PORTS® '22

Honolulu, Hawaii | September 18-21, 2022

Knowledge Sharing for a Better Tomorrow

Modeling and Resilient Design against Tsunami Hazards

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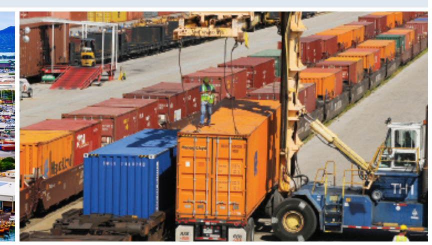
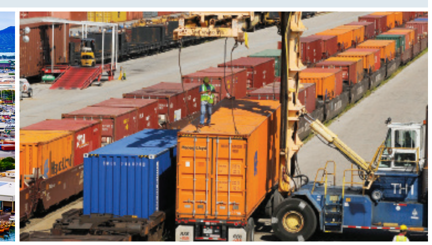


- **Tsunami sources**
- **Tsunami modeling**
- **Tsunami models benchmarked by NTHMP datasets**
- **ASCE-16 standard for resilient design against tsunamis**
- **FUNWAVE-TVD model**
- **New features of FUNWAVE-TVD**
- **Content of tutorial**

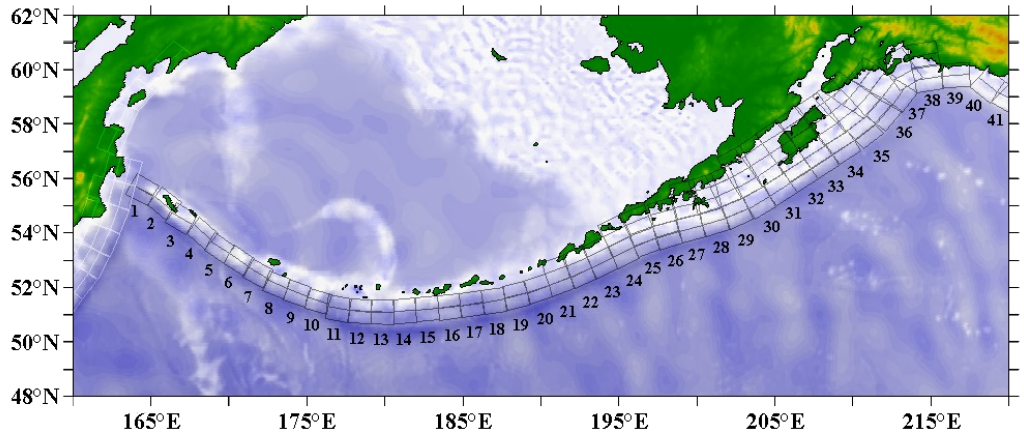


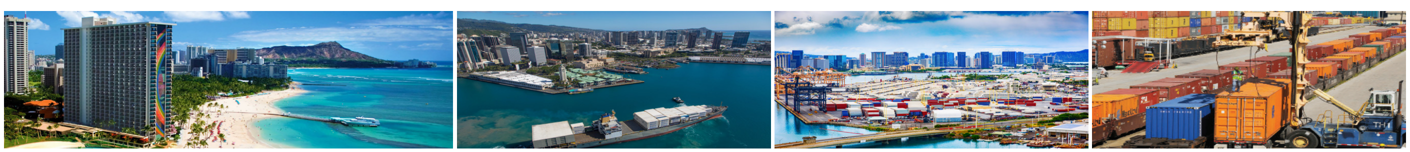



Tsunami sources

- Co-seismic source – earthquake
- Submarine mass failure (SMF)
- Submarine Volcano
- Combination of multiple sources

Unit sources along the Aleutian Islands (NOAA PMEL)
https://nctr.pmel.noaa.gov/propagation-database.html



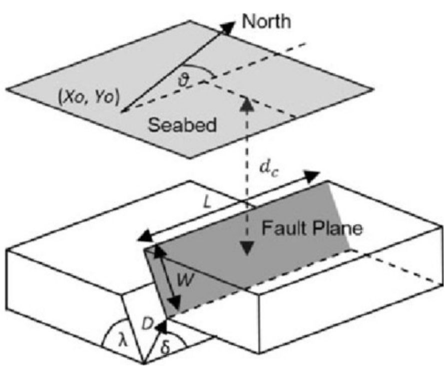


Tsunami sources

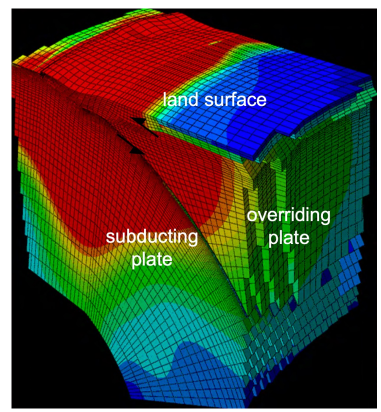
Modeling tsunami sources

- Co-seismic source

Okada source formulation (1989)



Numerical model (e.g., Masterlark, 2012)



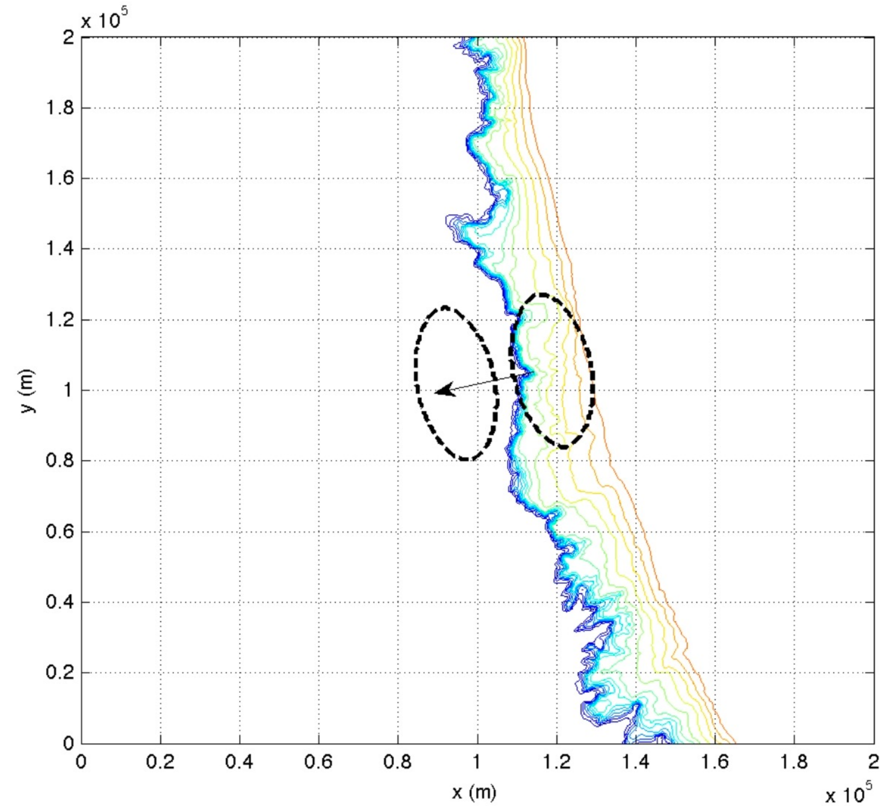
Tsunami sources

Modeling tsunami sources

- Submarine mass failure (SMF)

Static source

Conventional dynamic source



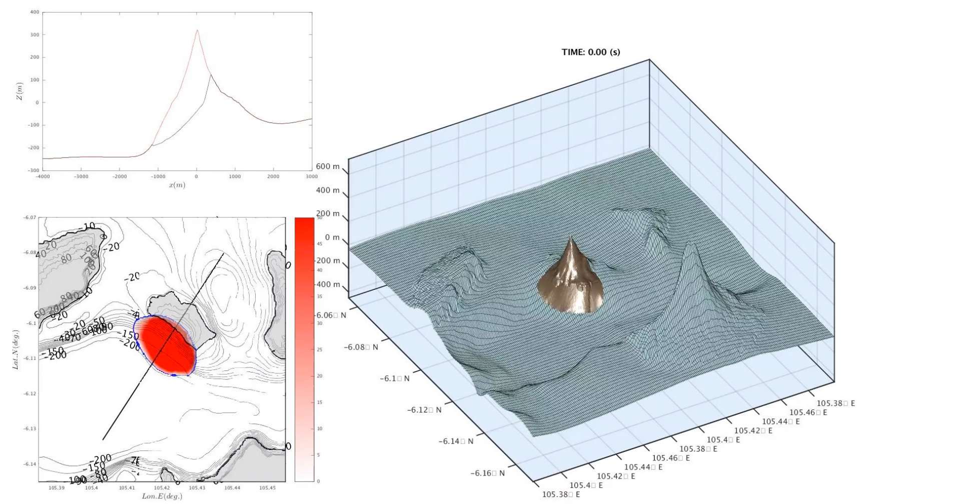
Tsunami sources

Modeling tsunami sources

- Submarine mass failure (SMF)

  Modeled dynamic source

  (e.g., numerical model NHWAVE)



Tsunami sources

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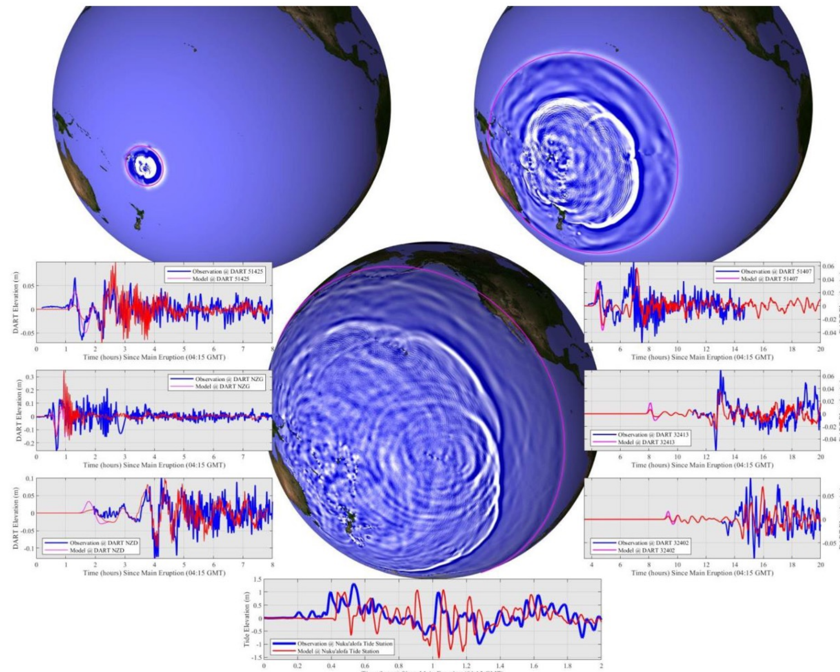


Modeling tsunami sources

- Submarine Volcano

  (e.g., Hunga Tonga-Hunga Ha'apai

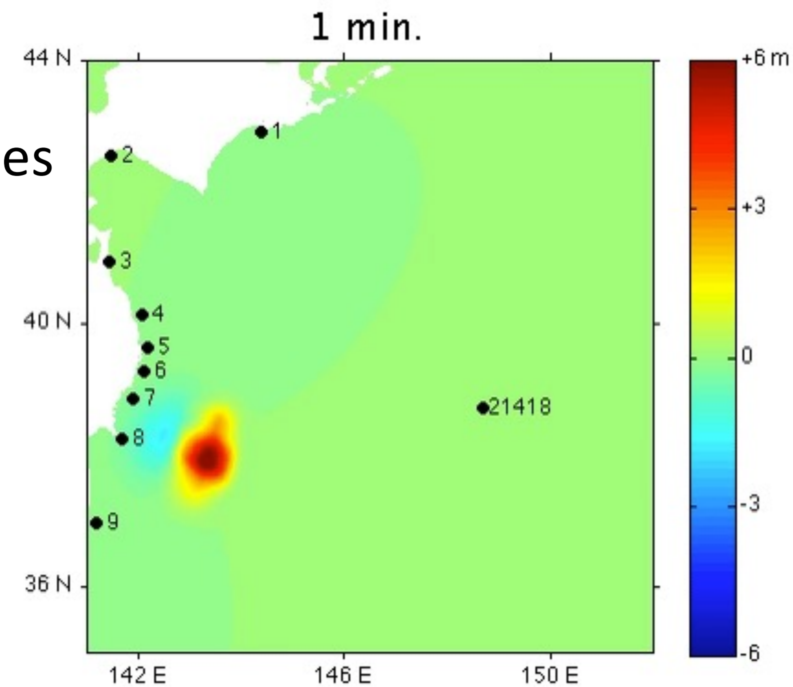
  eruption and tsunami)

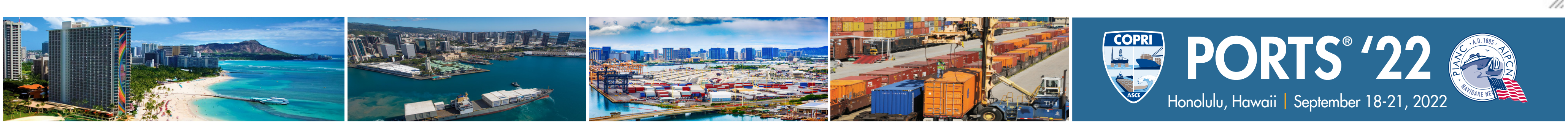
Tsunami sources

Modeling tsunami sources

- Combination of multiple sources

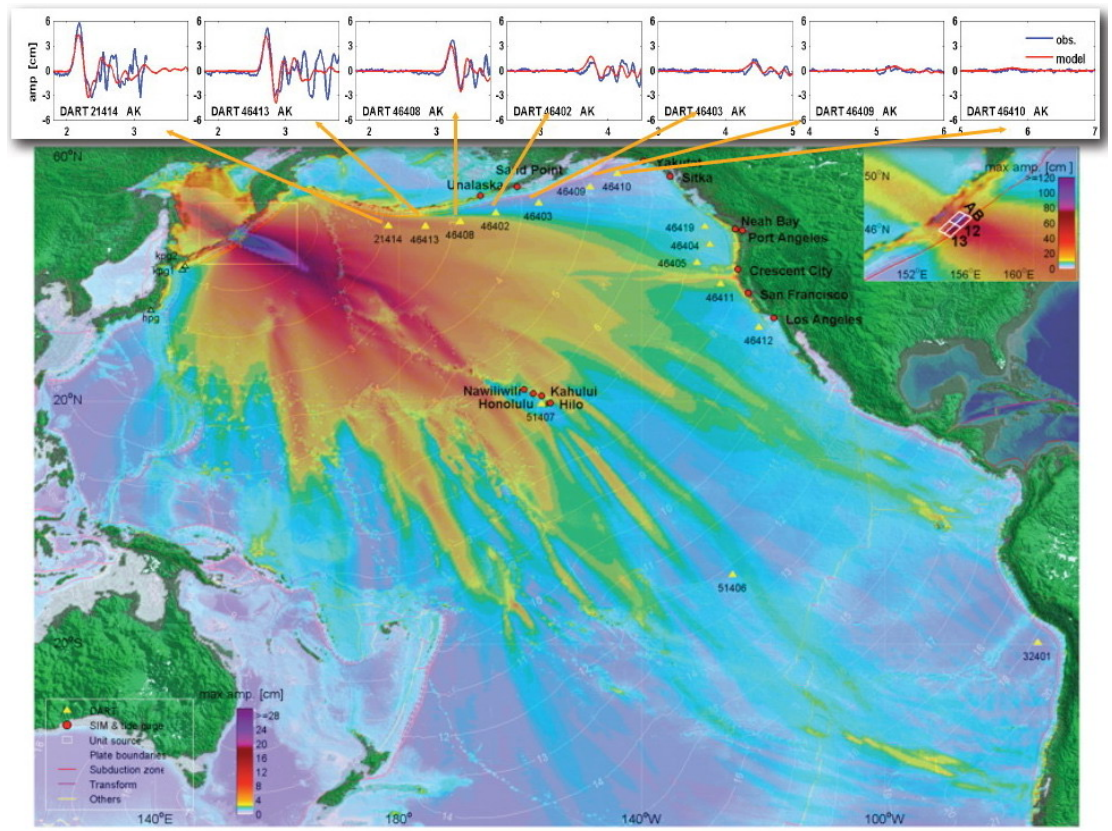
  (e.g., Tappin et al., 2014)





Tsunami modeling

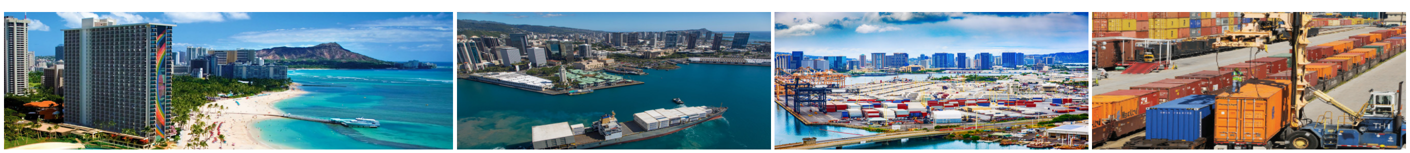
https://nctr.pmel.noaa.gov/propagation-database.html



Tsunami modeling

for different purposes

- ➢ Tsunami prediction
  (A lot of information online
  e.g., NOAA PMEL, SIFT…)



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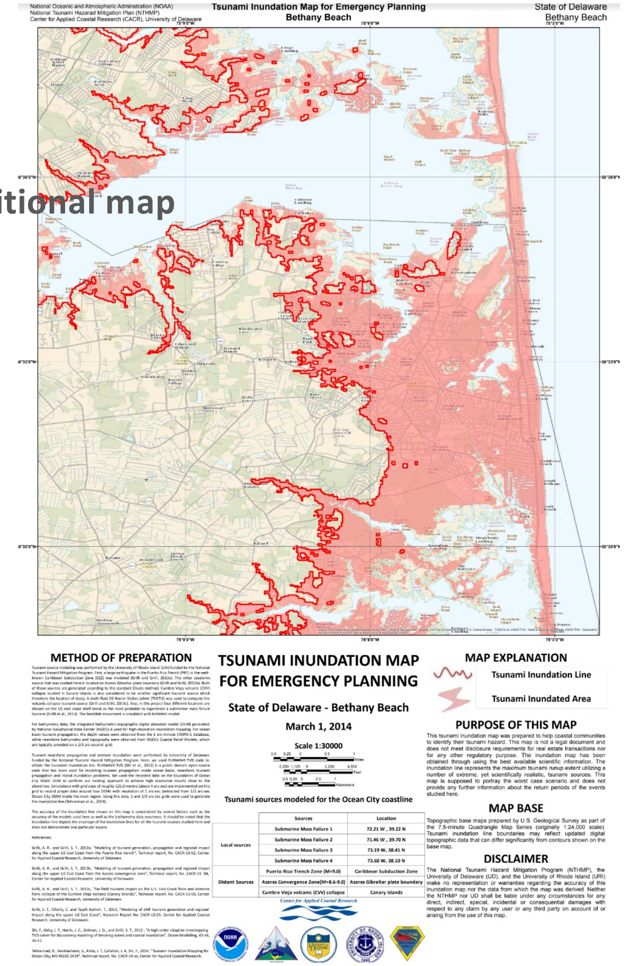
Tsunami modeling

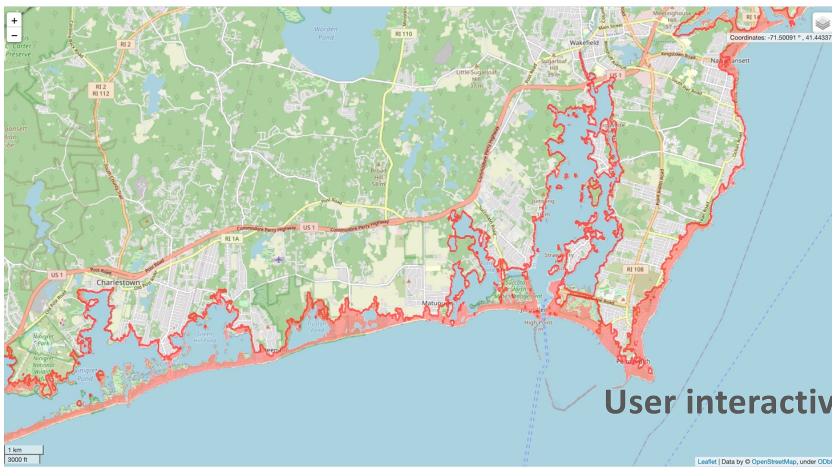
Tsunami modeling for different purposes

- ➢ Tsunami inundation maps

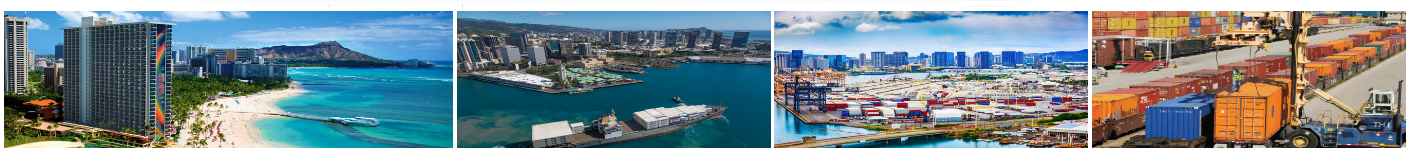
  (National Tsunami Hazard Mitigation Program, NTHMP)

Traditional map





User interactive map

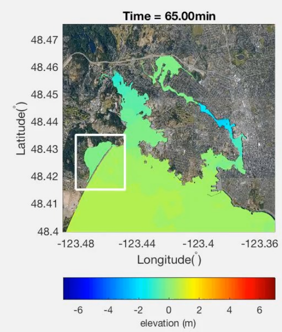


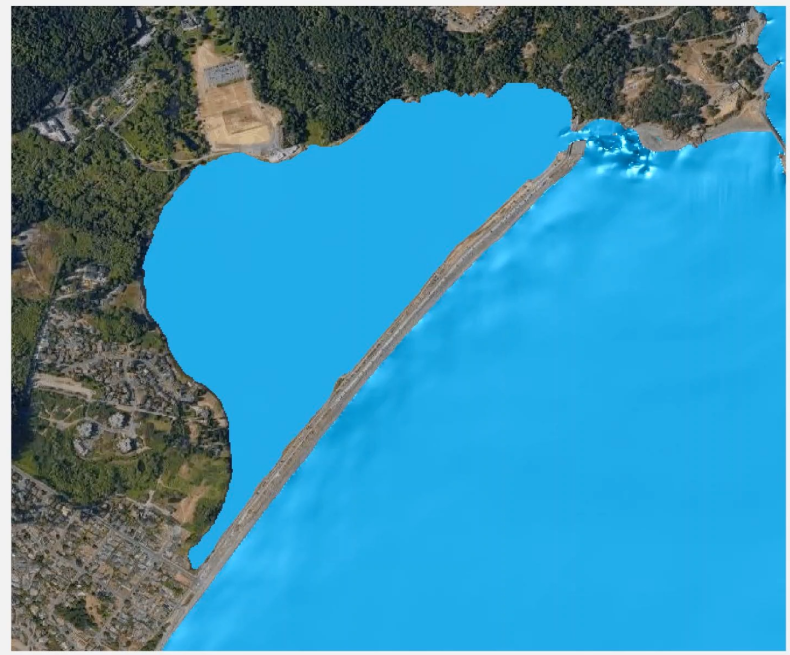
Tsunami modeling

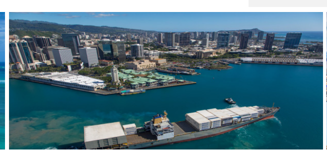
Tsunami modeling

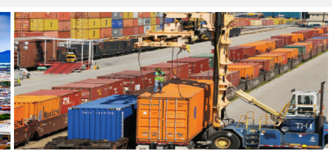
for different purposes

- ➢ Education





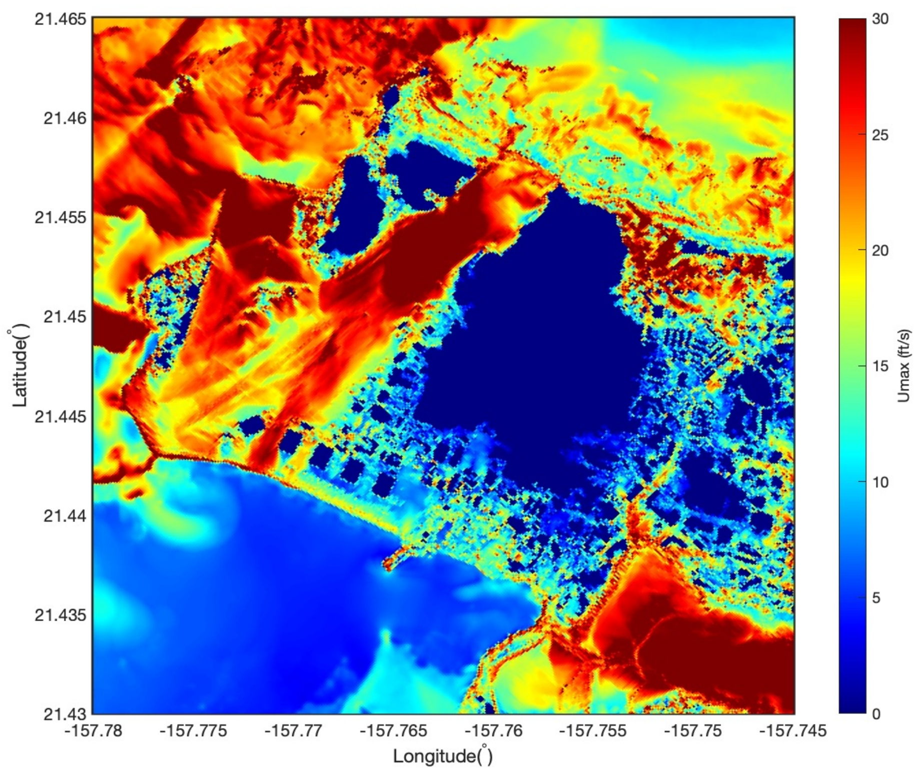


Tsunami modeling

Tsunami modeling

for different purposes

- ➢ Engineering design



Tsunami models

List of models benchmarked for tsunami applications by test data sets designated by the NTHMP program.

Model Name	Equations Solved [Spatial Dimensions]	Numerical Approach	Numerical Treatment of Convection Terms	Numerical Accuracy of Other Gradient Terms	Numerical Treatment of Time Integration
ALASKA GI'-T	Nonlinear Shallow Water (NSW) [2D]	FD	Upwind (1st-order accurate)	Centered (2nd-order accurate)	Semi-implicit (1st-order accurate)
NAMI DANCE	Nonlinear Shallow Water (NSW) [2D]	FD	Upwind (1st-order accurate)	Centered (2nd-order accurate)	Explicit (2nd-order accurate)
MOST	Nonlinear Shallow Water (NSW) [2D]	FD	Centered (2nd-order accurate)	Centered (2nd-order accurate)	Explicit (1st-order accurate)
Cliffs	Nonlinear Shallow Water (NSW) [2D]	FD	Centered (2nd-order accurate)	Centered (2nd-order accurate)	Explicit (1st-order accurate)
GeoClaw	Nonlinear Shallow Water (NSW) [2D]	FV	Limiter-based (1st-order near shocks, 2nd-order when smooth)	Centered (2nd-order accurate)	Explicit (2nd-order accurate)
GeoClaw -AECOM	Nonlinear Shallow Water (NSW) [2D]	FV	Limiter-based (1st-order near shocks, 2nd-order when smooth)	Centered (2nd-order accurate)	Explicit (2nd-order accurate)
Tsunami-HySEA	Nonlinear Shallow Water (NSW) [2D]	FV	Limiter-based (2nd-order near shocks, 3rd-order when smooth)	Centered (2nd-order accurate)	Explicit (3rd-order accurate)
pCOULWAVE	Highly Nonlinear Boussinesq-type [2D]	FV	Limiter-based (2nd-order near shocks, 4th-order when smooth)	Centered (4th-order accurate)	Semi-implicit (4th-order accurate)
FUNWAVE-TVD	Highly Nonlinear Boussinesq-type [2D]	FV / FD	Limiter-based (2nd-order near shocks, 5th-order when smooth)	Centered (4th-order accurate)	Explicit (3rd-order accurate)
BOSZ	Weakly Nonlinear Boussinesq-type [2D]	FV	Limiter-based (2nd-order near shocks, 5th-order when smooth)	Centered (5th-order accurate)	Explicit (2nd-order accurate)
NEOWAVE	One-Layer, Non-Hydrostatic [2D]	FD	Upwind (1st-order near shocks, 2nd-order when smooth)	Centered (2nd-order accurate)	Semi-implicit (2nd-order accurate)
TSUNAMI3D	Navier-Stokes [3D]	FD	Upwind (1st-order accurate)	Centered (2nd-order accurate)	Explicit (2nd-order accurate)
SCHISM	Navier-Stokes, Hydrostatic [3D]	FE / FV	Limiter-based (1st-order near shocks, 2nd-order when smooth)	Centered (2nd-order accurate)	Semi-implicit (2nd-order accurate)

Tsunami modeling

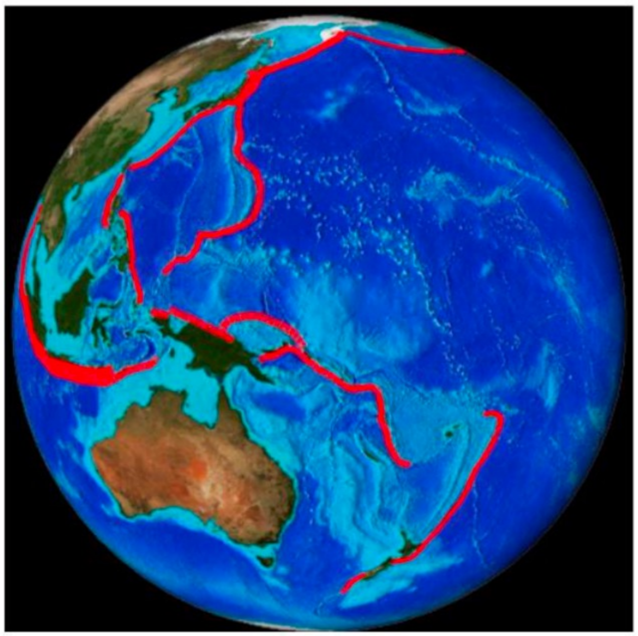
Focus of this course

Simulation of earthquake-generated tsunami

- ➢ Okada source
- ➢ Wave modeling
- ➢ Postprocessing
- ➢ Optional: brief introduction to the landslide model NHWAVE

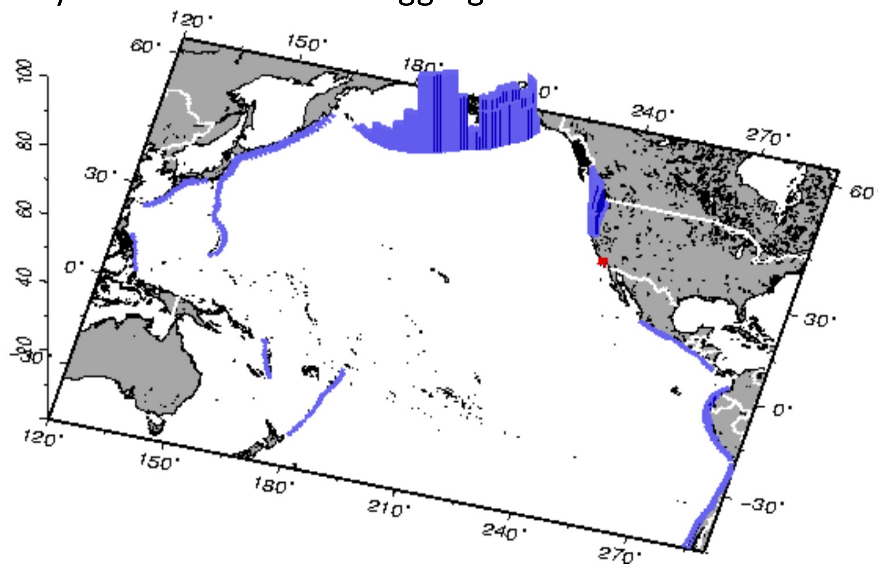
ASCE-7-16 Standard for resilient design against tsunamis

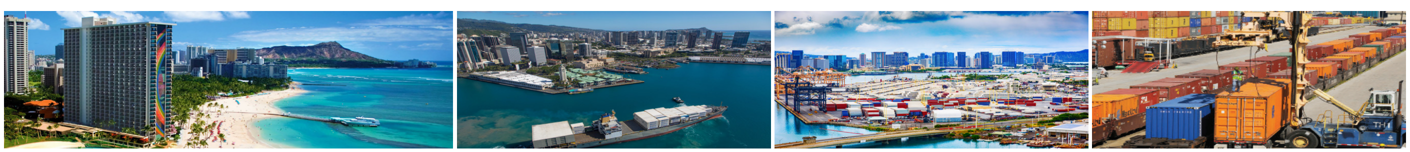
Unit sources (NOAA NCEP)



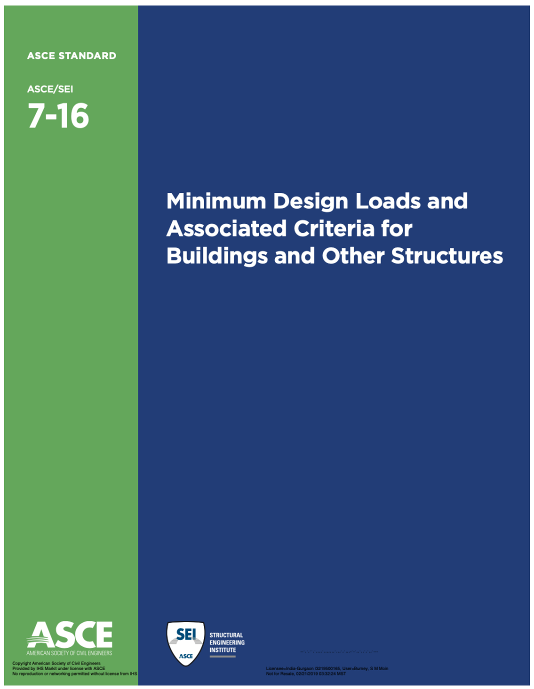
Probabilistic Tsunami Hazard Analysis (PTHA)

2500-year PTHA source disaggregation for a site

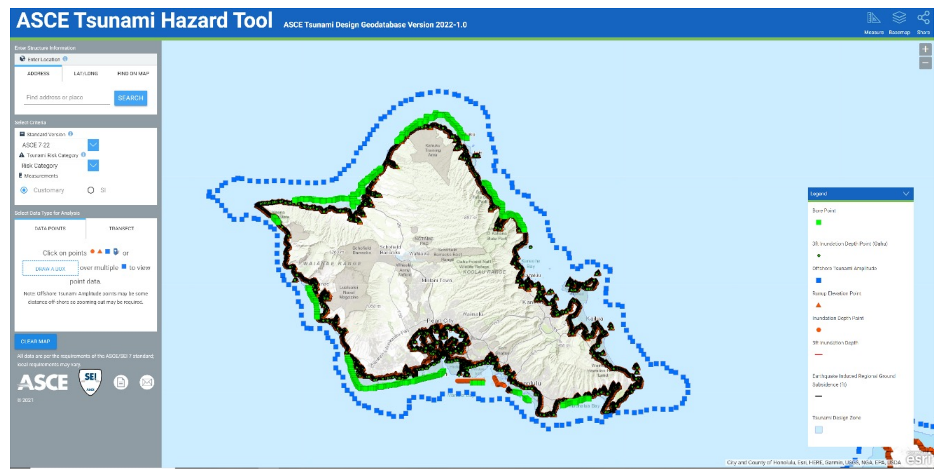




ASCE-7-16 Standard for resilient design against tsunamis



PTHA results at Oahu



ASCE-7-16 Standard for resilient design against tsunamis

Boundary condition at 100-m bathymetry contour

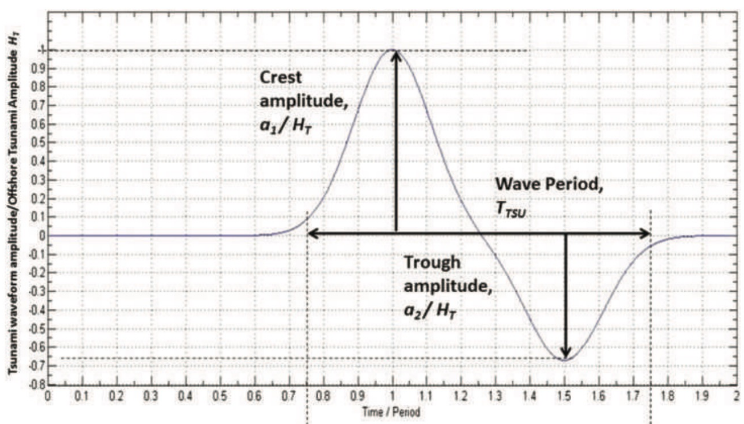


FIGURE 6.7-2 Illustration of Tsunami Offshore Incident Waveform Parameters at 328-ft (100-m) Depth

$$\eta = a_1 e^{-[\omega(t-t_o)]^2} + a_2 e^{-[\omega(t-\frac{T_{TSU}}{2}-t_o)]^2} \qquad (6.7\text{-}1)$$

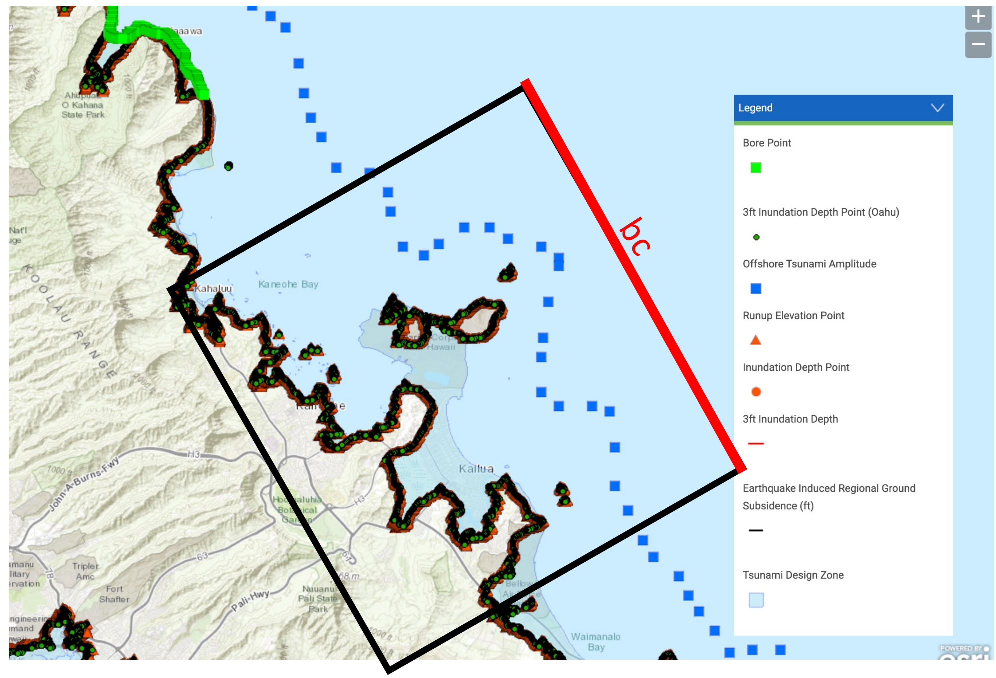
where the total wave height of the waveform is = $\mathrm{abs}(a_1) + \mathrm{abs}(a_2)$, and

η = the free surface elevation (in ft or m) as a function of time, t, used to drive the offshore boundary condition at the 328-ft (100-m) depth contour;
a_1 = the amplitude of the leading pulse (in ft or m); it shall be negative for a leading depression tsunami;
a_2 = the amplitude of the following, or second, pulse (in ft or m);
T_{TSU} = wave period, or the time from the start of the first pulse to the end of the second pulse;
ω = angular frequency of the waveform, equal to $2\pi/T_{TSU}$; and
t_o = offset time of the wave train, generally set equal to T_{TSU}

ASCE-7-16 Standard for resilient design against tsunamis

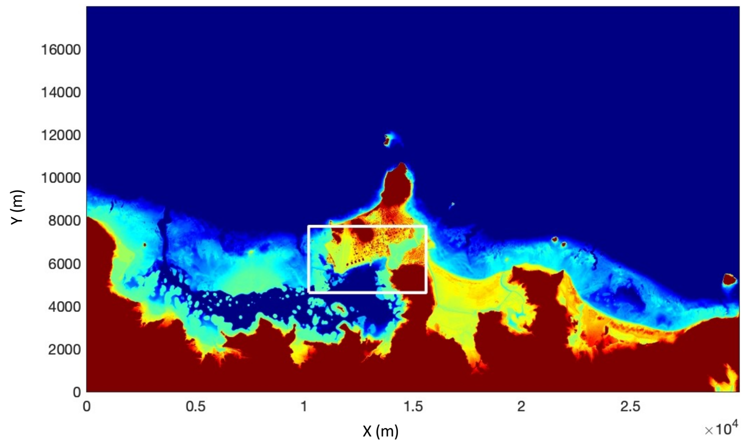
An example of model domain setup

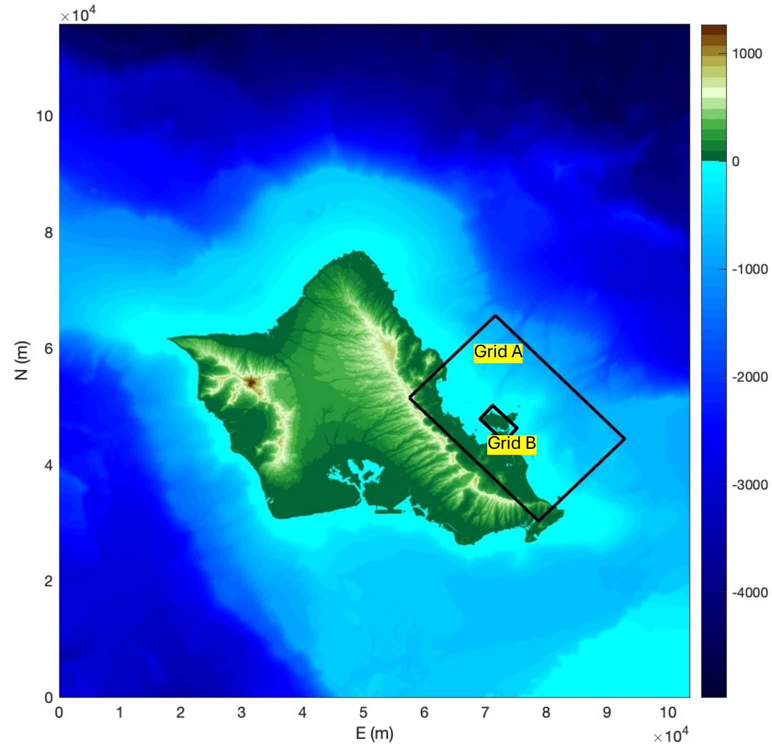
NOTE: no requirement for modeled wave direction in ASCE-7-16



ASCE-7-16 Standard for resilient design against tsunamis

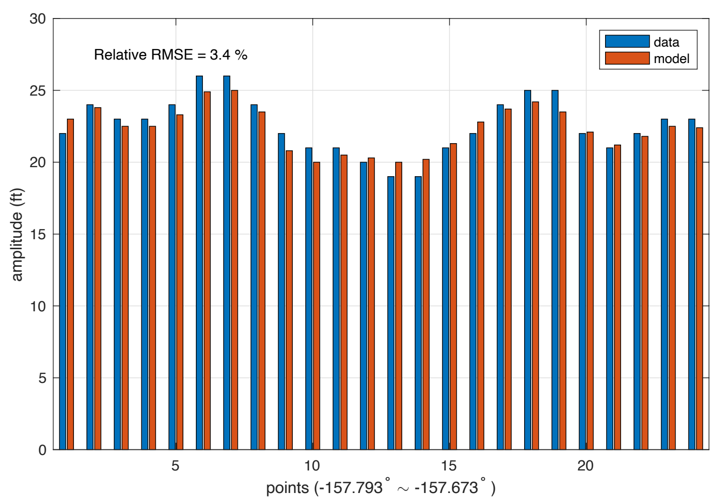
An example of model domain setup

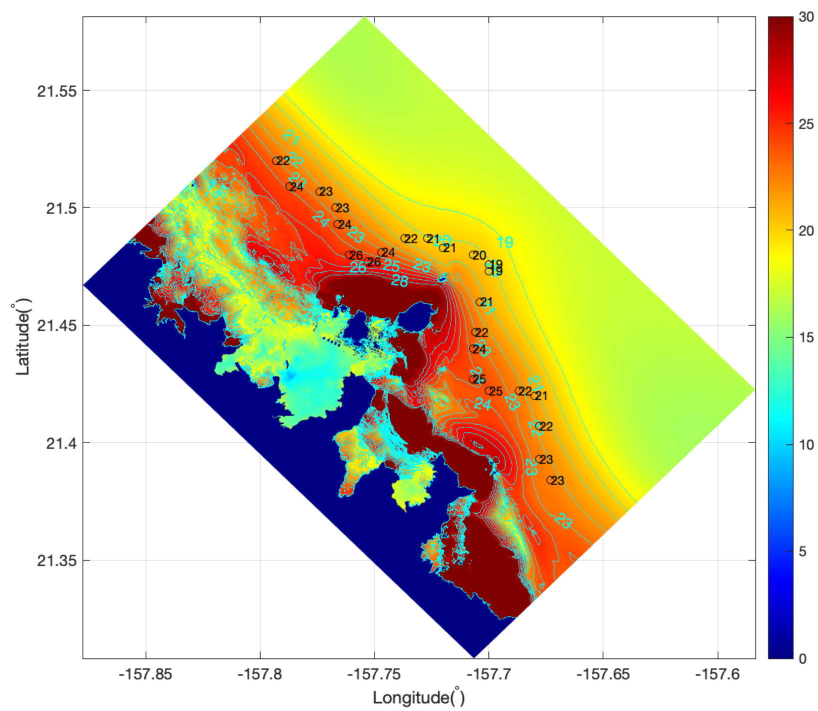




ASCE-7-16 Standard for resilient design against tsunamis

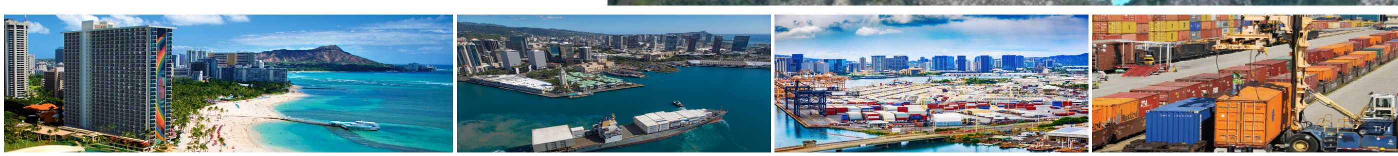
An example of model domain setup





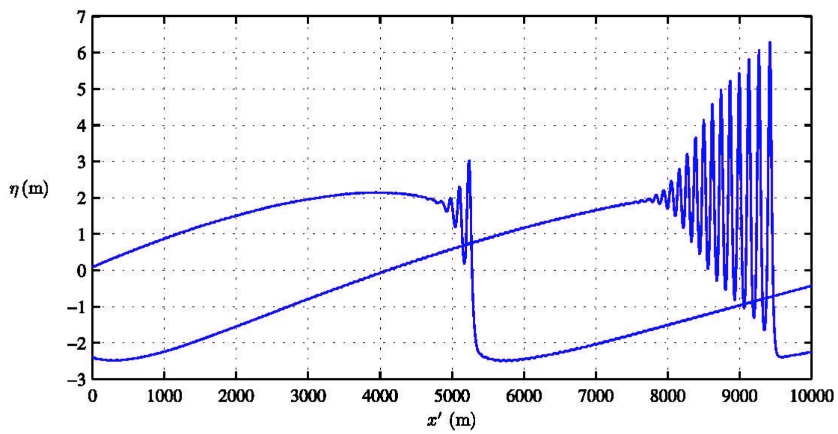
ASCE-16 standard for resilient design against tsunamis

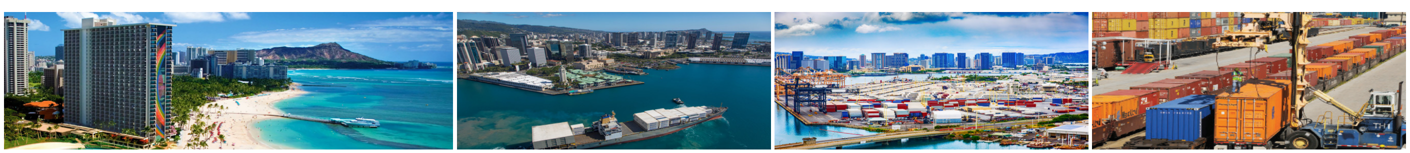
An example of model domain setup



FUNWAVE-TVD

Why Boussinesq?





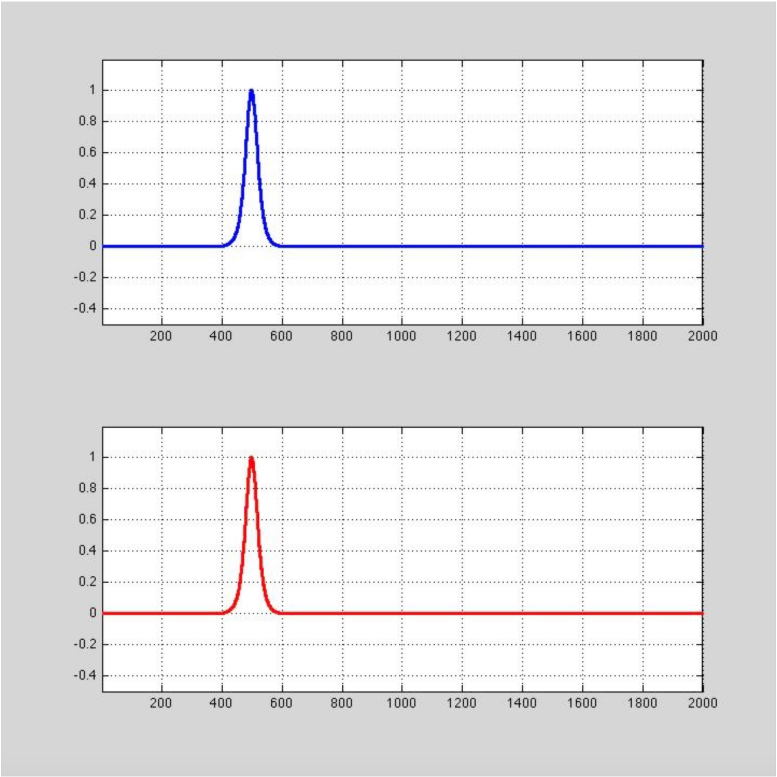
FUNWAVE-TVD

Why Boussinesq?

Boussinesq equations

Shallow water equations

$$c = \sqrt{g(h+\eta)}$$



FUNWAVE-TVD

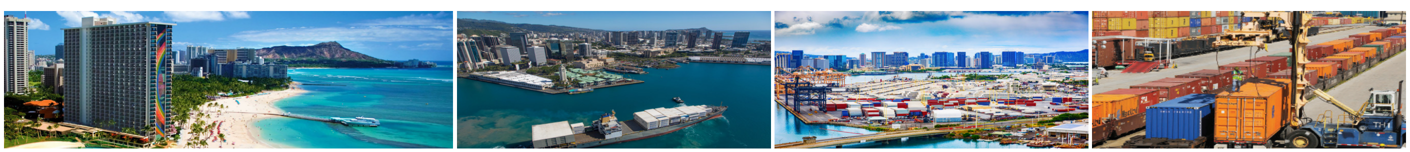
- Why FUNWAVE-TVD?

  - **Open source and well documented**
    https://github.com/fengyanshi/FUNWAVE-TVD
    https://fengyanshi.github.io/build/html/index.html
  - **TVD scheme, very stable**
  - **Parallelized, CPU(MPI) and GPU codes**
  - **Benchmarked (NTHMP standard)**
  - **Large user group**

    https://groups.google.com/forum/?hl=en#!forum/funwave-tvd

FUNWAVE-TVD

- How many versions of FUNWAVE?
  - FUNWAVE (Wei et al., 1995, Wei and Kirby, 1995, Kennedy et al., 2000, Chen et al., 2000)
  - FUNWAVE 2 (Shi et al., 2001, Long and Kirby, 2006)
  - GEOWAVE (TOPICS+FUNWAVE, Grilli, Watts, 2003)
  - FUNWAVE-TVD (Shi et al., 2012)



FUNWAVE-TVD

- FUNWAVE equations

Mass conservation

$$\eta_t + \nabla \cdot \mathbf{M} = 0$$

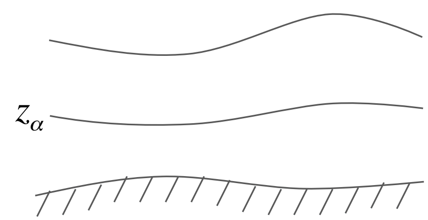
where $\mathbf{M} = H\left\{\mathbf{u}_\alpha + \overline{\mathbf{u}}_2\right\}$

$$\overline{\mathbf{u}}_2 = \frac{1}{H}\int_{-h}^{\eta} \mathbf{u}_2(z)dz = \left(\frac{z_\alpha^2}{2} - \frac{1}{6}(h^2 - h\eta + \eta^2)\right)\nabla B + \left(z_\alpha + \frac{1}{2}(h-\eta)\right)\nabla A$$

$$\begin{aligned} A &= \nabla \cdot (h\mathbf{u}_\alpha) \\ B &= \nabla \cdot \mathbf{u}_\alpha \end{aligned}$$

$$z_\alpha = -h + \beta H = (\beta - 1)h + \beta\eta = \zeta h + (1+\zeta)\eta$$

Kennedy et al., 2001



FUNWAVE-TVD

- FUNWAVE equations

Momentum equations:

$$\mathbf{u}_{\alpha,t} + (\mathbf{u}_\alpha \cdot \nabla)\mathbf{u}_\alpha + g\nabla\eta + \mathbf{V}_1 + \mathbf{V}_2 + \mathbf{V}_3 + \mathbf{R} = 0$$

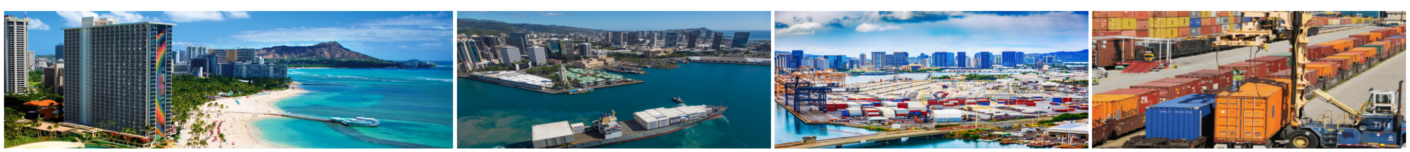
Dispersive terms

$$\begin{aligned}
\mathbf{V}_1 &= \left\{ \frac{z_\alpha^2}{2}\nabla B + z_\alpha \nabla A \right\}_t - \nabla\left[\frac{\eta^2}{2} B_t + \eta A_t) \right] \\
\mathbf{V}_2 &= \nabla\left\{ (z_\alpha - \eta)(\mathbf{u}_\alpha \cdot \nabla)A + \frac{1}{2}(z_\alpha^2 - \eta^2)(\mathbf{u}_\alpha \cdot \nabla)B + \frac{1}{2}[A + \eta B]^2 \right\}
\end{aligned}$$

Second order effect of the vertical vorticity (Chen, 2006)

$$\mathbf{V}_3 = \omega_0 \mathbf{i}^z \times \overline{\mathbf{u}}_2 + \omega_2 \mathbf{i}^z \times \mathbf{u}_\alpha$$

$$\begin{aligned}
\omega_0 &= (\nabla \times \mathbf{u}_\alpha) \cdot \mathbf{i}^z = v_{\alpha,x} - u_{\alpha,y} \\
\omega_2 &= (\nabla \times \overline{\mathbf{u}}_2) \cdot \mathbf{i}^z = z_{\alpha,x}(A_y + z_\alpha B_y) - z_{\alpha,y}(A_x + z_\alpha B_x)
\end{aligned}$$

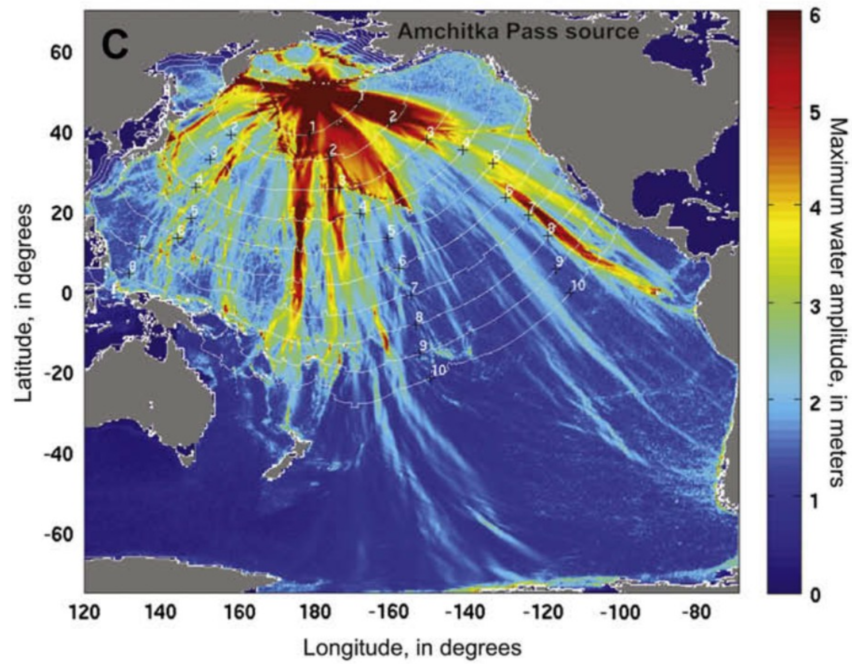


FUNWAVE-TVD

- FUNWAVE equations

Spherical mode: Weakly nonlinear Boussinesq equations in spherical coordinates (Kirby et al. 2013)

$$
\begin{aligned}
&H_t + \frac{1}{r_0 \cos\theta}\{(Hu)_\phi + (Hv\cos\theta)_\theta\} = 0 \\
&u_t - fv + \frac{1}{r_0\cos\theta} u u_\phi + \frac{1}{r_0} v u_\theta + \frac{g}{r_0\cos\theta}\eta_\phi \\
&+ \frac{1}{r_0^2\cos^2\theta}\left\{\frac{h^2}{6}\left[u_{\phi\phi t} + (v\cos\theta)_{\phi\theta t}\right] - \frac{h}{2}\left[(hu_t)_{\phi\phi} + (h\cos\theta v_t)_{\phi\theta}\right]\right\} \\
&-\tau_b^x + \frac{1}{r_0\cos\theta}(BFT)_\phi = 0 \\
&v_t + fu + \frac{1}{r_0\cos\theta} u v_\phi + \frac{1}{r_0} v v_\theta + \frac{g}{r_0}\eta_\theta \\
&+ \frac{1}{r_0^2}\left\{\frac{h^2}{6}\left[\frac{1}{\cos\theta}\{u_{\phi t} + (v\cos\theta)_{\theta t}\}\right]_\theta - \frac{h}{2}\left[\frac{1}{\cos\theta}\{(hu_t)_\phi + (h\cos\theta v_t)_\theta\}\right]_\theta\right\} \\
&-\tau_b^y + \frac{1}{r_0}(BFT)_\theta = 0
\end{aligned}
$$



FUNWAVE-TVD

- FUNWAVE equations

Numerical schemes

Spatial discretization

Combined finite volume and finite difference scheme

•Fourth-order MUSCL-TVD scheme (Yamamoto and Daiguji, 1993)
•HLL Riemann solver
•Surface gradient scheme for pressure gradient term (Zhou et al., 2001)

Time stepping

The third-order Strong Stability-Preserving (SSP) Runge-Kutta scheme

Adaptive time step

$$\Delta t = C\min\left(\min\frac{\Delta x}{|u_{i,j}|+\sqrt{g(h_{i,j}+\eta_{i,j})}}, \min\frac{\Delta y}{|u_{i,j}|+\sqrt{g(h_{i,j}+\eta_{i,j})}}\right)$$

Moving boundary condition

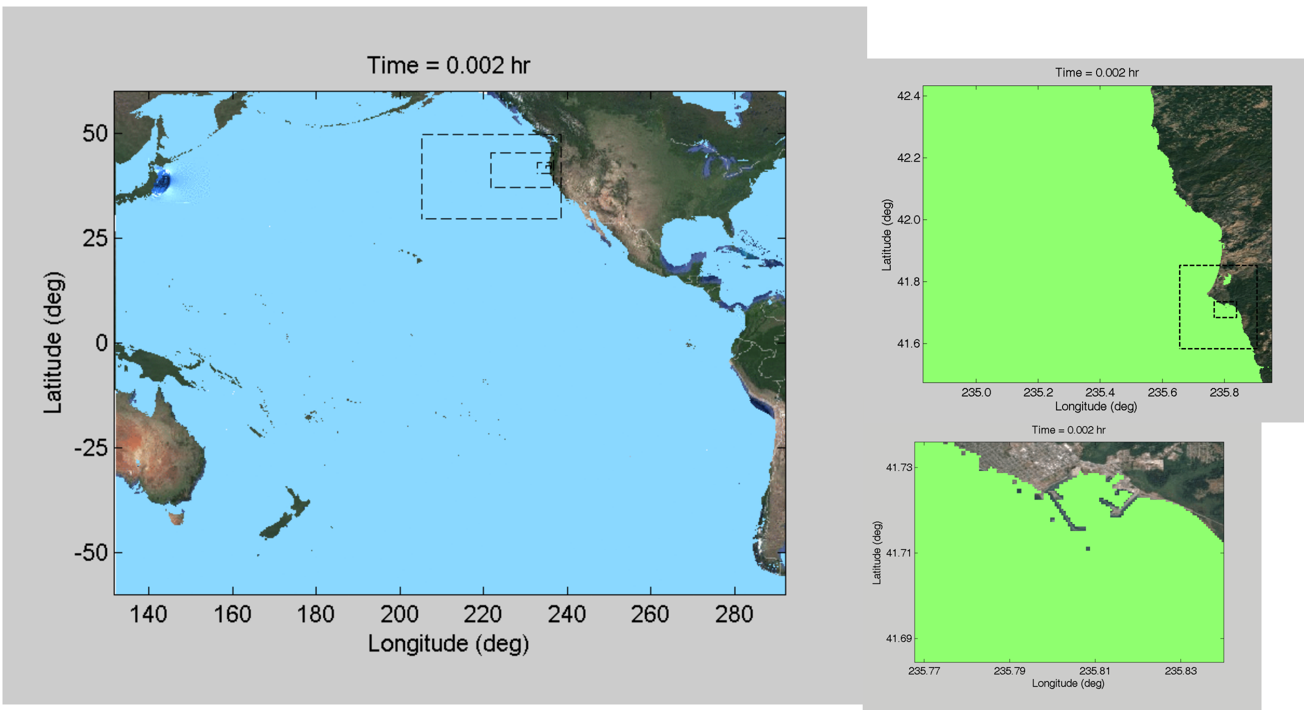
wetting and drying with correction of wave speed in Riemann solver

Wave breaking

switch between NSWE and Boussinesq (Tonelli and Petti, 2009)

New features of FUNWAVE-TVD

Multi-grid Nesting Interface (Choi et al., 2022)



New features of FUNWAVE-TVD

HPC

40-node cluster based on Intel Xeon Gloden 6150 CPUs
40*36=1440 cores
~120 kW, $600,000

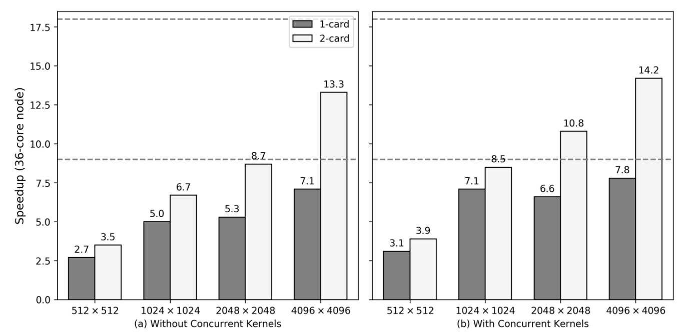
GPU

4 Nvidia V100 GPU cards
@
1 Intel 36-cores node

20480 cores
Performance: 56 TFLOPS
3.5 kW, $40,000

Yuan et al., 2021

- PGI 18.4 Cuda Fortran
- CUDA 10.0
- MPI + Single/multi GPU



Speedup tests: GPU vs. CPU.
36 cores on 1 CPU node, 5120 cores/card

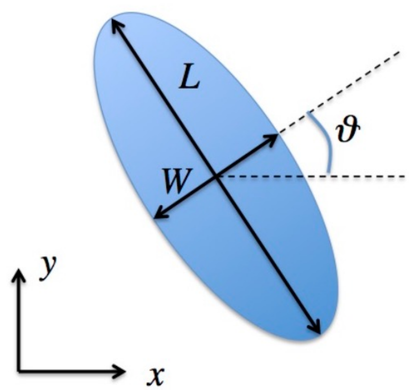
New features of FUNWAVE-TVD

Meteo-tsunami module

Meteotsunamis are modeled using a pressure source with a two-dimensional Gaussian distribution:

$$P = dPexp\left(-(\frac{(x' - x_0)^2}{2\sigma_x^2} + \frac{(y' - y_0)^2}{2\sigma_y^2})\right) \quad (97)$$

where dP is the pressure anomaly in mb, and (x', y') are the coordinates rotated to the pressure moving direction (angle is θ as indicated in the figure below). σ_x and σ_y are paramters representing the length and width of the pressure source, respectively.

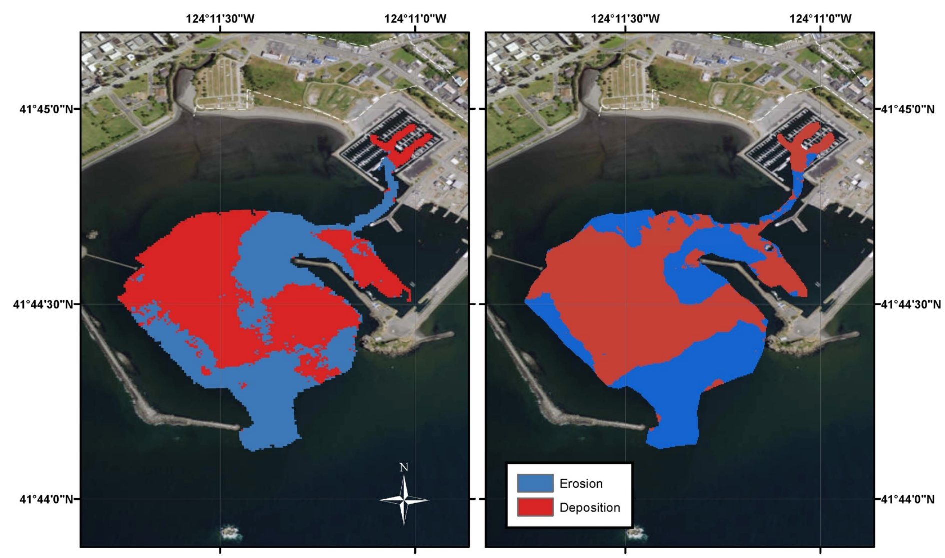


New features of FUNWAVE-TVD

Sediment transport module

Quasi-steady state-based sediment transport equation (Tehranirad et al., 2016)

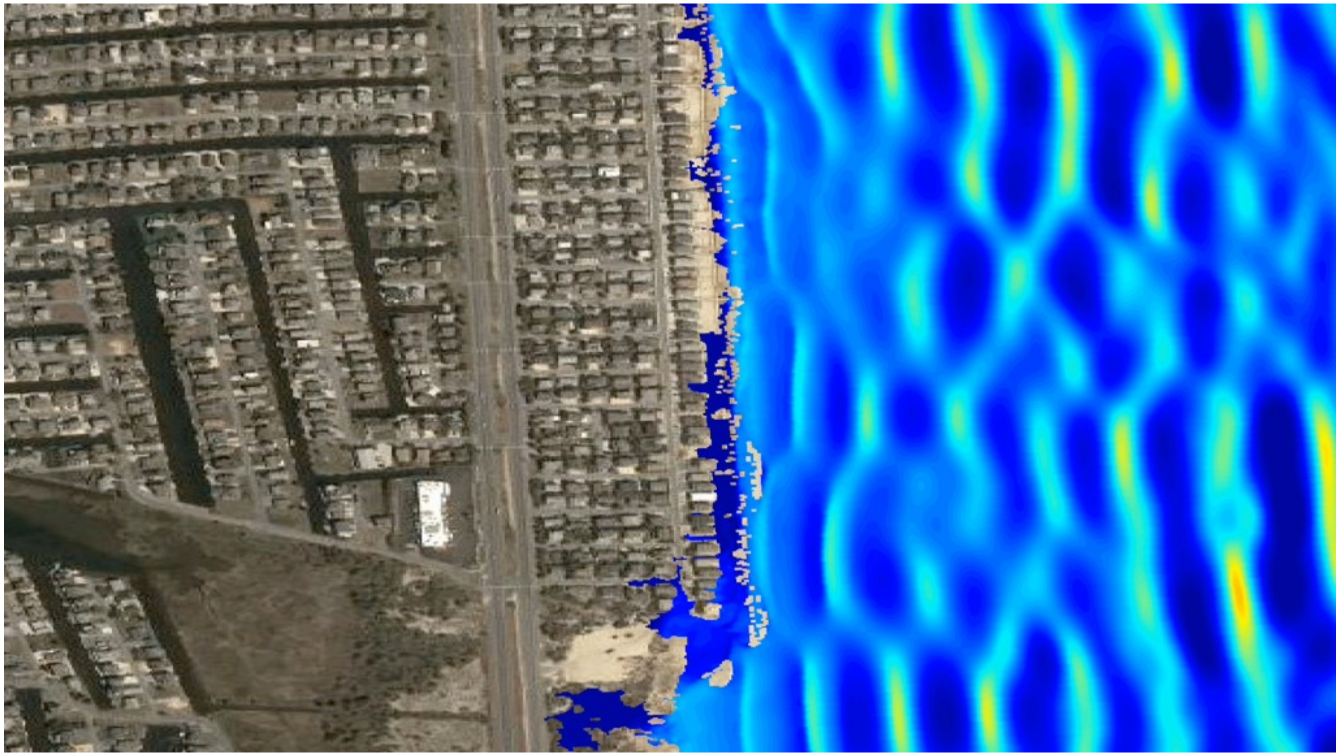
2011 tsunami inside Crescent City harbor.



Measured (Wilson et al., 2012) **Calculated**

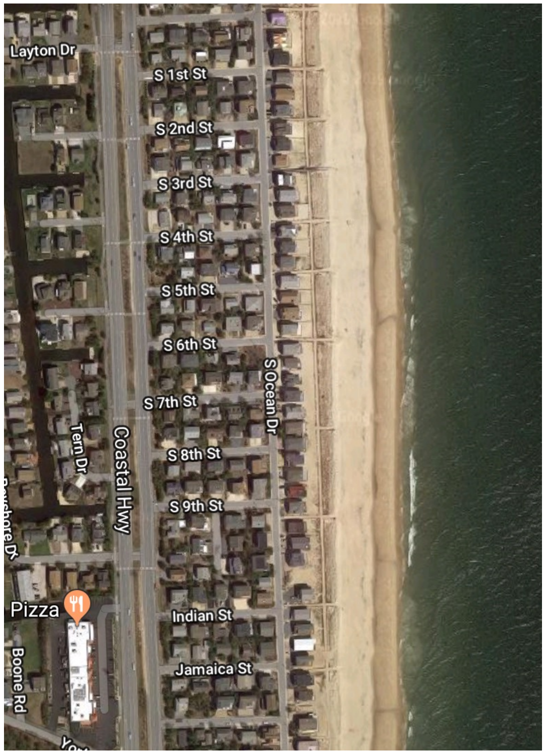
New features of FUNWAVE-TVD

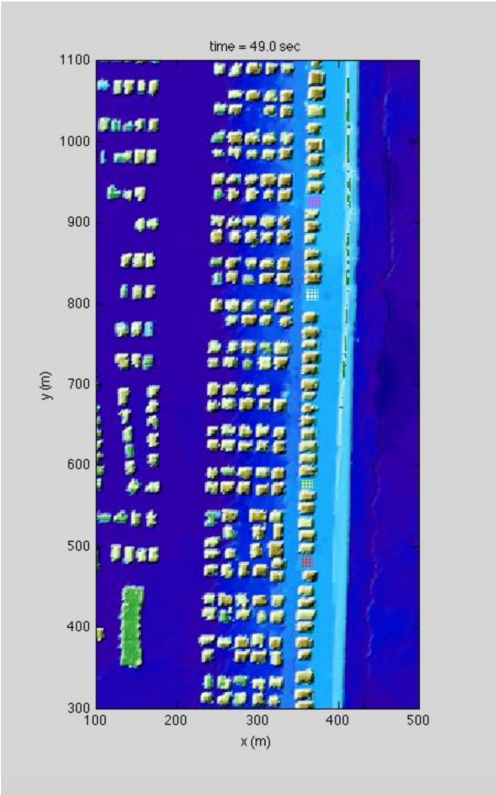
Lagrangian Particle Tracking



New features of FUNWAVE-TVD

Lagrangian Particle Tracking

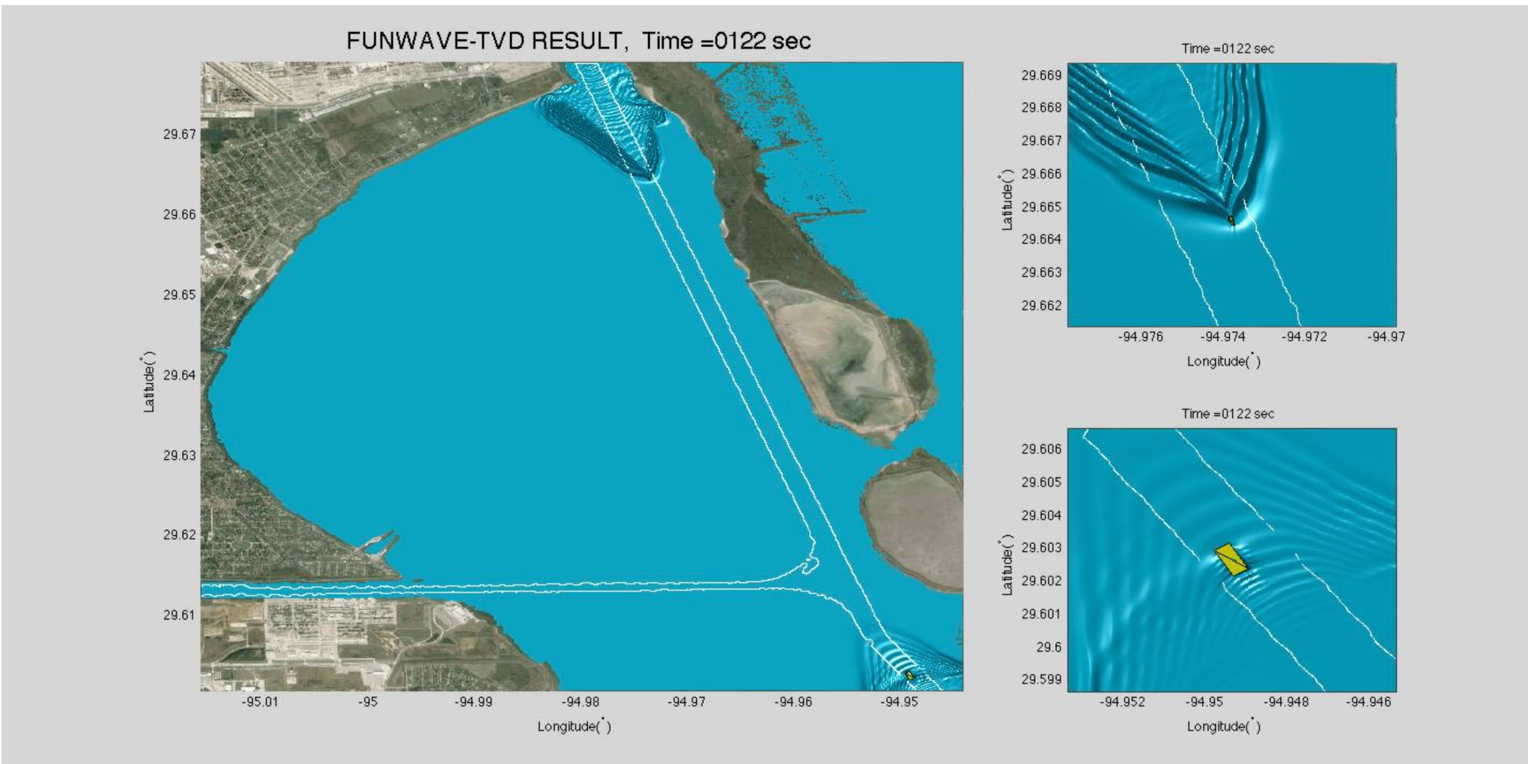




PORTS'22

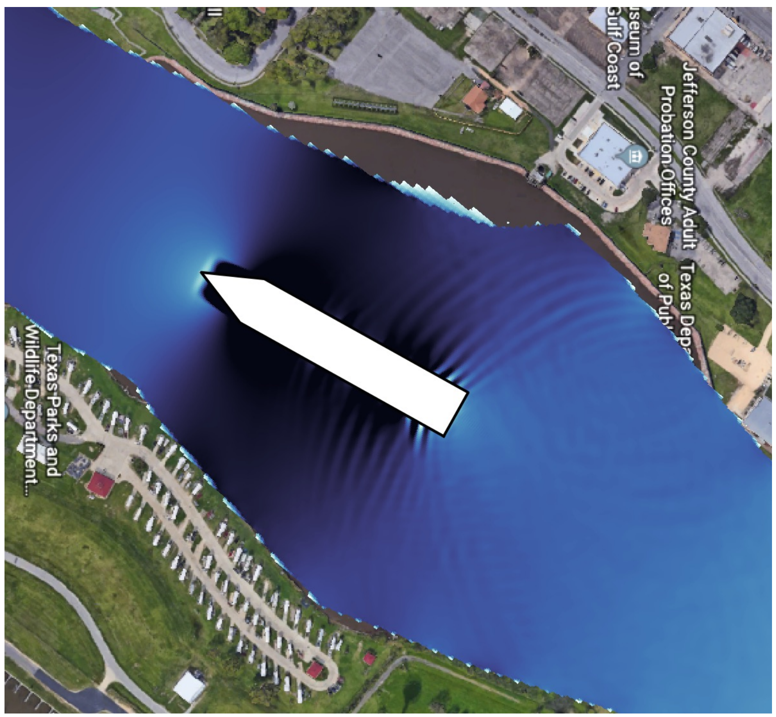
New features of FUNWAVE-TVD

Ship-wake module



New features of FUNWAVE-TVD

Ship-wake module



Tutorial

- FUNWAVE WIKI page
- Install and compile the model
- Model input/output
- Simple cases
- Modeling Tohoku Tsunami (other sources, such as 1964 Alaska, Cape Fear Landslide, are provided for practice)
- Grid nesting/coupling
- Landslide tsunami generation (optional)