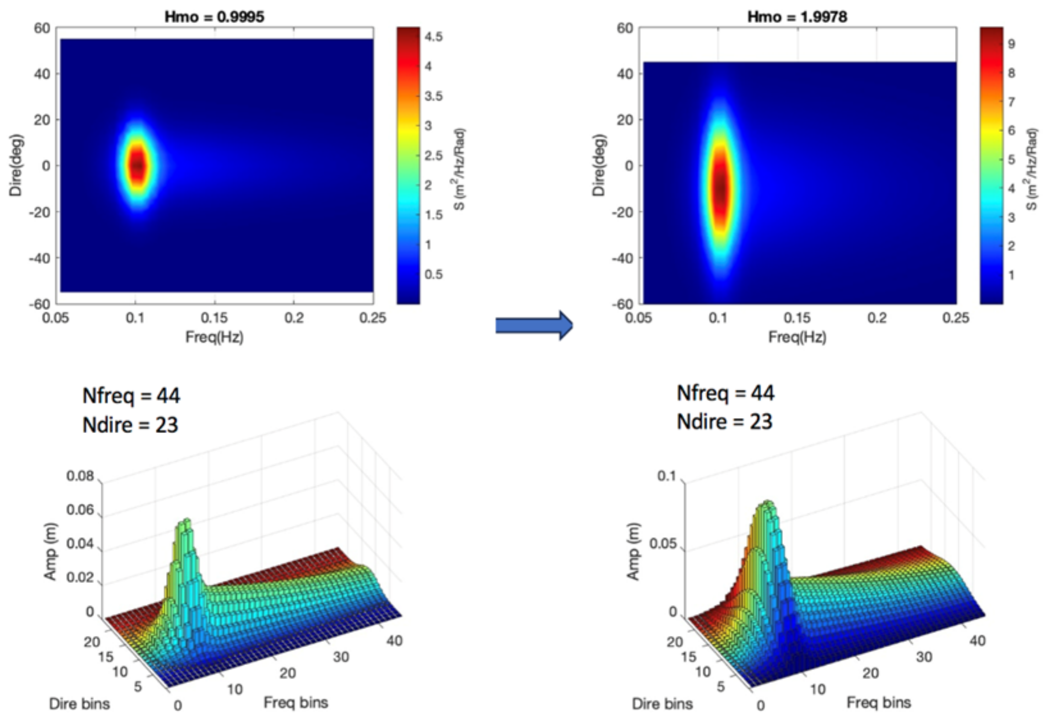
APPLICATION

Application of the new tide/surge module to predict the total water level in military installations



https://ud-projects.github.io/ESTCP/interactive_map/Funwave/FUNWAVE_snap.html

TIME-VARYING SPECTRA WAVEMAKER



Input File

```
WAVEMAKER = TIME_SPECTRA
SPECTRA_FILE = spectra_file.txt
TIDAL_BC_GEN_ABS = T
TideBcType = DATA
TideWestFileName = tide_data_west.txt
```

Malej M. and Shi F., Development of the water level variation module in FUNWAVE-TVD, in preparation for a journal publication

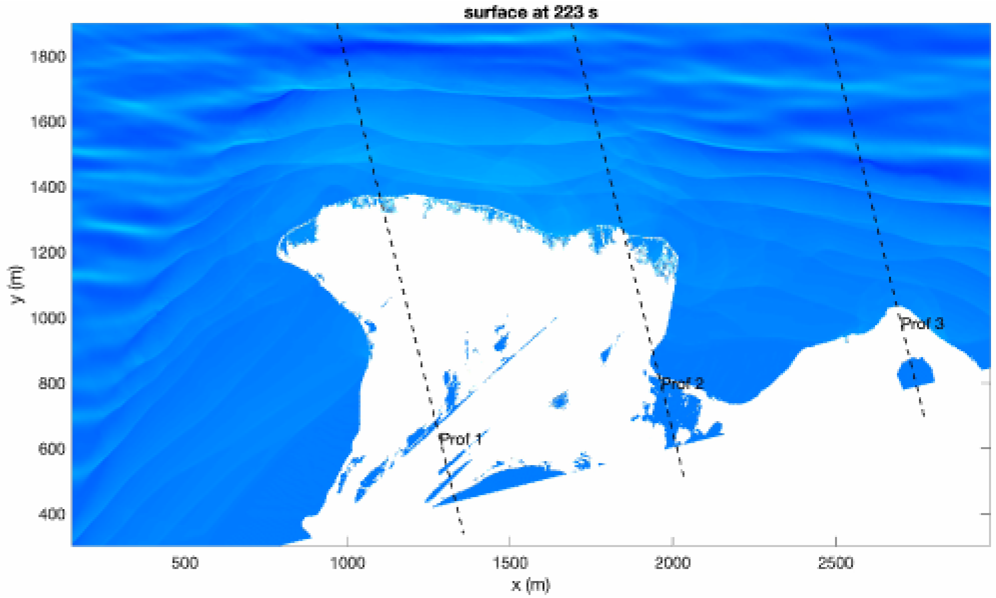
https://fengyanshi.github.io/build/html/absorbing_generating_wavemaker.html

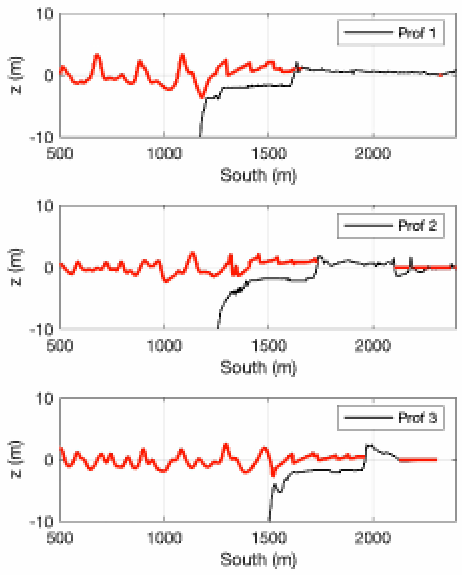
INFRA-GRAVITY WAVE GENERATOR

ERDC

Roi Namur & Kwajalein Atoll

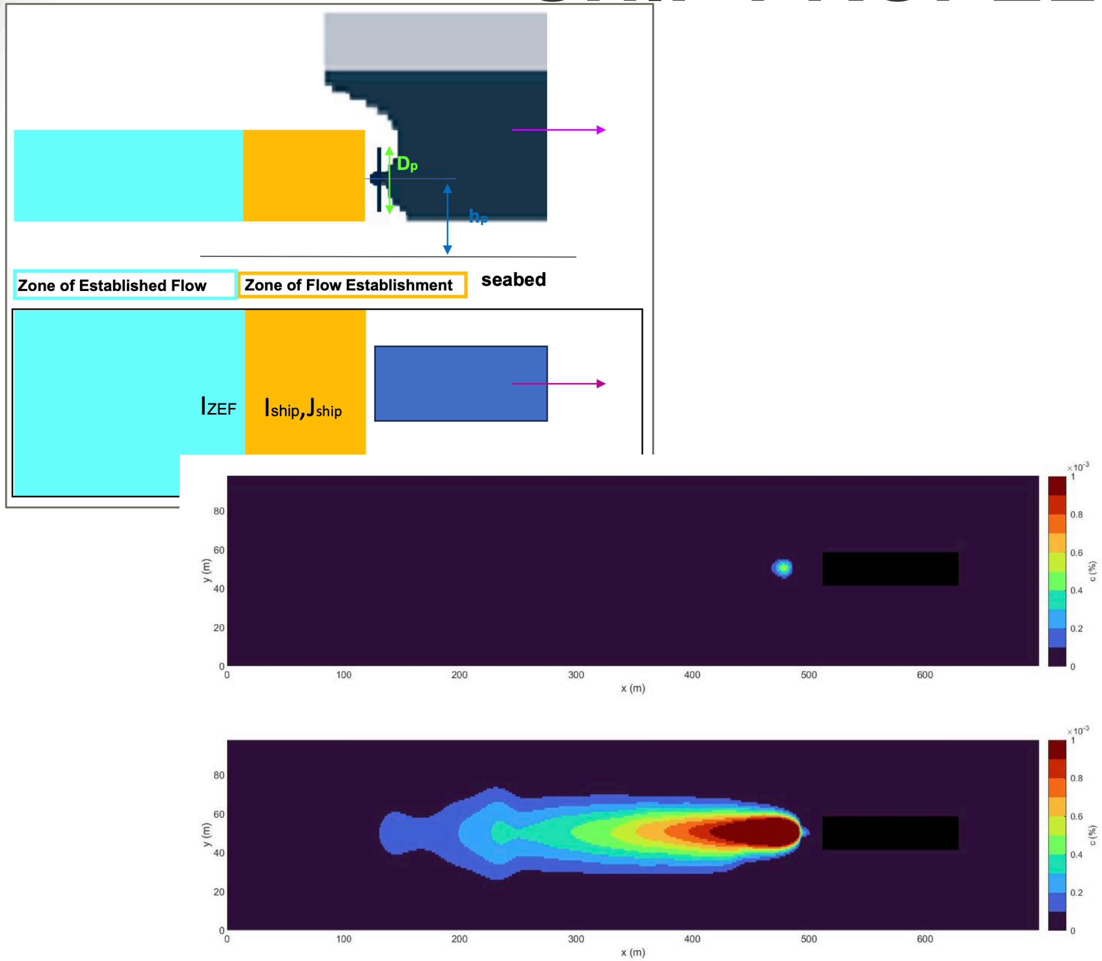
(Infra-gravity wave-induced wave over-wash)

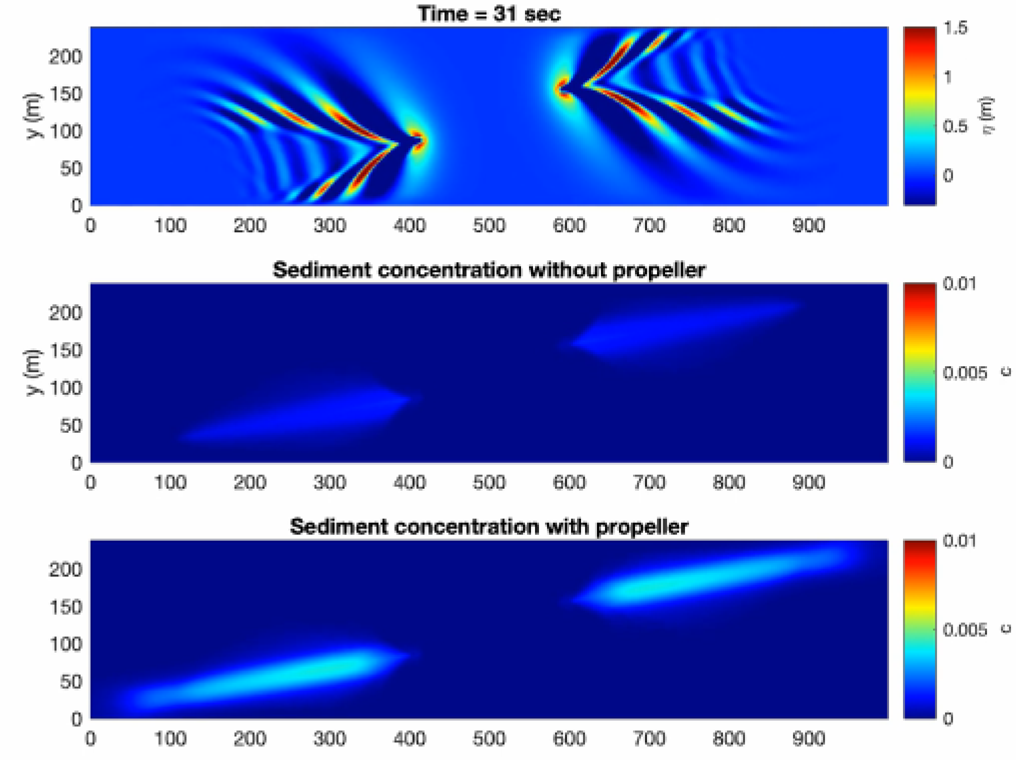




Malej et al., 2021, Boussinesq-type modeling of low-frequency wave motions at Marina di Carrara, Journal of Waterway, Port, Coastal and Ocean Engineering, 147(6): 05021015

SHIP PROPELLER EFFECTS

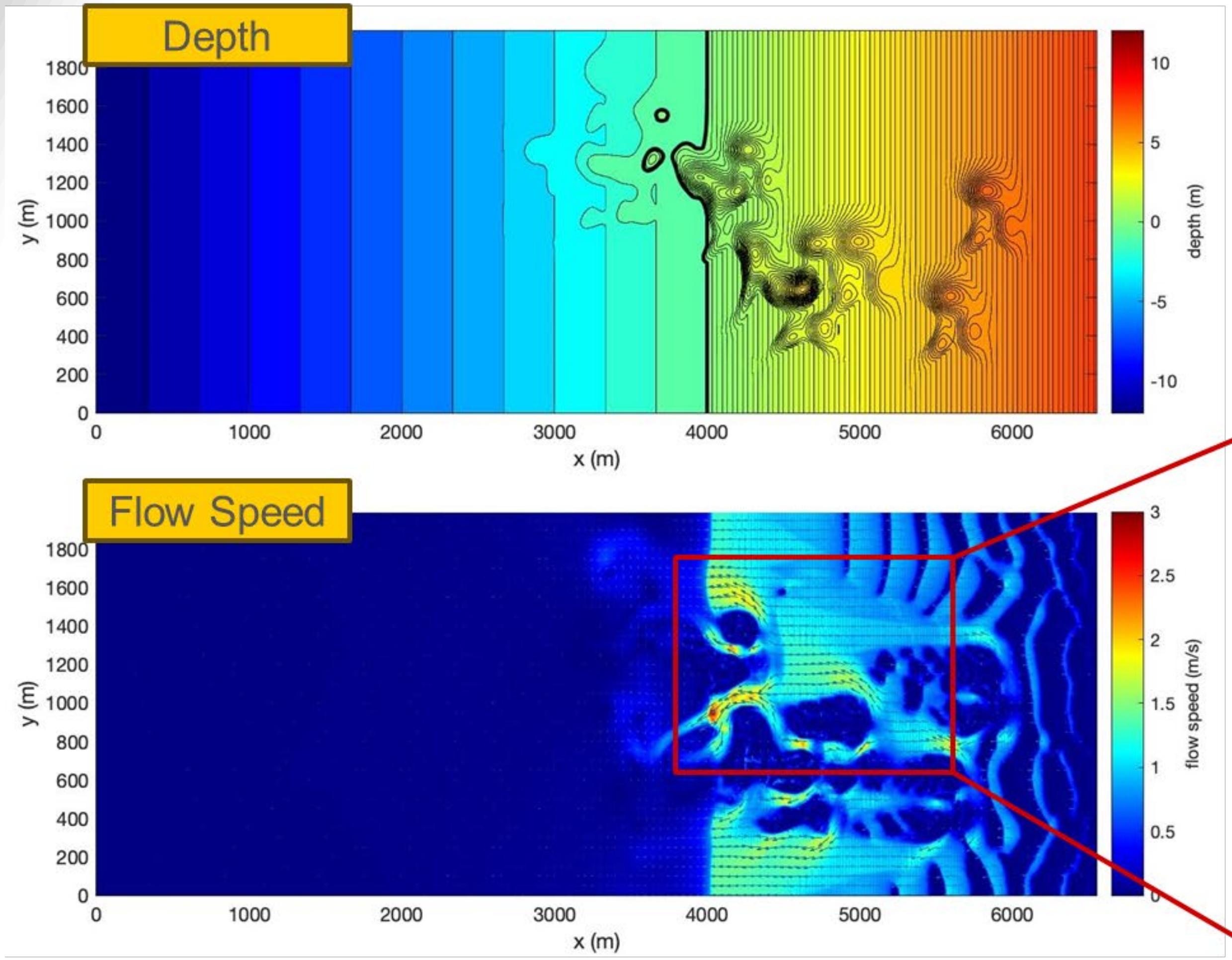




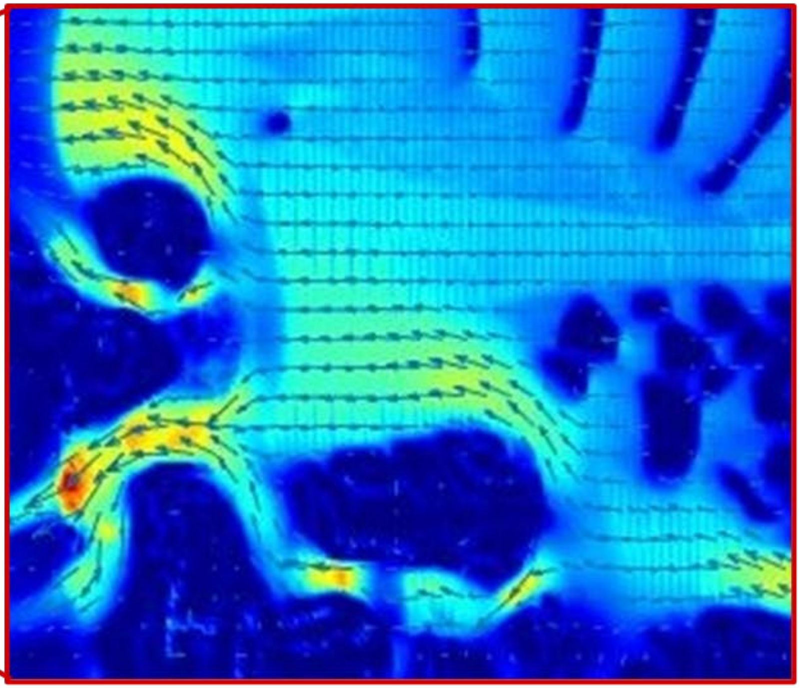
Colangeli et al., 2024, Ship-forced sediment transport: A new model for propeller jet flow, Water 16(12):1647

https://fengyanshi.github.io/build/html/sed_propeller.html

PRECIPTATION MODULE



- New input for time and spatially varying input flow rate (mm/hour)
- Source term in the conservation of mass equation



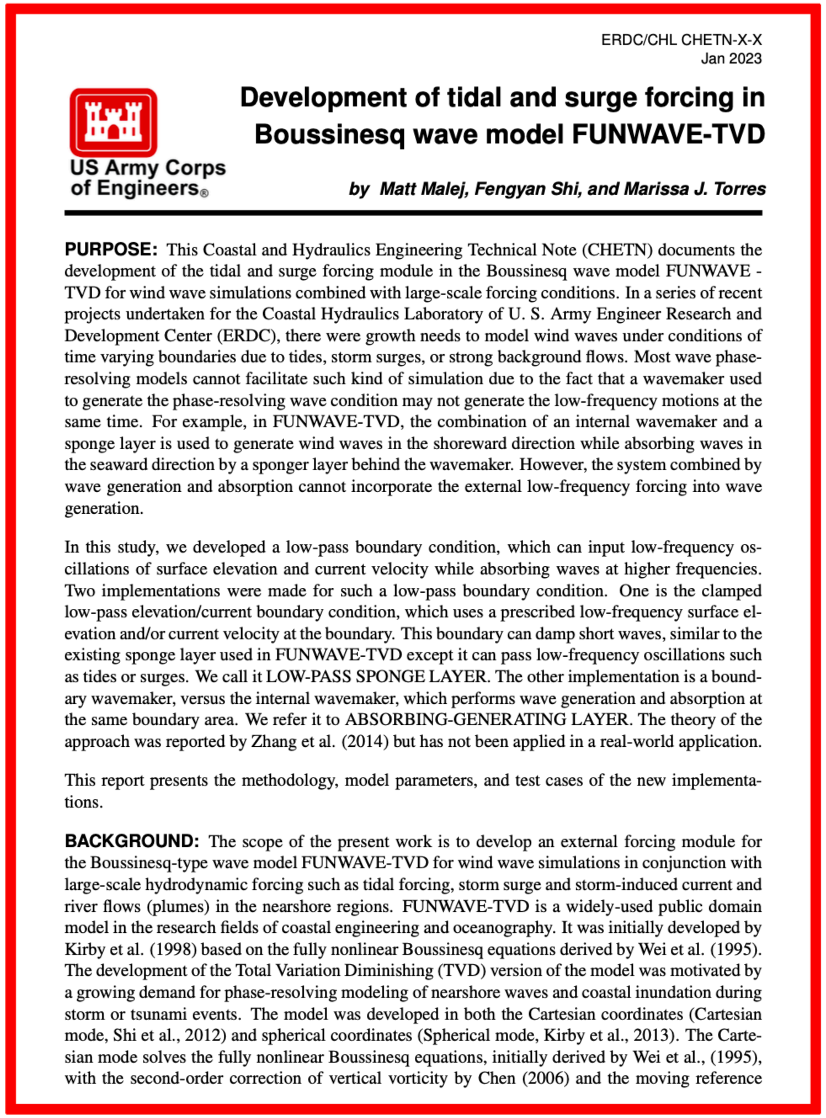
https://fengyanshi.github.io/build/html/precipitation.html

DOCUMENTATION

- Malej M., Shi F., Torres, M., 2024, Development of tidal and surge forcing in Boussinesq wave model FUNWAVE-TVD, submitted to ERDC/CHL CHETN, in review
- Malej, M., Shi, F., Lam, M, Salgado-Dominguez, G., and Torres, M. J., A highly-dispersive model for simulating waves induced by vessels and winds in relatively deep water, to be submitted to ERDC/CHL CHETN
- Malej M. and Shi F., Development of the water level variation module in FUNWAVE-TVD, in preparation for a journal publication
- Malej M. and Shi, F., Modeling the higher harmonics of ship-wakes using a highly dispersive wave model, to be submitted to Ocean Engineering

Upcoming Workshops (USACE only)

Beginners: 21 July 2025
Specialized Topic: 11 August 2025
Signup: https://forms.osi.apps.mil/r/8T56JEKKrB



ERDC/CHL CHETN-X-X
Jan 2023

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Development of tidal and surge forcing in Boussinesq wave model FUNWAVE-TVD

by Matt Malej, Fengyan Shi, and Marissa J. Torres

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) documents the development of the tidal and surge forcing module in the Boussinesq wave model FUNWAVE - TVD for wind wave simulations combined with large-scale forcing conditions. In a series of recent projects undertaken for the Coastal Hydraulics Laboratory of U. S. Army Engineer Research and Development Center (ERDC), there were growth needs to model wind waves under conditions of time varying boundaries due to tides, storm surges, or strong background flows. Most wave phase-resolving models cannot facilitate such kind of simulation due to the fact that a wavemaker used to generate the phase-resolving wave condition may not generate the low-frequency motions at the same time. For example, in FUNWAVE-TVD, the combination of an internal wavemaker and a sponge layer is used to generate wind waves in the shoreward direction while absorbing waves in the seaward direction by a sponger layer behind the wavemaker. However, the system combined by wave generation and absorption cannot incorporate the external low-frequency forcing into wave generation.

In this study, we developed a low-pass boundary condition, which can input low-frequency oscillations of surface elevation and current velocity while absorbing waves at higher frequencies. Two implementations were made for such a low-pass boundary condition. One is the clamped low-pass elevation/current boundary condition, which uses a prescribed low-frequency surface elevation and/or current velocity at the boundary. This boundary can damp short waves, similar to the existing sponge layer used in FUNWAVE-TVD except it can pass low-frequency oscillations such as tides or surges. We call it LOW-PASS SPONGE LAYER. The other implementation is a boundary wavemaker, versus the internal wavemaker, which performs wave generation and absorption at the same boundary area. We refer it to ABSORBING-GENERATING LAYER. The theory of the approach was reported by Zhang et al. (2014) but has not been applied in a real-world application.

This report presents the methodology, model parameters, and test cases of the new implementations.

BACKGROUND: The scope of the present work is to develop an external forcing module for the Boussinesq-type wave model FUNWAVE-TVD for wind wave simulations in conjunction with large-scale hydrodynamic forcing such as tidal forcing, storm surge and storm-induced current and river flows (plumes) in the nearshore regions. FUNWAVE-TVD is a widely-used public domain model in the research fields of coastal engineering and oceanography. It was initially developed by Kirby et al. (1998) based on the fully nonlinear Boussinesq equations derived by Wei et al. (1995). The development of the Total Variation Diminishing (TVD) version of the model was motivated by a growing demand for phase-resolving modeling of nearshore waves and coastal inundation during storm or tsunami events. The model was developed in both the Cartesian coordinates (Cartesian mode, Shi et al., 2012) and spherical coordinates (Spherical mode, Kirby et al., 2013). The Cartesian mode solves the fully nonlinear Boussinesq equations, initially derived by Wei et al., (1995), with the second-order correction of vertical vorticity by Chen (2006) and the moving reference