FUNWAVE:

DEVELOPMENT OF DYNAMICALLY VARYING WATER LEVELS AND DEEPER/MORE DISPERSIVE MODEL

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2 OCT 2024

COASTAL INLETS RESEARCH PROGRAM

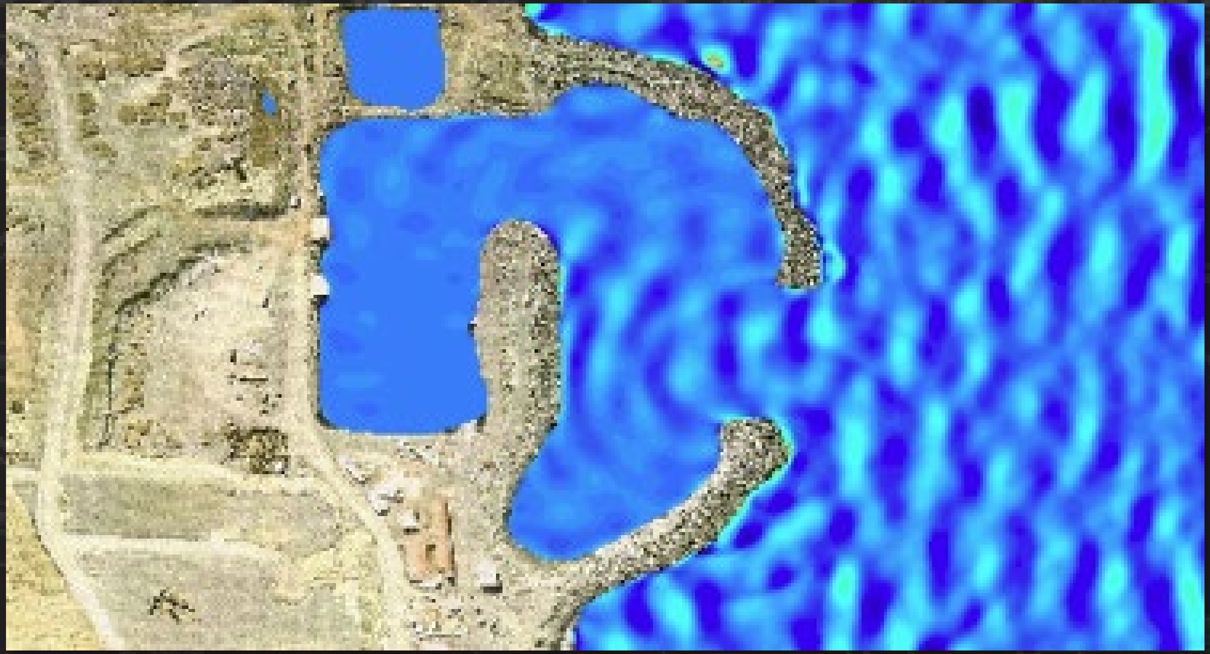
FY24 IN PROGRESS REVIEW

U.S. ARMY

US Army Corps of Engineers®

ERDC

CIRP



PROBLEM STATEMENT

- **Boussinesq-type models have become popular in the last two decades, mainly for two reasons:**
  A. the growth of HPC resources has made the application of Boussinesq-type models more practical and
  B. a balance between removal of third dimension (z; depth-averaged) and weak dispersion speeds up computation greatly.
- **To date, there were <u>two</u> major limitations in practical applications of the FUNWAVE model:**
  A. highly dispersive waves, common in intermediate to deep-water regions; and
  B. external forcing associated with variable water levels and large-scale processes, such as tides and storm surges.
- **Common approaches to extend Boussinesq models from 2nd to 4th order in *kh* have been rendered computationally expensive and notoriously unstable**.

Statement of Need: SON-N-1694 & SON-N-1754

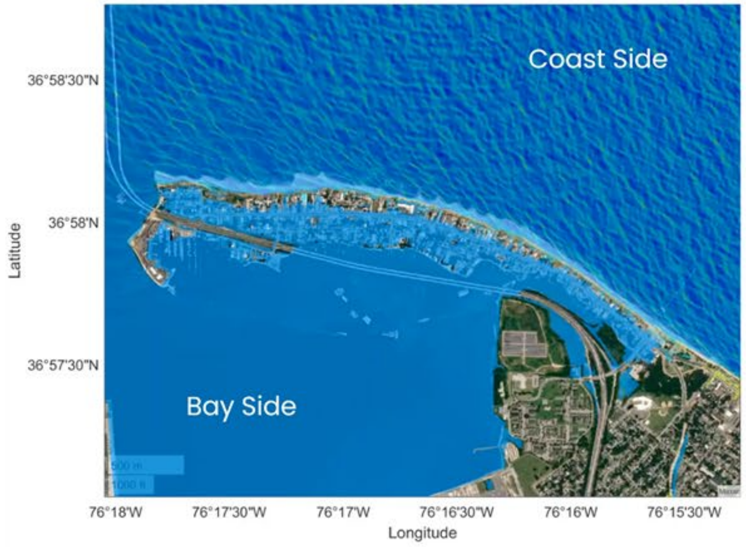
FY24 was Year 3 of 3

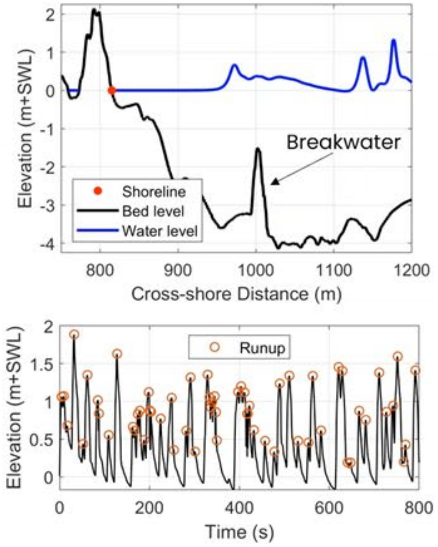
CAPABILITY AND STRATEGIC IMPACT

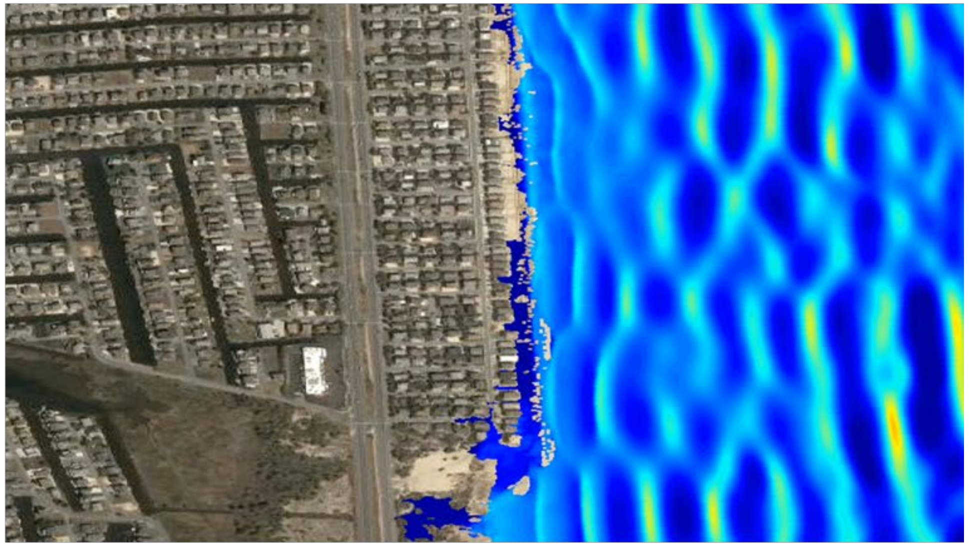
- The new modules/products will enhance the predictive capability of simulating surface waves, ship-wakes, and wave-induced processes, especially those involving wave interactions with shorelines in larger temporal and spatial domains. This will place ERDC/CHL at the forefront of phase-resolving wave modeling.

- Civil Works (CW) Strategic Focus Areas (SFA):

➔ *Improved model accuracy and efficiency in simulating event-scale hydrodynamics, such as hazardous waves, coastal flooding, and ship-wake-induced coastal erosion.*







- Military Applications (partnerships and leveraging of limited resources – time, personnel, funds)

FUNWAVE

FUNWAVE is a phase-resolving numerical wave model for shallow-to-intermediate water depths that resolves many physical wave processes in littoral regions, such as:

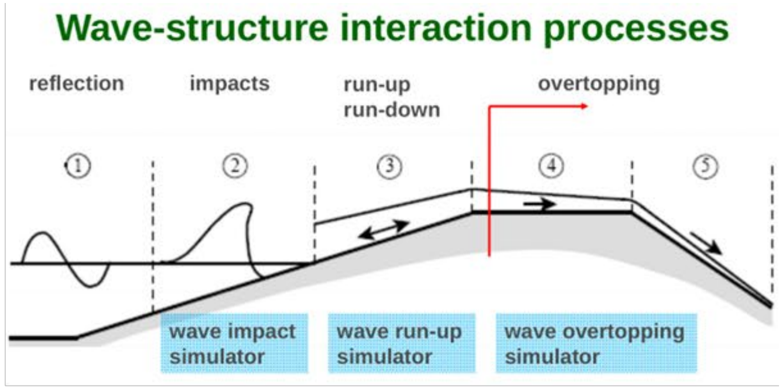
- ✓ nearshore wave propagation & transformation, including refraction, **<u>diffraction</u>** & nonlinear shoaling (Littoral Entry Operations)
- ✓ bottom friction & wave-induced current, nonlinear wave-wave & wave-current interactions
- ✓ wave breaking with **<u>runup</u>** & **<u>overtopping of structures</u>** (Flooding threats)
- ✓ **<u>harbor resonance</u>** and **<u>infragravity (IG) waves</u>** (Important for understanding austere ports of entry)
- ✓ **<u>vessel-generated waves</u>** & sediment transport with morphology change
- ✓ landslide-generated tsunamis (regional and global ocean basin)
- ✓ High-Performance Computing (HPC) Portal web-based access with GUI

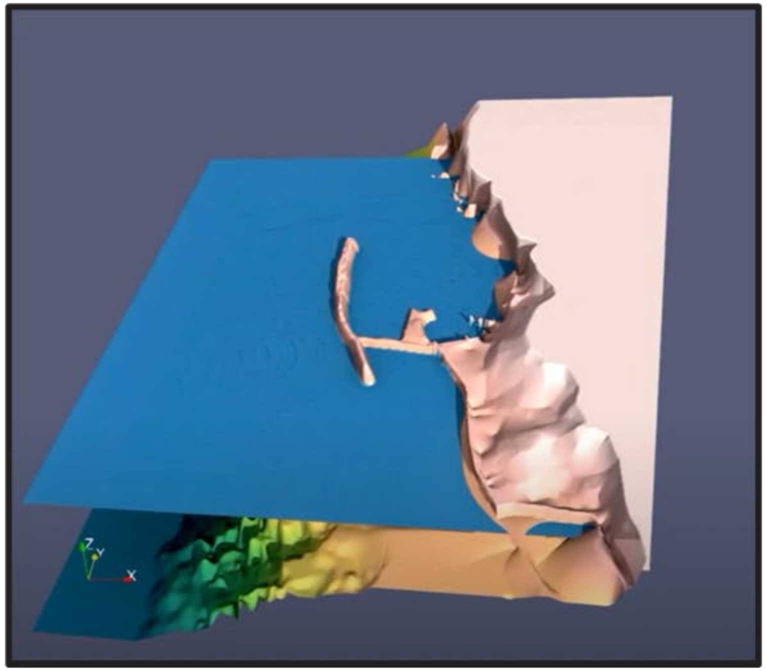
DOD HPC DEPARTMENT OF DEFENSE HIGH PERFORMANCE COMPUTING PORTAL

* **<u>underline/bold</u>** not available in phase-averaged models!
* (blue) military application

Model Access: FUNWAVE has a comprehensive Wiki page with source code access via a version-controlled online repository and an extensive suite of test cases at https://fengyanshi.github.io/build/html/index.html

Bridging the Gap: Utilize FUNWAVE to pre-calculate surfzone wave dynamics swash zone <u>runup & overtopping</u> to provide rapid surrogate modeling between high-fidelity N-S equation models and phase-averaged ones.





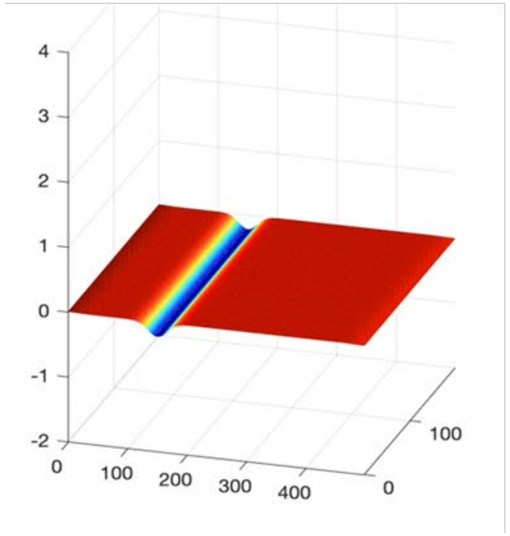
SURGE/TIDAL FORCING

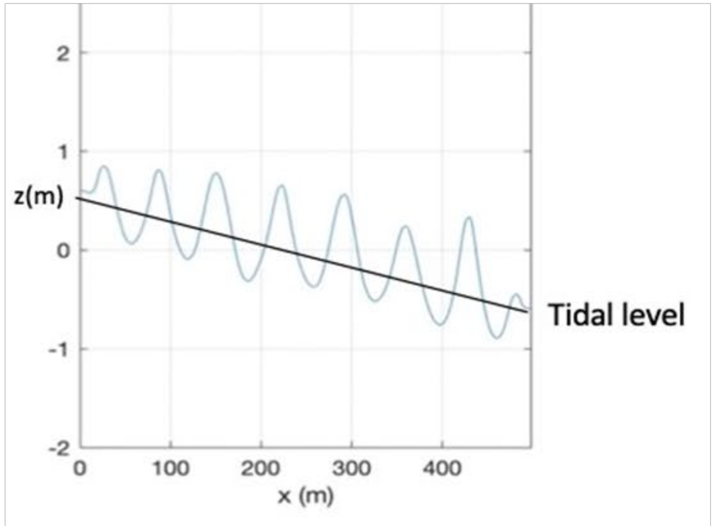
A. Absorbing Tidal Boundary Condition (BC)

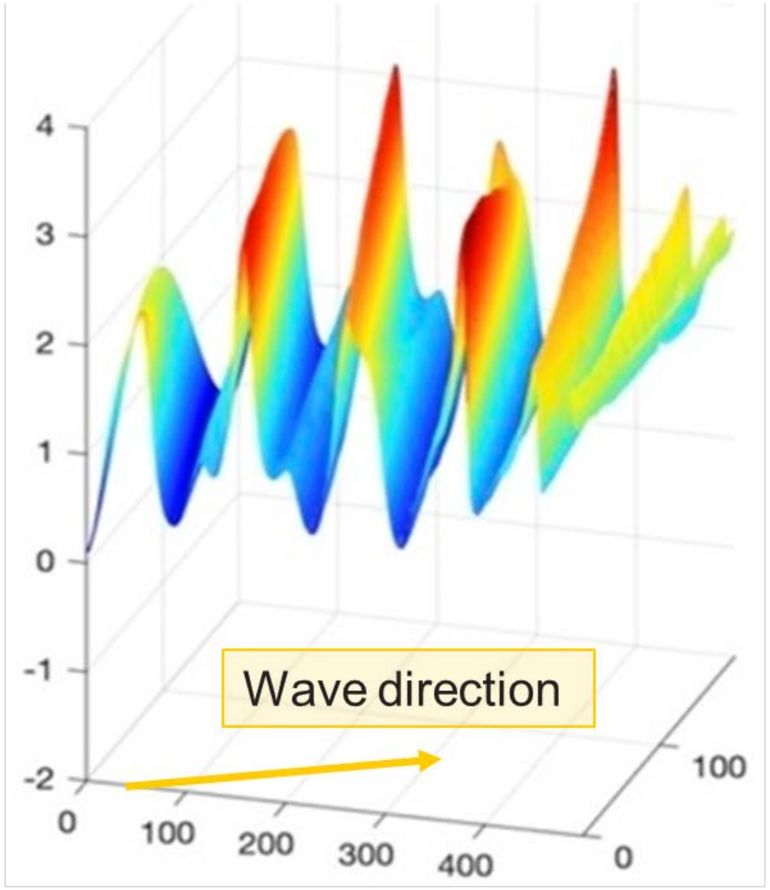
- It can be applied at any boundary

A. Absorbing-Generating Tidal BC:

- Simplifies coupling of wavemaker and absorbing tidal BC
- This can only be applied to the one (locally west) boundary
- For now, there is a limited selection of wave maker types





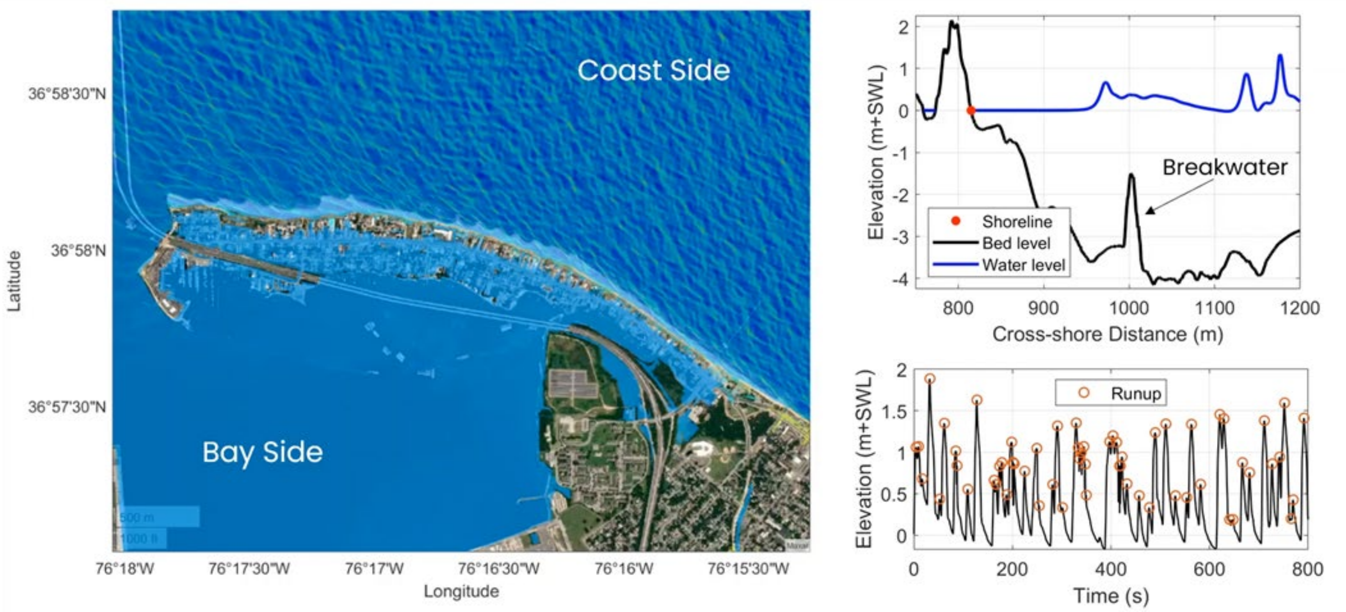


NOTE: Either sponge layer or absorbing tidal BC at each boundary

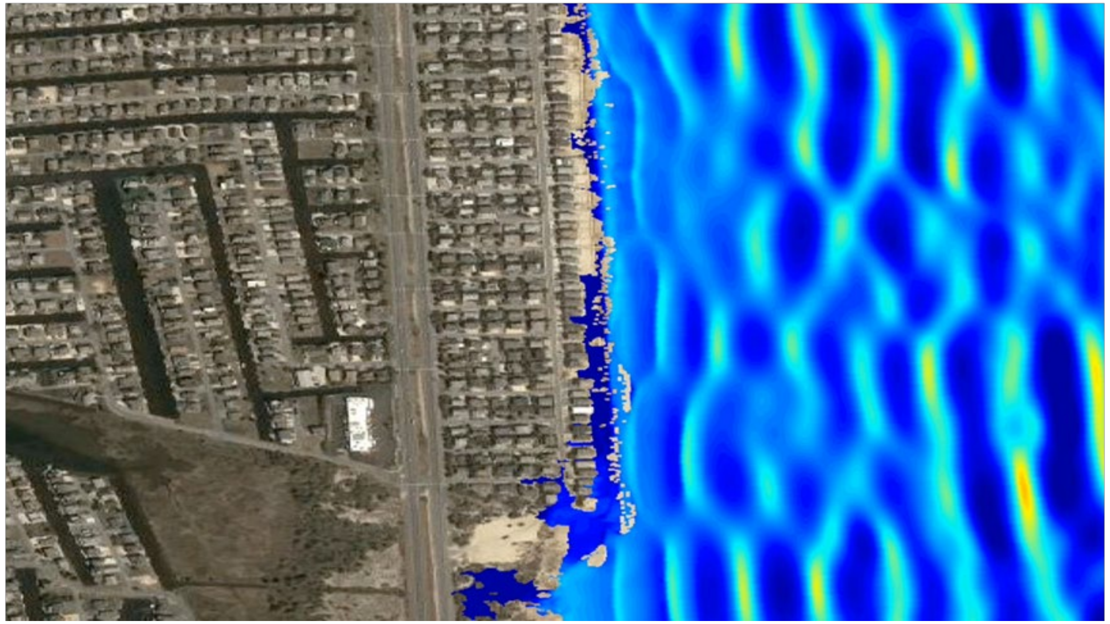
TIDAL/SURGE EXAMPLE

While called the tidal module, storm surge data may also be used as input.

(Tidal) Hurricane Irene at Norfolk



(Surge) 100-year storm at South Bethany Beach



Joint work with University of Delaware

PUBLICATIONS

- **Published [JP]:** Malej, M., Shi, F., 2024*, Modeling the optical signature induced by wave breaking using the Boussinesq-type wave model FUNWAVE-TVD*, Ocean Engineering - Elsevier, doi: https://doi.org/10.1016/j.oceaneng.2024.118160
- **Published [TR]:** Malej, M., Shi, F., Tozer, N., Smith, J.M., Lofthouse, E., Cuomo, G., Salgado-Dominguez, G., Lam, M. Y-H., Torres, M., 2024 *FUNWAVE-TVD Testbed: Analytical, Laboratory, and Field Cases for Validation and Verification of the Phase-Resolving Nearshore Boussinesq-type Numerical Wave Model*, ERDC Technical Report – ERDC/CHL TR-24-14, doi: http://dx.doi.org/10.21079/11681/49183.
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ERDC/CHL CHETN-X-X
Jan 2023

US Army Corps of Engineers

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

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

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

BACKGROUND: The scope of the present work is to develop an external forcing module the Boussinesq-type wave model FUNWAVE-TVD for wind wave simulations in conjunction v large-scale hydrodynamic forcing such as tidal forcing, storm surge and storm-induced current river flows (plumes) in the nearshore regions. FUNWAVE-TVD is a widely-used public don model in the research fields of coastal engineering and oceanography. It was initially develope Kirby et al. (1998) based on the fully nonlinear Boussinesq equations derived by Wei et al. (19 The development of the Total Variation Diminishing (TVD) version of the model was motivate a growing demand for phase-resolving modeling of nearshore waves and coastal inundation du storm or tsunami events. The model was developed in both the Cartesian coordinates (Carte mode, Shi et al., 2012) and spherical coordinates (Spherical mode, Kirby et al., 2013). The Ca sian mode solves the fully nonlinear Boussinesq equations, initially derived by Wei et al., (19 with the second-order correction of vertical vorticity by Chen (2006) and the moving refere

ERDC/CHL CHETN-X-X
Jun 2024

US Army Corps of Engineers

A highly-dispersive wave solver for simulating shorter waves induced by vessels and winds in a phase-resolving model framework

by Matt Malej, Fengyan Shi, Michael-Angelo Y.-H. Lam, Gabriela Salgado-Dominguez, and Marissa J. Torres

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) documents the development of a highly-dispersive wave model which can be used for modeling ship-wakes and wind waves in relatively deep water. The current phase-resolving wave model used in the Coastal Hydraulics Laboratory of U. S. Army Engineer Research and Development Center (ERDC) is a Boussinesq-type wave model, FUNWAVE-TVD. In a series of recent projects, it was recognized that the short wave bands appearing in wind wave spectra or ship-wake spectrogram were not properly simulated due to the weak dispersion restriction of FUNWAVE-TVD. In this study, we developed a highly dispersive model. Based on the surface flow technique used for a non-hydrostatic model, the present model has a multiple layer system, which can be configured by a user for a wave application in the highly dispersive wave regime. Compared with a conventionally non-hydrostatic model, e.g., SWASH (Zijlema et al., 2011), NHWAVE (Ma et al., 2012), the model efficiency has been greatly improved by using a partially implicit finite difference (PIFD) scheme.

The development of the highly-dispersive wave model followed the existing FUNWAVE-TVD model framework. The model I/O files are consistent with that of FUNWAVE-TVD, facilitating the existing FUNWAVE-TVD users to use the new solver. In this report, we present the results from tests of wave dispersion and model efficiency. Two examples are also included to demonstrate the model's capability of simulating ship-wakes and wind waves in relatively deep water.

BACKGROUND: The success of the Boussinesq-type wave model, FUNWAVE-TVD, is noted in modeling the surface wave evolution from intermediate water depth to the swash zone. It uses a reference velocity as a dependent variable introduced by Nwogu (1993) and removes the restriction of the weak nonlinearity (Wei et al., 1995), demonstrating significant improvements of wave dispersion property and nonlinearity. Currently, there a major limitation in practical applications of the model, highly dispersive waves formally prevalent in deep to intermediate water depths.

The current version of FUNWAVE-TVD can model waves up to $kh \sim 3.14159$ (π), where kh is a parameter to measure the wave dispersion, k is the wavenumber and h is the water depth. For surface waves beyond this range, the model accuracy decreases considerably due to errors in calculating wave celerity. The performances of Boussinesq-type wave models have been evaluated by a number of researchers, theoretically and numerically, in modeling of wind wave, or episodic ship-wave propagation and evolution. The recent study of ship-wake modeling also suggested that the traditional 2nd order in kh Boussinesq-type model is not able to predict the Kelvin-wave system properly as the dispersion parameter $kh > \pi$ (Forlini et al., 2020). Therefore, for modeling highly dispersive waves, the Boussinesq-type models have apparent disadvantage in applications

DEEP(ER) WATER EXTENSION

- FUNWAVE is limited to waves satisfying:

$$kh < \pi \Leftrightarrow h/L < 1/2.$$

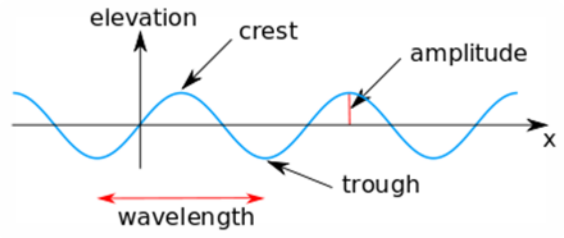
  Increasing kh barrier would allow:

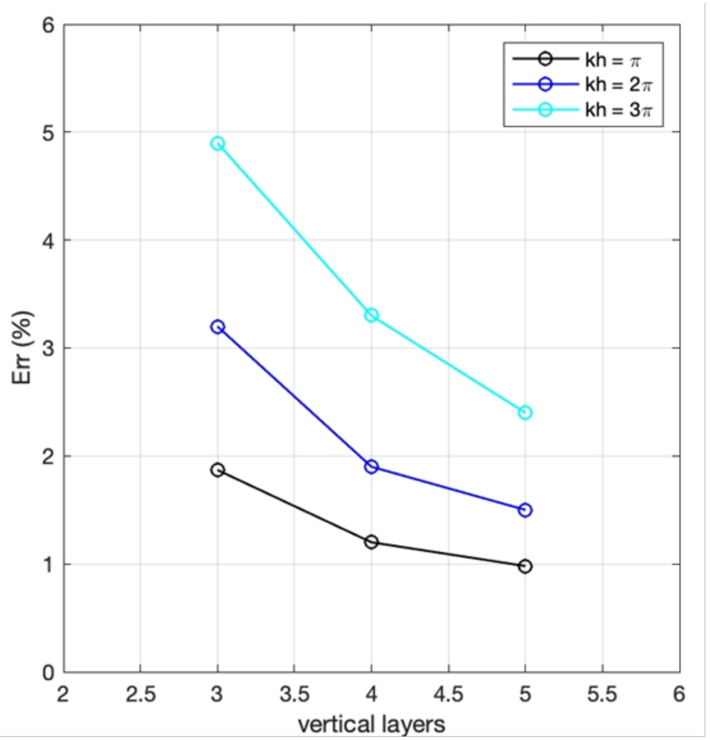
  A. Deeper waters (larger h), and/or

  B. Shorter waves (smaller $L \Leftrightarrow$ larger k).

- 4th order (kh) Boussinesq type models are highly unstable.

- Based on surface flow techniques commonly used for non-hydrostatic models.



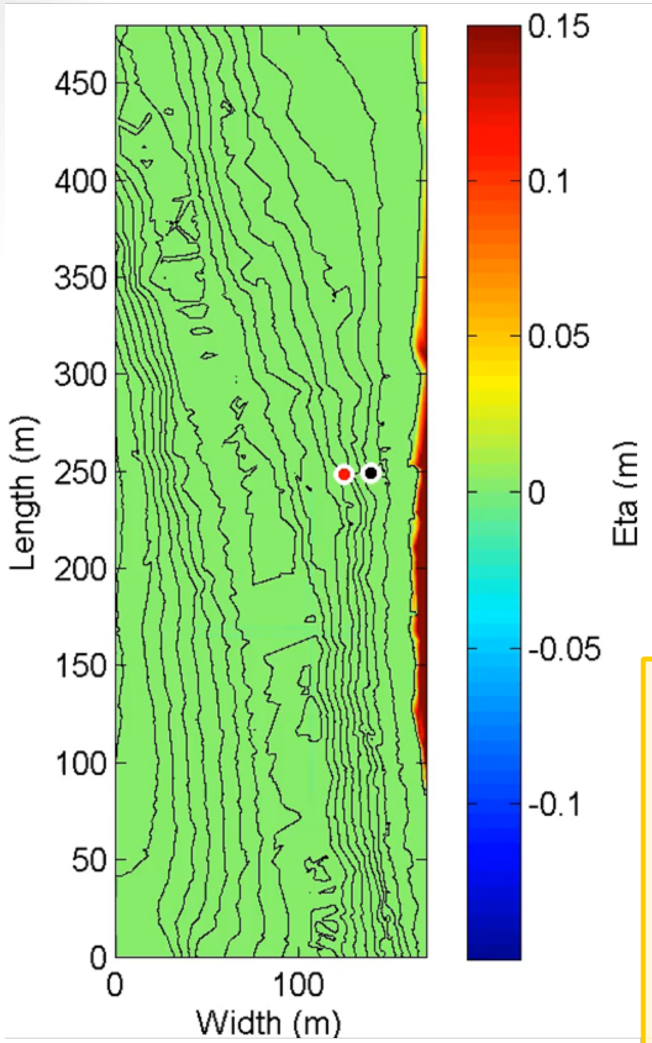


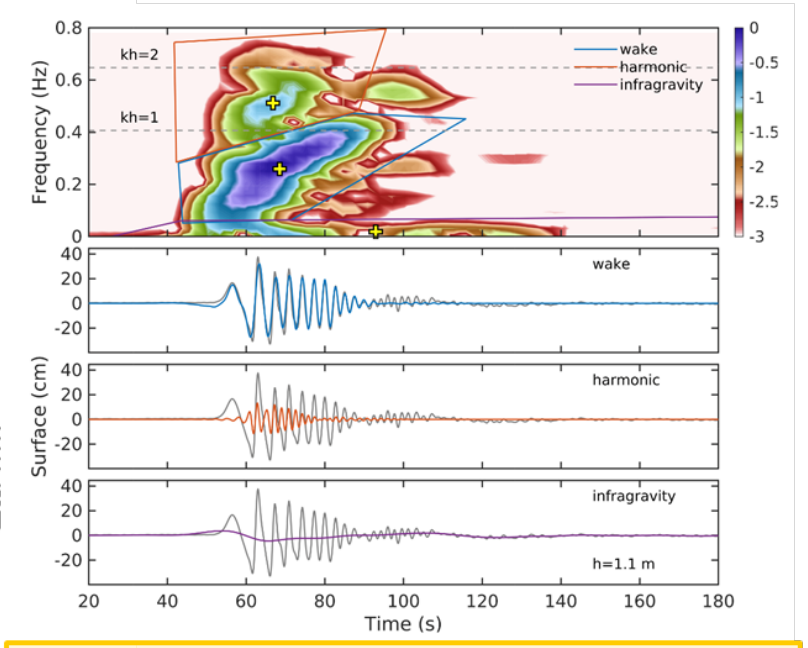
k – Wave Number

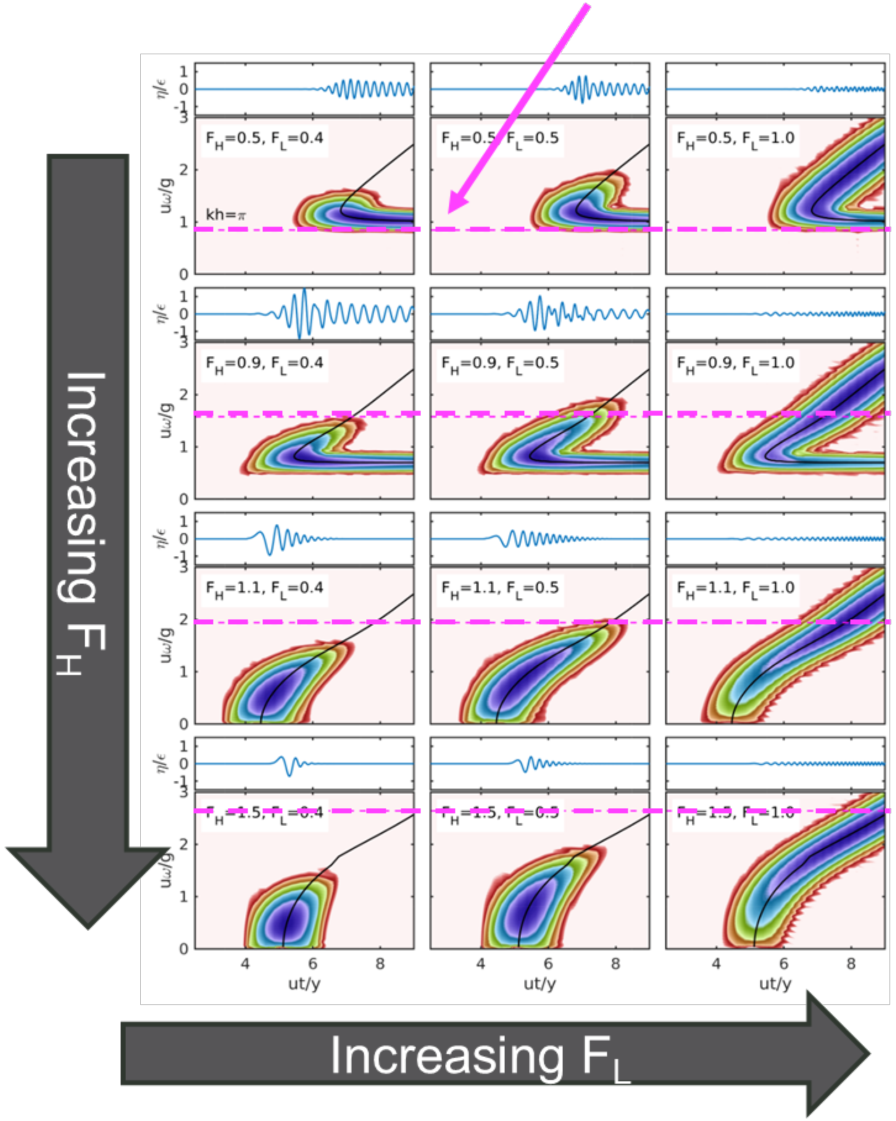
L – Wavelength $\qquad L = \dfrac{2\pi}{k}$

h – Depth

MOTIVATION - VESSEL GENERATED WAVES ($kh < \pi$)







Froude Number: Which reference length?

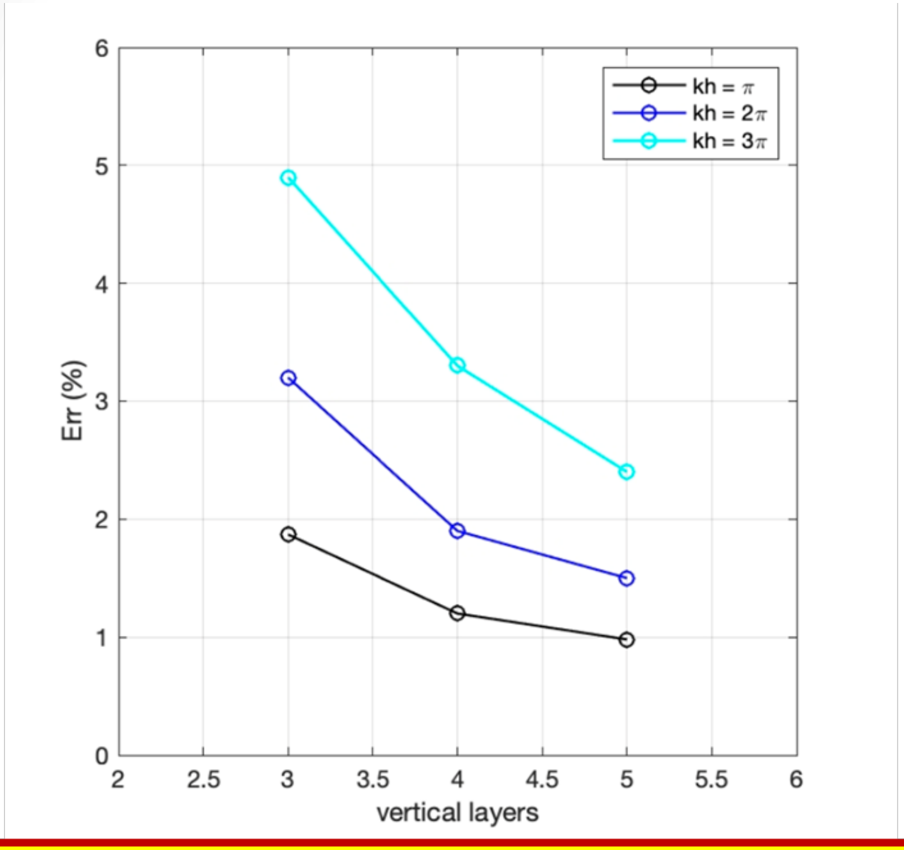
$$F_H = \frac{U}{\sqrt{gH}} \qquad F_L = \frac{U}{\sqrt{gL}}$$

L – length of vessel H – depth

U – speed of vessel g – gravity

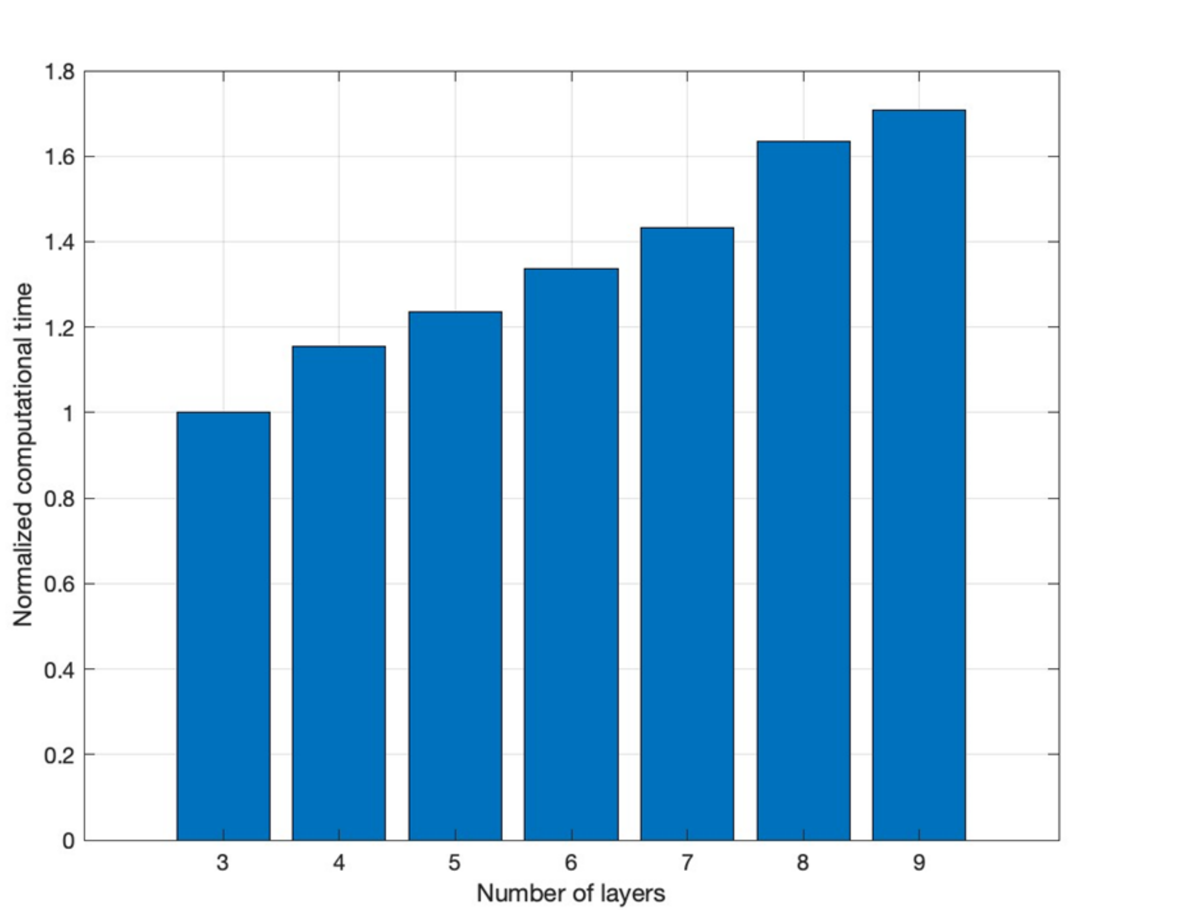
PRELIMINARY TESTS (WIND WAVES)

- Dispersion tests:
  standard standing wave experiments with different kh



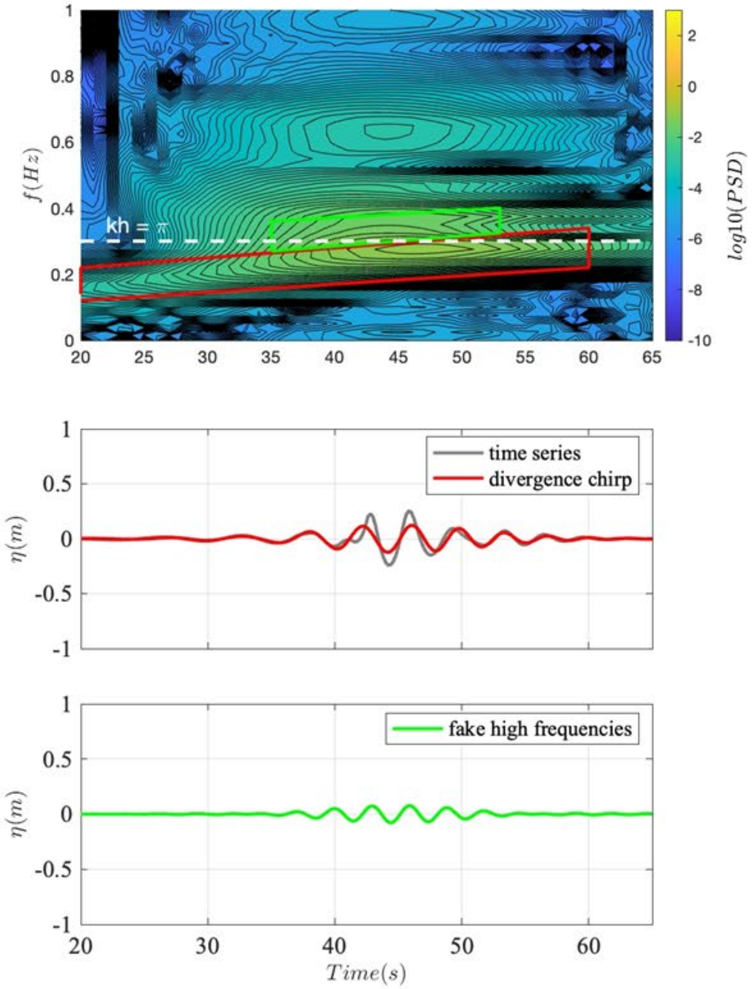
Numerical errors as a function of the number of vertical layers and wave dispersion parameter kh.

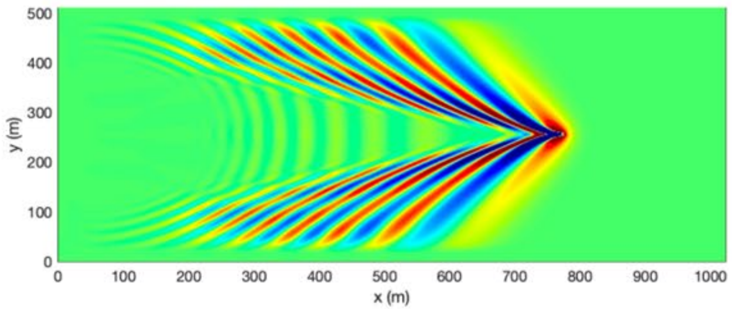
- Efficiency
  computational burden

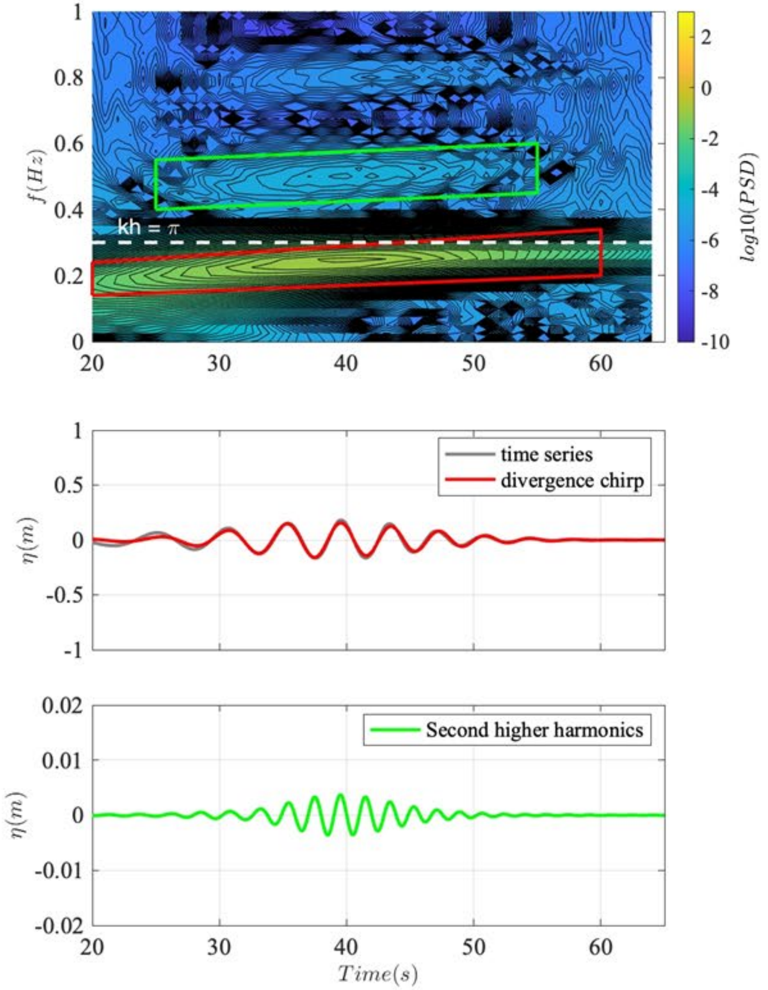


Tripling the number of layers only doubles the computational time

PRELIMINARY TESTS (VESSEL WAKES)







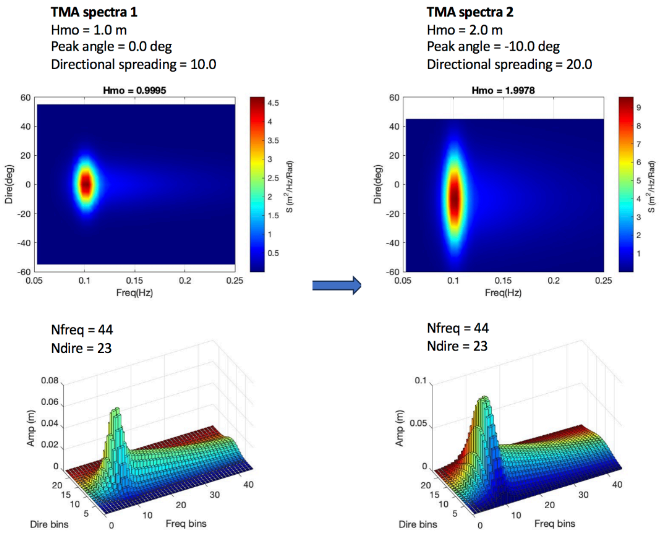
FUNWAVE-TVD

Highly-Dispersive Module (6 layers)

WORK IN PROGRESS
(COMPLETION: Q1/Q2 FY25)

Time varying spectra

Time-dependent wave spectra can be specified in a series of data files containing wave spectra. The files keep the same number of wave components thus that an instant wave energy in each bin can be interpolated in time. The figure below shows two TMA spectra at different times, TMA spectra 1 and TMA spectra 2, respectively. The upper panel shows 2D plots of directional spectra, and the bottom panel shows the wave amplitudes in the discrete bins. Here, the wave energy in each bin is converted to the wave amplitude for the traditional reason. Model input includes the same number of spectra bins, i.e., Nfreq = 44 and Ndire = 23. Note that the values of (Freq(i),i=1:44) and (Dire(j), j=1:23) will not change in the entire simulation. The only change in the input is the amplitude in different time. For a wave energy bin $E(i,j)$ the wave amplitude can be calculated by $a(i,j) = \sqrt{2E(i,j)}$.



An example is provided in /time_spectra/. In input.txt, set

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

FUNWAVE

FUNWAVE Documentation » BASICS » Sediment Transport Module » Ship Propeller Effects on Sediment Transport

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Ship Propeller Effects on Sediment Transport

The effects of ship propeller-induced jet flow on sediment transport were presented by Colangeli et al. (2023).

Theory

Efflux velocity

The magnitude of the efflux velocity generated by a propeller was estimated using the empirical formulas given by Hamill and Kee (2016) and Hamill and McGarvey (1997) (NEED UPDATE)

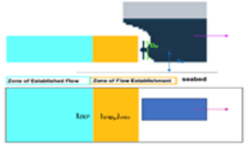
$$V_0 = E_0 n D_p \sqrt{C_t} \quad (107)$$

where $E_0 = (D_p/D_h)^{-0.403} C_t^{-1.79} \mathrm{BAR}^{0.744}$, in which D_p and D_h are the propeller diameter and hub diameter, respectively. C_t is the C thrust parameter, and BAR is defined as the thrust and Blade Area. n is the RPM.

Axial flow distribution (NEED UPDATE)

$$U_p = V_0 \exp\left(-2\frac{y'^2 + h_p^2}{D_p^2}\right) \text{ in ZFE: } x' \le \frac{D_p}{2c} \quad (108)$$

$$U_p = V_0 \frac{1}{2c} \exp\left(-\frac{1}{2c^2}\frac{y'^2 + h_p^2}{x'^2}\right) \text{ outside ZFE: } x' > \frac{D_p}{2c} \quad (109)$$



FUNWAVE

FUNWAVE Documentation » BASICS » Precipitation Module

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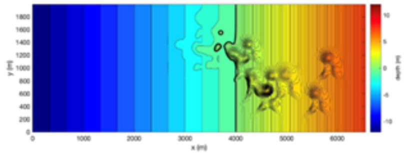
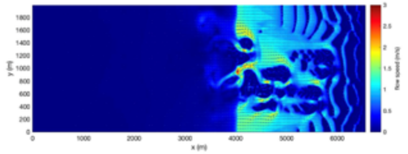
Precipitation Module

- Theory
- Compile the code for a precipitation case
- Example





SUMMARY

FY24 Major Advancements in Capability

Tide/Surge Forcing Module Enhancements

- Available in the latest version of FUNWAVE
- Documentation available on Wiki and in the TN

Deep Water (Highly-Dispersive) Module

- The beta version of the code was completed
- Preliminary Test are very promising

FY24/25 Products & Advancements

- Completion of deep-water module with the release of open-source code, benchmarking and guidance
- Technical Note/Report on deep water module with test cases
- Workshop/Mini-workshop on deep water module and tide module

FY24 Major Products & Collaborations

Publications

- **Published [JP]:** Malej, M., Shi, F., 2024, *Modeling the optical signature induced by wave breaking using the Boussinesq-type wave model FUNWAVE-TVD*, Ocean Engineering - Elsevier, doi: https://doi.org/10.1016/j.oceaneng.2024.118160
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Collaborator

- Districts: LRB, NWP, LRE, SAJ, POH, SPL, and SWG.
- Academia: University of Florida, University of Delaware, Georgia Tech, University of Rhode Island