HySEA model
Benchmark problems 1, 2, 3, 4 and 5

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Mapping & Modeling Benchmarking Workshop: Tsunami Currents

The HySEA model

Plan for the presentation

1. The HySEA model (in few words)
2. (Previous) Validation
3. Benchmark 1 - SB4_02 Lloyd & Stansby (1995)
4. Benchmark 2 - Hilo Harbour
5. Benchmark 3 - Tauranga Harbour
6. Benchmark 4 - Seaside (Oregon)
7. Benchmark 5 - Triangular shaped shelf with an island

1. The HySEA model

A family of codes

- Non-linear Shallow Water Equations
- Structured and non-structures meshes (multiGPU)
- UTM and lat/lon coordinates (multiGPU)
- Weakly dispersive (MS model). Beta version.
- Two-Layer Savage-Hutter shallow water system (multiGPU)
- Shallow-Water Exner system on structured and non-structured meshes (bedload transport). GPU
- and others (turbidity currents, coupling biology and hidrodynamics, multilayer,...)

Simulating...

- Earthquake generated tsunamis (**tsunami-HySEA**)
- Submarine and aerial landslide genereted tsunamis (**landslide-HySEA**)
- Sediment bedload transport
- Turbidity currents and sedimentary plumes
- Physical-biological coupled processes
- others

1. Tsunami-HySEA

Numerics: A family of Finite Volume numerical schemes

- **Scenarios**: WAF method (LW+HLL)[1] and higher order
- **TEWS**: hybrid 2s+WAF[2]
- **Laboratory experiments**: higher order methods
- Wet/Dry front treatment[3,4,5]
- Nested meshes and/or AMR (GPU)

[1] **de la Asunción et al. (2012).** Efficient GPU implementation of a two waves TVD-WAF method for the two-dimensional one layer shallow water system on structured meshes, *Computers & Fluids.*

[2] Article in progress

[3] **Castro, González-Vida, Parés (2005).** Numerical treatment of wet/dry fronts in shallow water flows with a modified Roe scheme. *Math. Mod. and Meth. in Applied Sci.*

[4] **Gallardo, Parés, Castro (2007)**. On a well-balanced high-order finite volume scheme for shallow water equations with topography and dry areas. *J. Comput. Phys.*

[5] **Castro, Fernández, Ferreiro, García, Parés (2009)**. High order extensions of Roe schemes for two dimensional nonconservative hyperbolic systems. *J. Sci. Comput.*

1. Tsunami-HySEA

Numerics: A family of Finite Volume numerical schemes

- **Scenarios**: WAF method (LW+HLL)[1] and higher order
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Nice properties

- Well-balanced (avoid spurious oscillations)
- Transitions from sub to super critical situations (arrival to coast)
- Positivity (no negative layer thickness)
- Inundation area and runup heights are model outputs
- Discontinuities in data or solutions (no need to smooth bathymetry)

Implementation

- CUDA - GPU/Multi-GPU (very short computing times)

The HySEA model. Validation

NOAA benchmarks (Synolakis et al., 2008)[1]

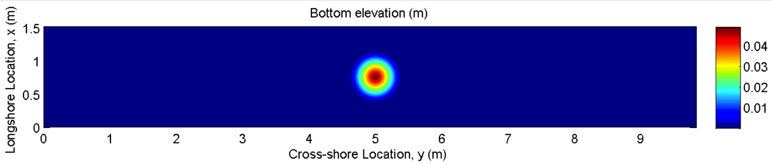
- **Analytical solutions**
  - Single wave on a simple beach
  - Solitary wave on composite beach
  - Subaerial landslide on simple beach
- **Laboratory benchmarking**
  - Solitary wave on a simple beach
  - Solitary wave on a composite beach
  - Solitary wave on a conical island
  - Tsunami runup onto a complex three-dimensional beach. Monai Valley
  - Tsunami generation and runup due to three-dimensional landslide
- **Field benchmarking**
  - Okushiri Island
  - Rat Islands tsunami

[1] **Millán (2014)**. Estudio y validación de un modelo de volúmenes finitos TVD-WAF 2D de aguas someras para la simulación de tsunamis. *Universidad de Málaga*, 101 pages.

Benchmark Problem 1

Setup

- Test case SB4_02 in Lloyd and Stansby (1995) Part II
- Steady discharge U=0.115 m/s
- Water depth h=0.054 m
- Reynolds number Re = 6210
- Ratio water depth to island height h/h_i = 1.10
- Bathymetry

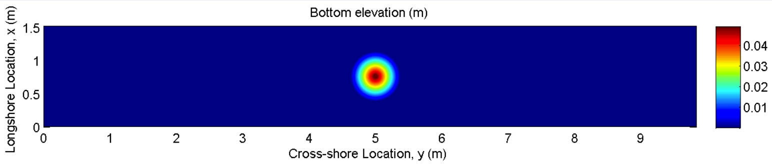


- Domain: $[0, 9.75(84)] \times [0, 1.52]$
- Resolution: $\Delta x = \Delta y = 0.0152$ m
- Mesh: 642×100

Benchmark Problem 1. **What we have done**

Numerical Experiments (112)

- **Order of the method**: 1^{st}, 2^{nd} and 3^{rd}
- **Friction law**:
  - Cuadratic (reference value $c_f = 0.006$)
  - Manning ($M_n = 0.01$)
- **Friction coefficient**: inviscid, 0.005 to 0.015 (step 0.001) - 12 cases -
- 3 **Boundary conditions** (different implementations of the same BC)
  - ghost cells
  - 1 sponge layer[1]
  - 2 sponge layer[1]



[1] **Lavelle and Thacker (2008).** Ocean Modelling.

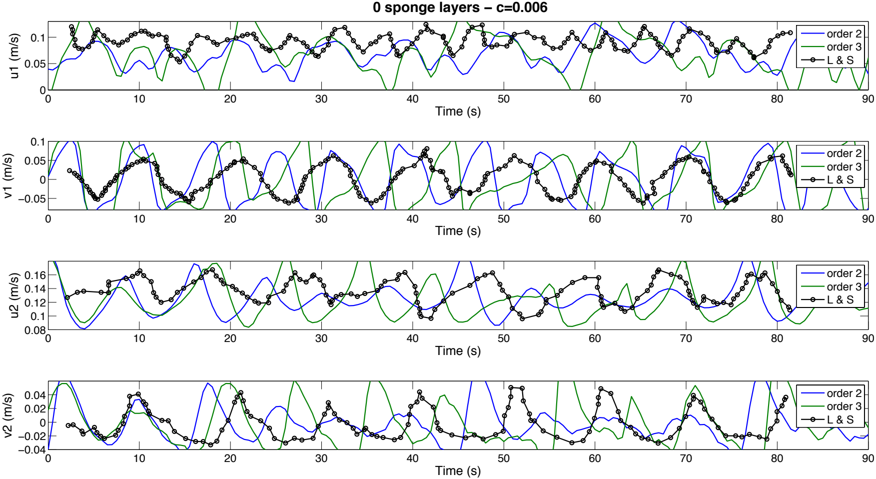
Benchmark Problem 1

Some comments

- Extremely sensitive problem
- 1^{st} order too diffusive (refinement?)
- Any perturbation not leaving the domain will highly interfere the solution

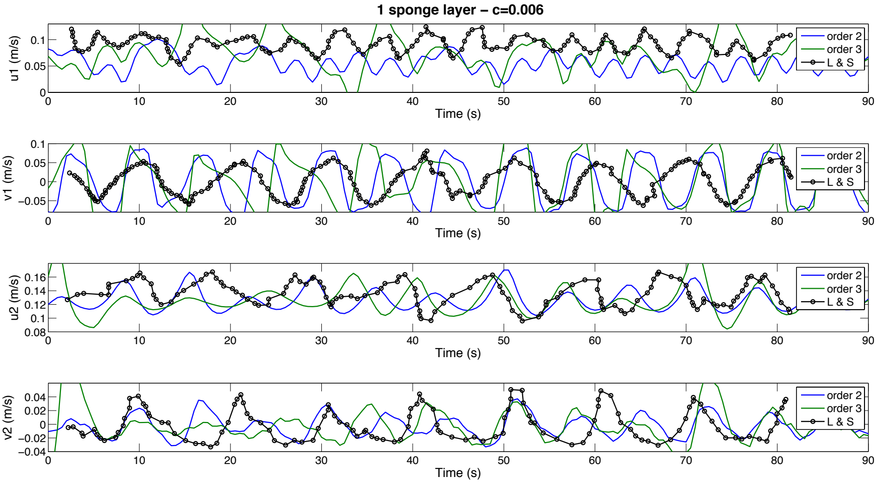
Benchmark Problem 1 - Boundary Condition 1

Configuration 1. Cuadratic friction with $C_f = 0.006$



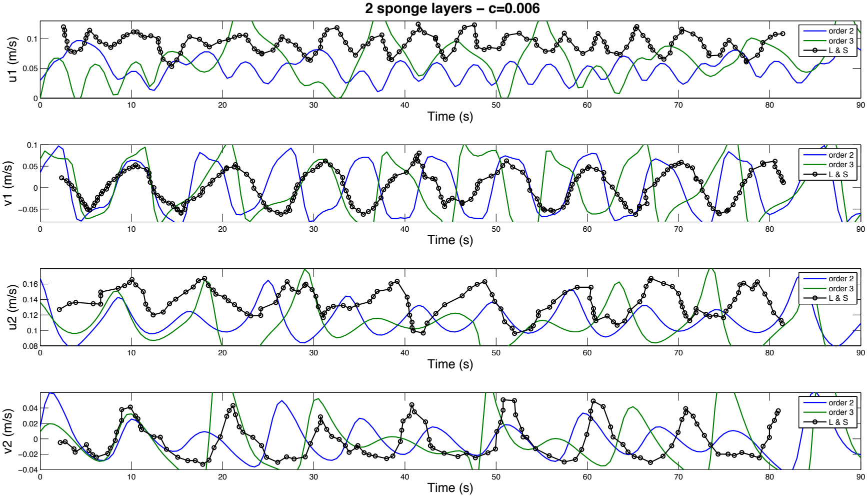
Benchmark Problem 1 - Boundary Condition 2

Configuration 1. Cuadratic friction with $C_f = 0.006$



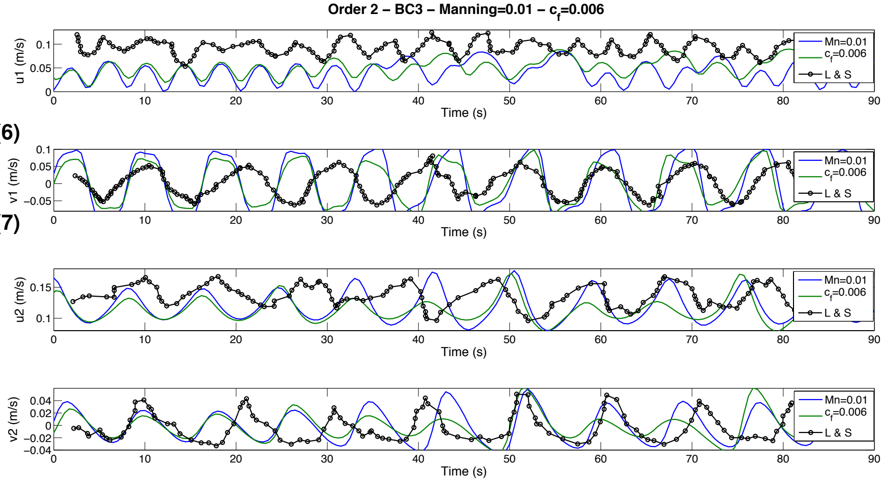
Benchmark Problem 1 - Boundary Condition 3

Configuration 1. Cuadratic friction with $C_f = 0.006$



Benchmark Problem 1 - Boundary Condition 3

Configuration 1. Cuadratic friction with $C_f = 0.006$ **and Manning** $M_n = 0.01$

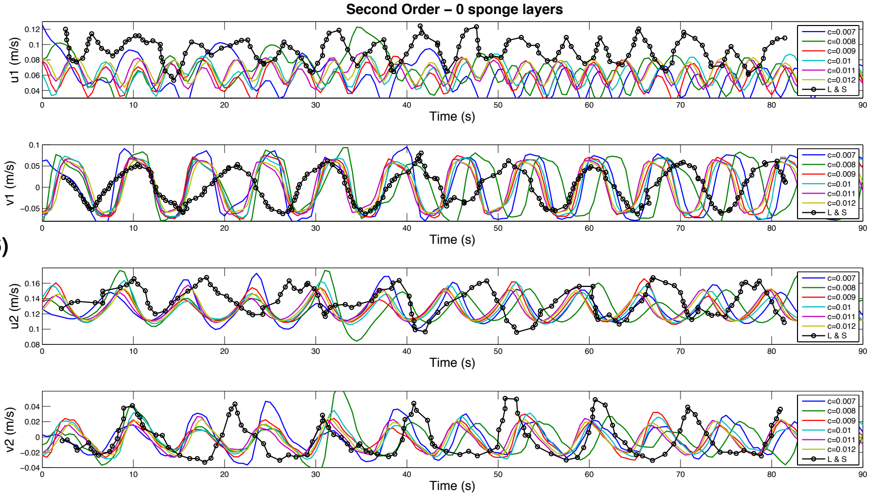


7 (6)

8 (7)

Benchmark Problem 1 - Boundary Condition 1 - 2^{nd} order

Configuration 2. Looking for the optimized friction

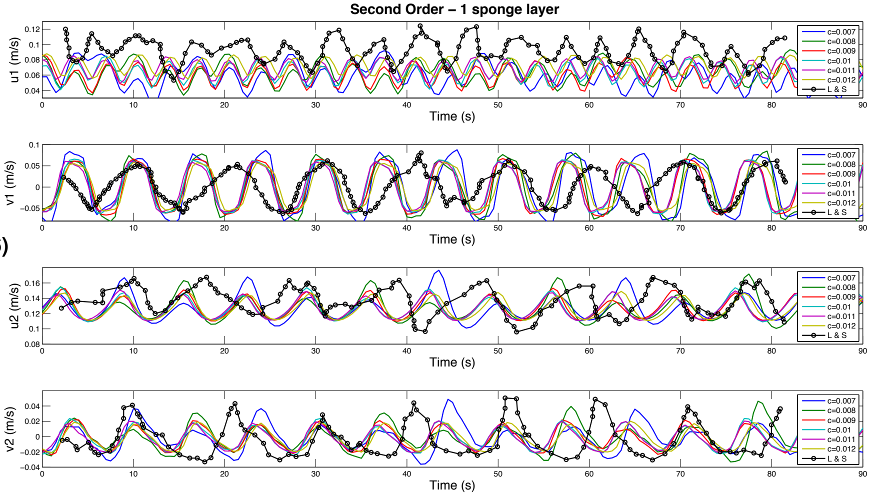


8 (6)

Benchmark Problem 1 - Boundary Condition 2 - 2^{nd} order

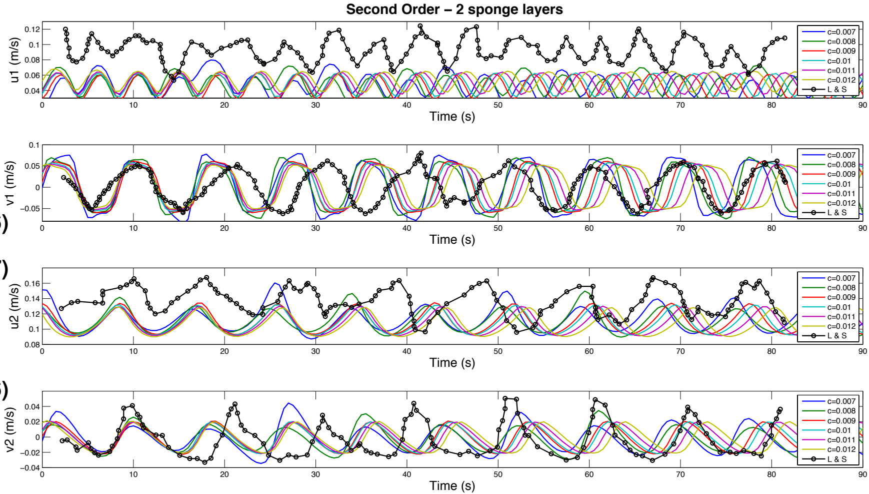
Configuration 2. Looking for the optimized friction

8 (6)



Benchmark Problem 1 - Boundary Condition 3 - 2^{nd} order

Configuration 2. Looking for the optimized friction



7 (6)

8 (7)

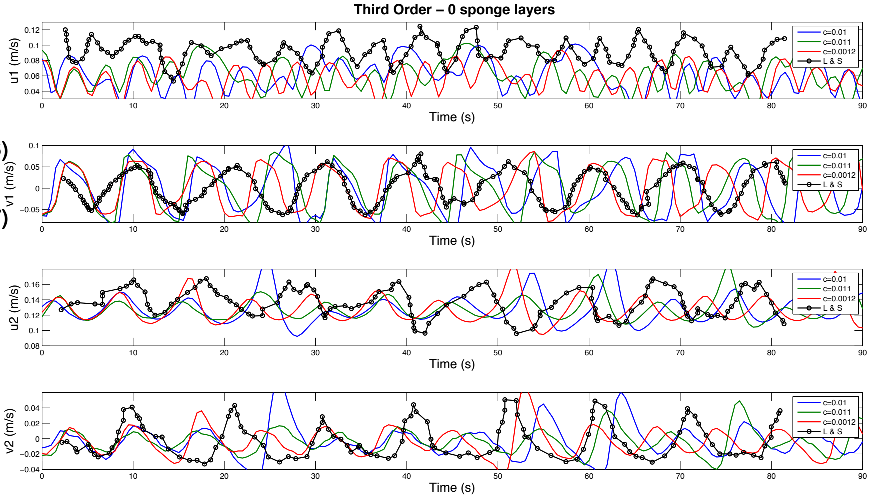
7 (6)

Benchmark Problem 1 - Boundary Condition 1 - 3rd order

Configuration 2. Looking for the optimized friction

8 (6)

9 (7)

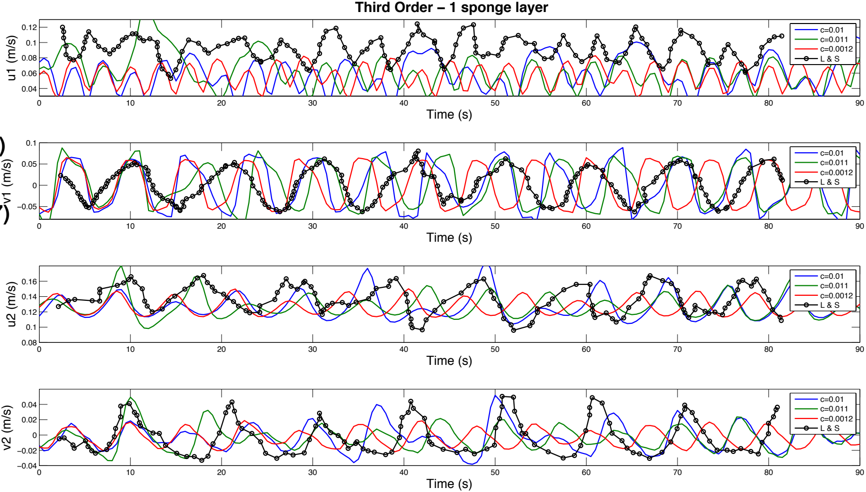


Benchmark Problem 1 - Boundary Condition 2 - 3rd order

Configuration 2. Looking for the optimized friction

9 (6)

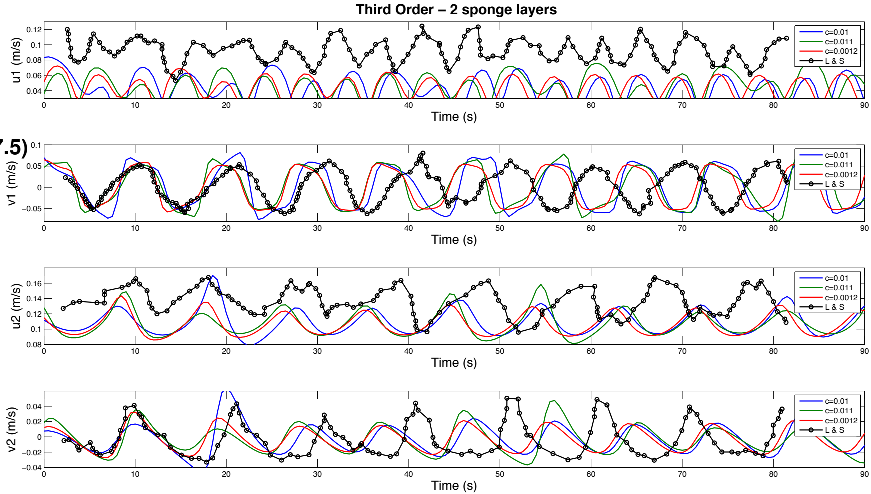
10 (7)



Benchmark Problem 1 - Boundary Condition 3 - 3rd order

Configuration 2. Looking for the optimized friction

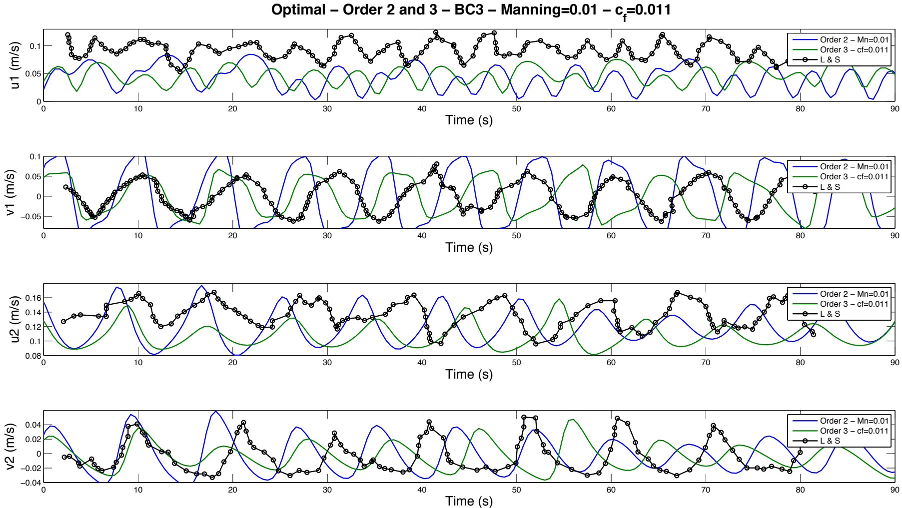
8 (7.5)



Benchmark Problem 1 - **Optimal choice**

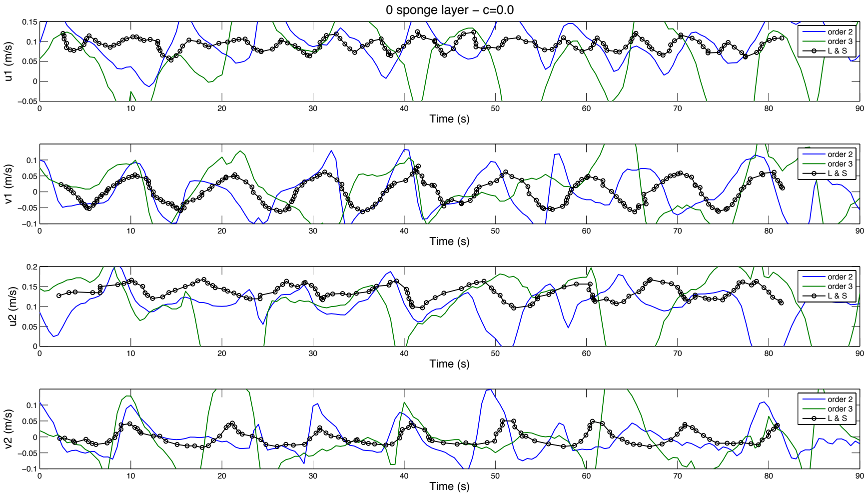
Just to make an "optimal" choice:

- Amplitude: Order 2 - BC3 - $M_n = 0.01$
- Frequency: Order 3 - BC3 - c_f various (0.01)



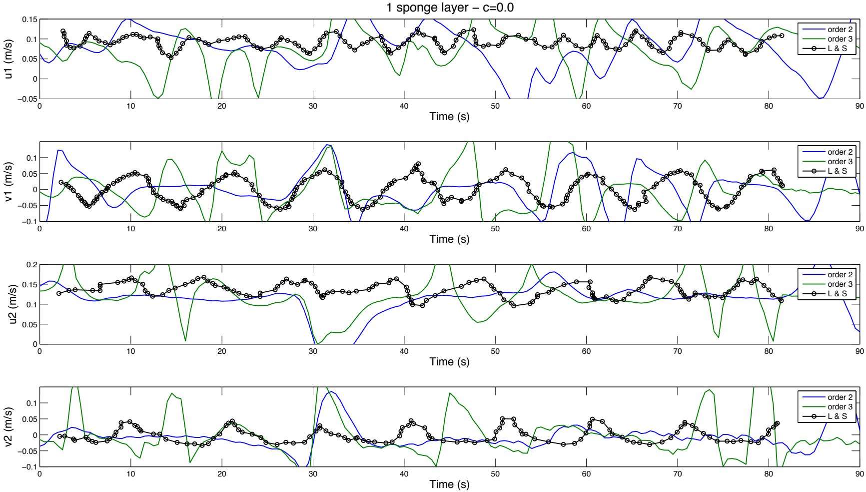
Benchmark Problem 1 - Boundary Condition 1

Configuration 3. Inviscid



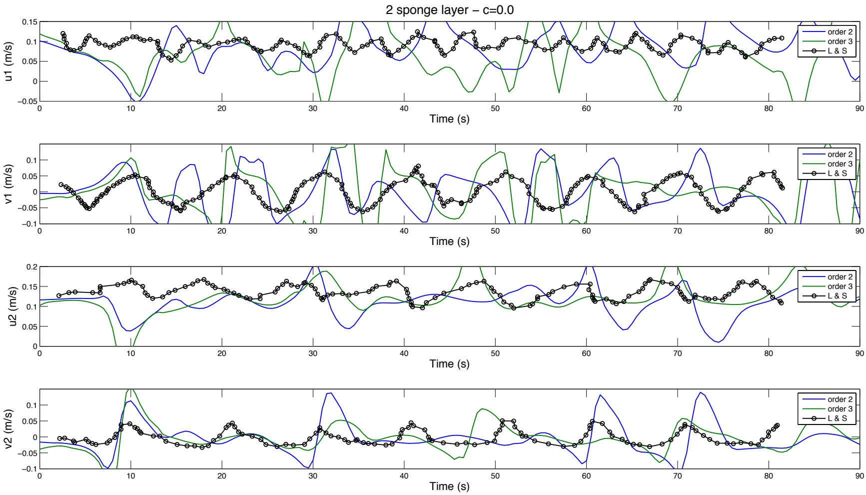
Benchmark Problem 1 - Boundary Condition 2

Configuration 3. Inviscid



Benchmark Problem 1 - Boundary Condition 3

Configuration 3. Inviscid



Benchmark Problem 1 - Conclusions

About the order

- Forget about 1^{st} order (at least for the given resolution $\Delta x = 0.01$)
- 3^{rd} order not necesarily better (why?)
- Higher the order better the BC must do

About the friction

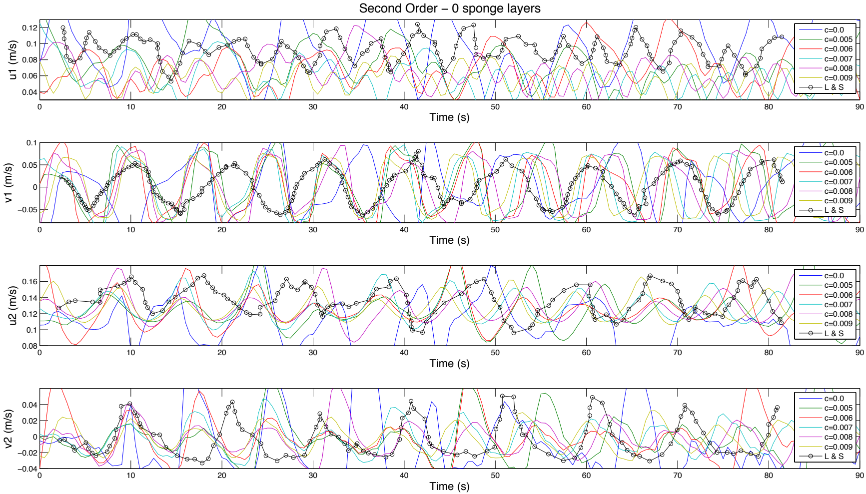
- High sensiblity for low values
- Low sensibility for higher values
- Regular, periodic solutions for high friction values
- The better you do (order and BC), sensibility for higher values increases (frequency)

About the BC

- The implementation of the BC is crucial
- So sensitive that perturbations must leave, if not ...
- But, disappointingly, no one it is the absolute better choice

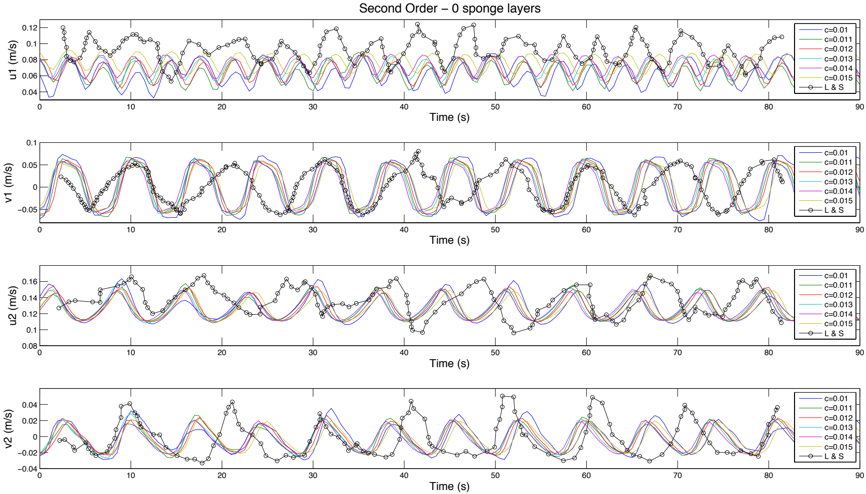
Benchmark Problem 1 - Sensitivity to friction

High sensitivity to low values



Benchmark Problem 1 - Sensitivity to friction

Low sensitivity to high values



Benchmark Problem 1 - **Conclusions**

About the order

- Forget about 1^{st} order (with the given resolution $\Delta x = 0.01$)
- 3^{rd} order not necesarily better (why?)
- Higher the order better the BC must do

About the friction

- High sensiblity for low values
- Low sensibility for higher values
- Regular, periodic solutions for high friction values
- The better you do (order and BC), sensibility for higher values increases
  - for 2^{nd} order 2 sponge layers modify the frequency
  - 3^{rd} order needs 2 sponge layers to homogenize the behaviour

About the BC

- The implementation of the BC is crucial
- So sensitive that perturbations must leave, otherwise ...

And finally

- Disappointedly, we do not have A better choice

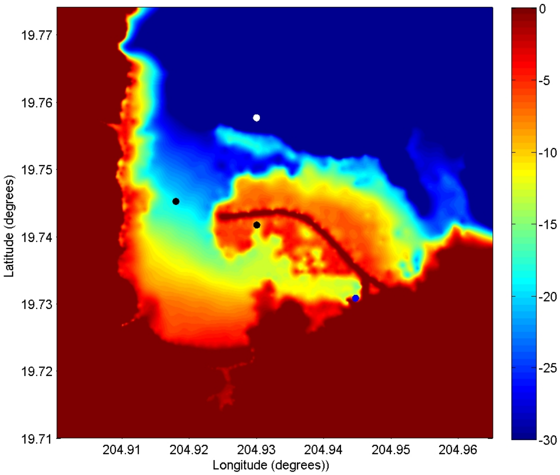
Benchmark Problem 2 - **Hilo Harbor**

Description and Aim

- **Field dataset** - Japan 2011 at Hilo Harbour (Hawaii)
- **Primary goal**: assess **model resolution** and **numerics** on the prediction of tsunami currents
    - Level of precision
    - Convergence (at least 3 resolutions: ≈20 m, ≈10 m and ≈5 m or lower)
    - Variation across different models

Benchmark Problem 2 - Hilo Harbor

Setup - Bathymetry



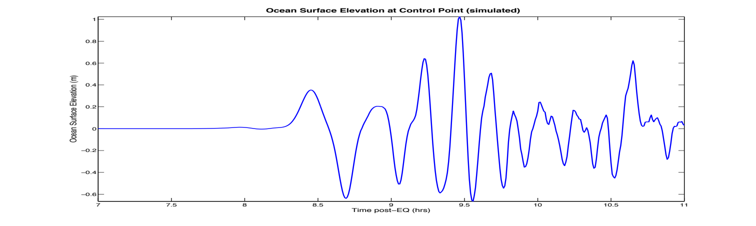
Benchmark Problem 2 - Hilo Harbor

Setup

- Domain: $[204.90, 204.96] \times [19.71, 19.773]$ (approx 7×7 km)
- Data Resolution: 1/3 arcsec ($\approx 10\,m$)
- Mesh: 692×701
- Max depth 30 m
- Manning coefficient $n = 0.025$ (But also $n = 0.030$ and 0.035)

Boundary Condition

- Offshore simulated free surface elevation
- Control point at (19.7576,204.93)
- Modellers chose the forcing



Benchmark Problem 2 - **What we have done**

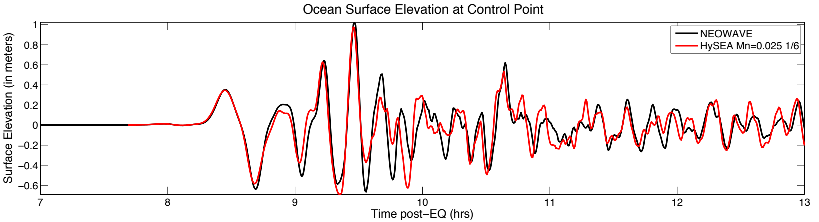
1. **Reduced domain** simulations at different resolutions (aim of the benchmark)
   - Three requested resolutions (2/3, 1/3 and 1/6 arcsec)
   - Sensitivity to friction (n=0.025, 0.030, and 0.035)

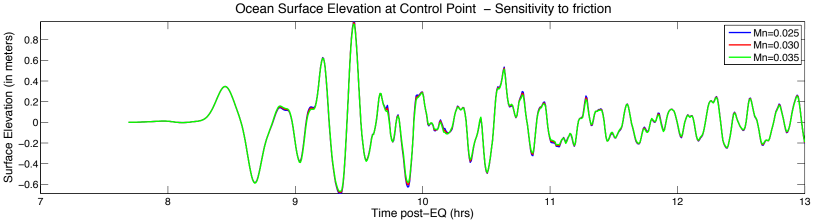
2. **Complete scenario** simulations at different resolutions (encouraged)
   - Three level nested mesh decomposition
   - Finer mesh of 2/3, 1/3 and 1/6 arcsec
   - Varying coarse meshes

Benchmark Problem 2 - Time series at control point

1. Comparison and Sensitivity to Friction

Control Point - [lat,lon] = (19.7576,204.93) - **Res 1/6 - Mn=0.025**

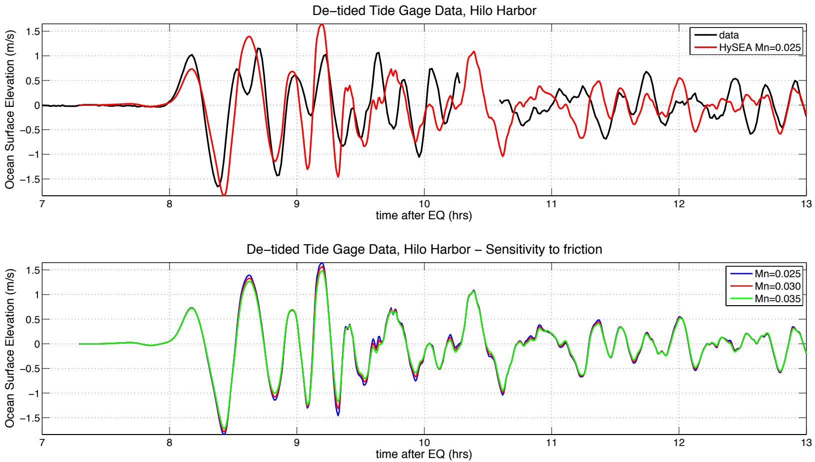




Benchmark Problem 2 - Free surface elevation at the tidal station

1. Comparison and Sensitivity to Friction

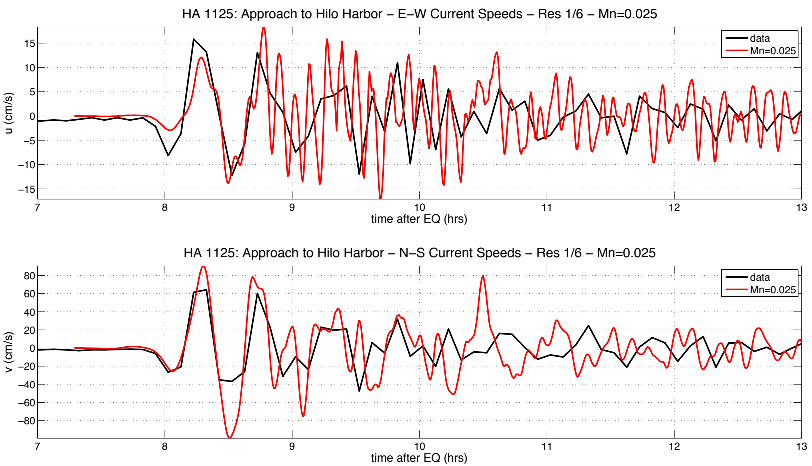
Hilo Tide Station - [lat,lon] = (19.7308,204.9447) - **Res 1/6 - Mn=0.025**



Benchmark Problem 2 - Depth-average horizontal velocity data

1. Comparison

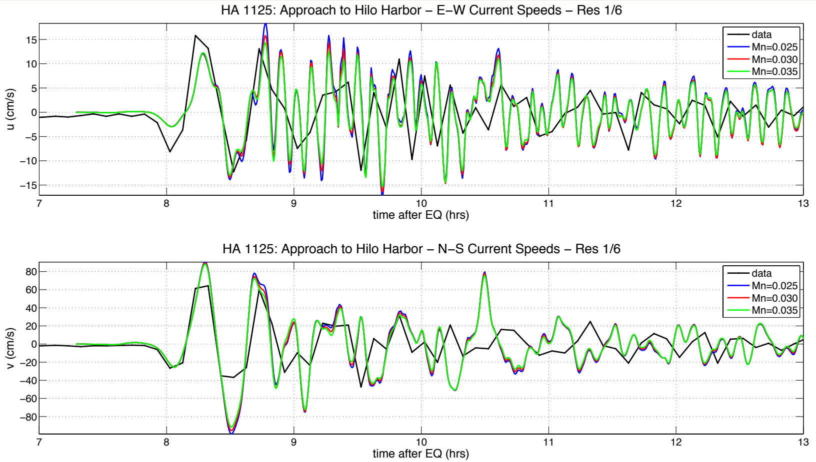
HA1125, Harbour entrance - [lat,lon] = (19.7452,204.9180) - **Res 1/6**



Benchmark Problem 2 - Depth-average horizontal velocity data

1. Sensitivity to Friction

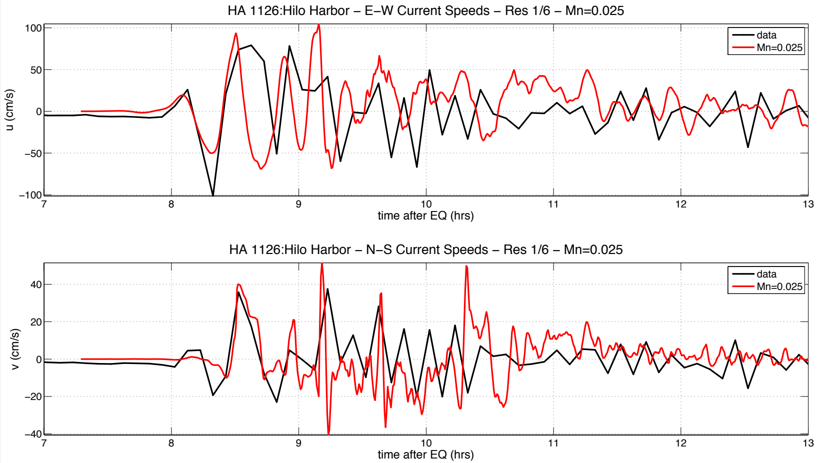
HA1125, Harbour entrance - [lat,lon] = (19.7452,204.9180) - **Res 1/6**



Benchmark Problem 2 - Depth-average horizontal velocity data

1. Comparison

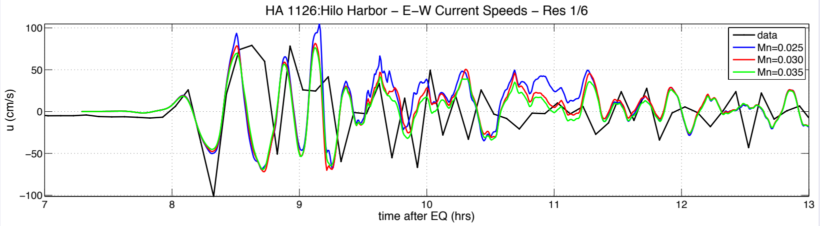
HA1126, Inside Harbour - [lat,lon] = (19.7417,204.9300) - **Res 1/6**

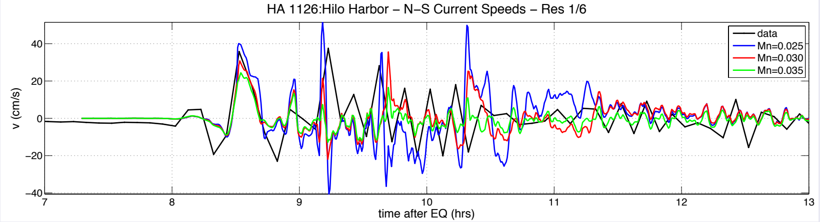


Benchmark Problem 2 - Depth-average horizontal velocity data

1. Sensitivity to Friction

HA1126, Inside Harbour - [lat,lon] = (19.7417,204.9300) - **Res 1/6**

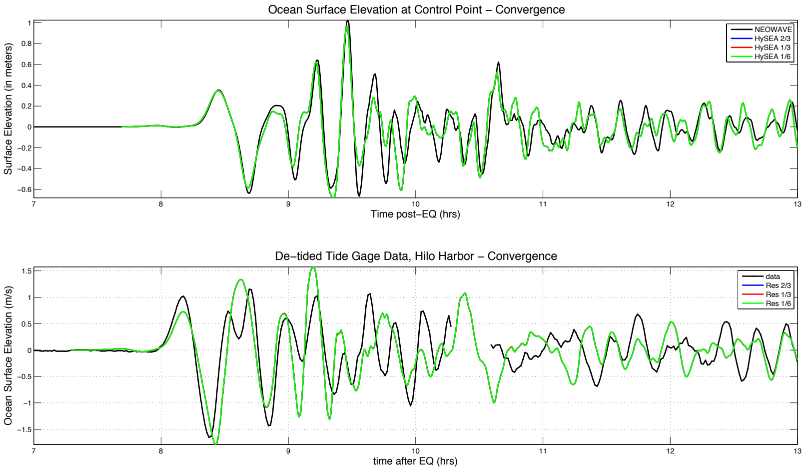




Benchmark Problem 2 - Model Resolution

2. Convergence: Mesh Refinement

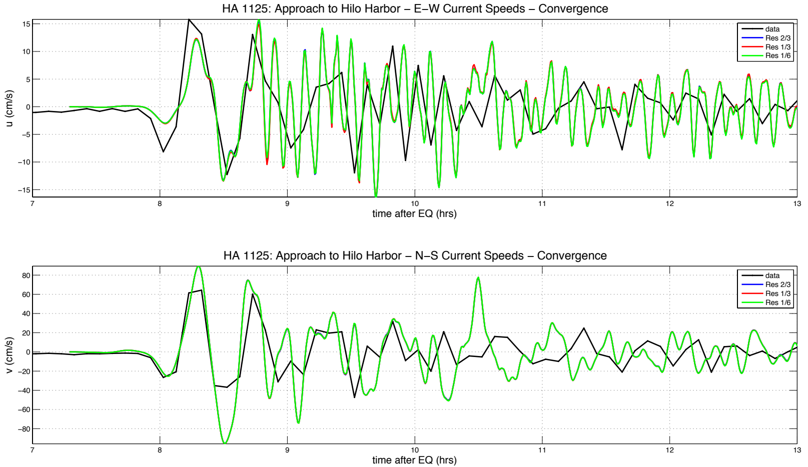
Sea Surface Elevation - Control Point and Hilo Tide Station



Benchmark Problem 2 - Model Resolution

2. Convergence: Mesh Refinement

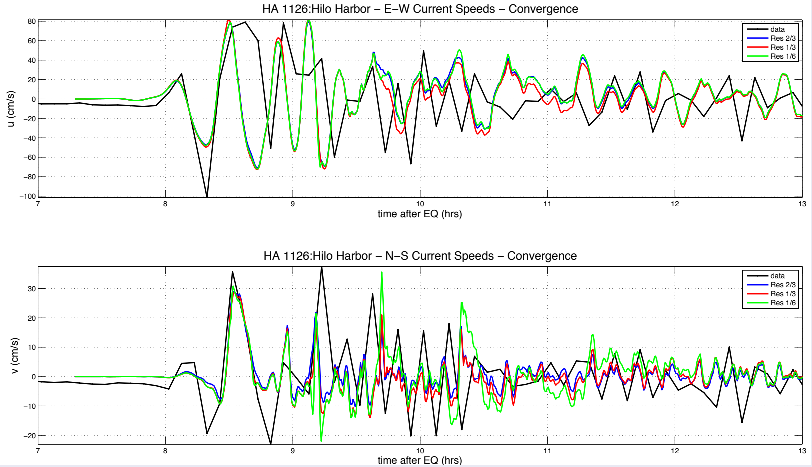
Currents at HA1125, Harbour entrance



Benchmark Problem 2 - Model Resolution

2. Convergence: Mesh Refinement

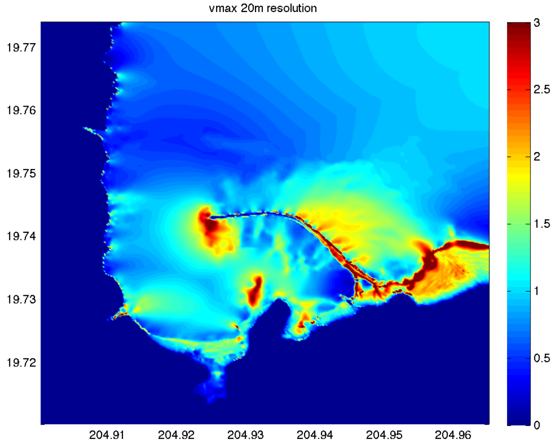
Currents at HA1126, Inside Harbour



Benchmark Problem 2 - Maximum Speed Maps

3. Convergence for Maximum Velocity

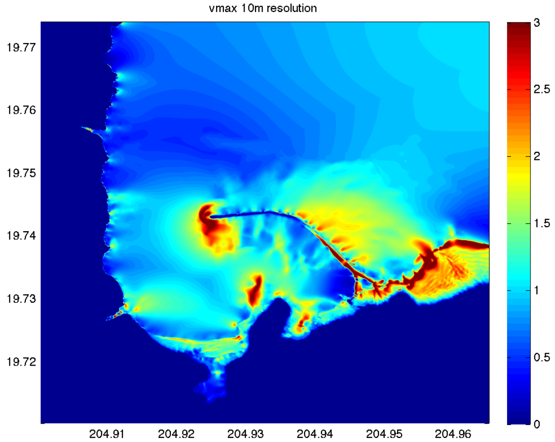
Maximum Speed Map



Benchmark Problem 2 - Maximum Speed Maps

3. Convergence for Maximum Velocity

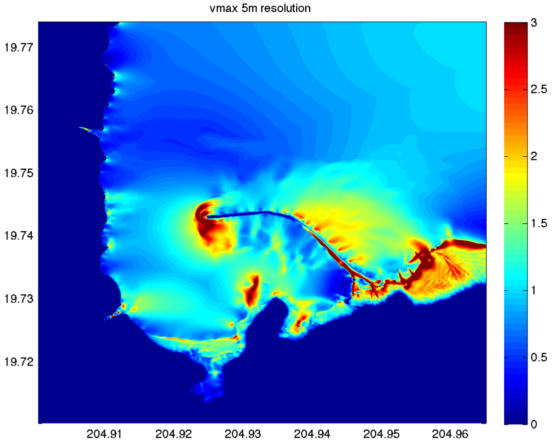
Maximum Speed Map



Benchmark Problem 2 - Maximum Speed Maps

3. Convergence for Maximum Velocity

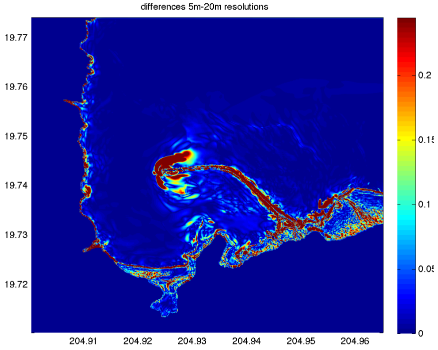
Maximum Speed Map

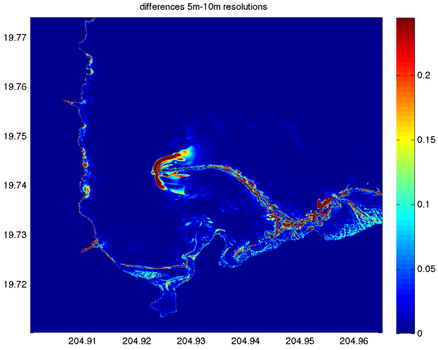


Benchmark Problem 2 - Maximum Speed Maps

3. Convergence for Maximum Velocity

Maximum Difference Speed Maps





Benchmark Problem 2 - **Complete scenario**

2. **Complete scenario** simulations at different resolutions (encouraged)

- Three level nested mesh decomposition
- Coarse ambient mesh 128/3 arc sec
- Intermediate 8/3 arc sec mesh
- Finer meshes of 2/3, 1/3 and 1/6 arcsec (three resolutions)
- But also varying in resolution coarse and intermediate meshes (256/3 and 16/3)
- Two sources (from NOAA and GeoClaw)

Computational domain [130, 206]$\times$[19.35,43]

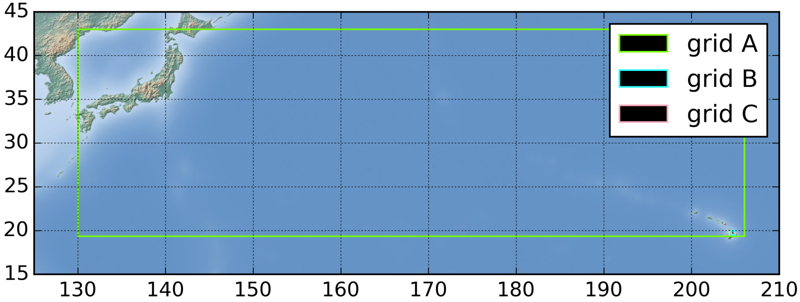
Nested Meshes

Mesh	Resolution	# of cells in lat	# of cells in lon	# of cells	cell size (m)
A	128/3 arc-sec	6,414	1,996	12,802,344	1,280
B	8/3 arc-sec	672	672	451,584	80
C1	2/3 arc-sec	360	352	126,720	20
C2	1/3 arc-sec	720	704	506,880	10
C3	1/6 arc-sec	1,424	1,392	1,982,208	5

Benchmark Problem 2 - Complete scenario

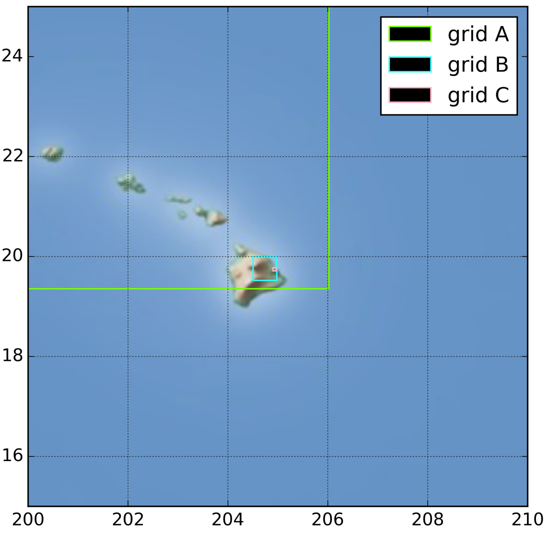
Nested meshes spatial extension

- Three level nested mesh decomposition
- A : [130, 206]×[19.35,43] (128/3 arc sec)
- B : [204.5,204.97]×[19.52,20] (8/3 arc sec)
- C : [204.9, 204.965]×[19.711,19.773] (2/3, 1/3 and 1/6 arcsec)



Benchmark Problem 2 - Complete scenario

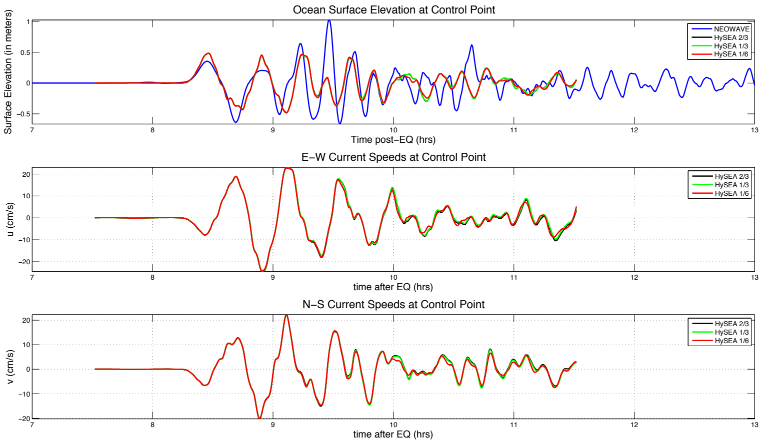
Nested meshes spatial extension



Benchmark Problem 2 - Complete scenario -Time series at control point

1. Sensitivity to mesh refinement - Inner Mesh

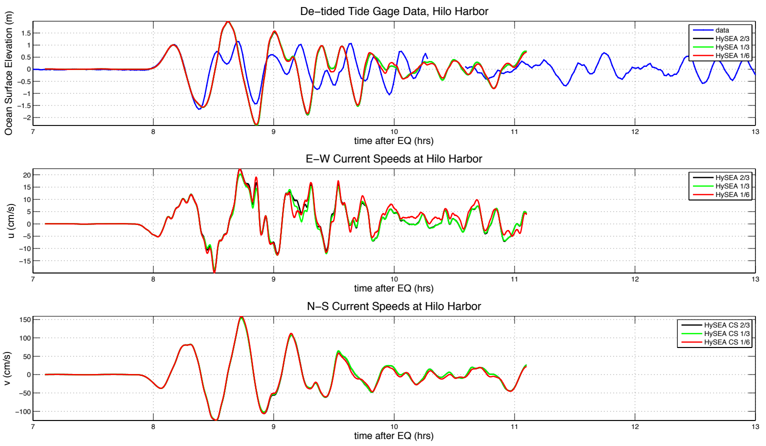
Control Point - [lat,lon] = (19.7576,204.93)



Benchmark Pb 2 - Complete scenario -Time series at the tidal station

1. Sensitivity to mesh refinement - Inner Mesh

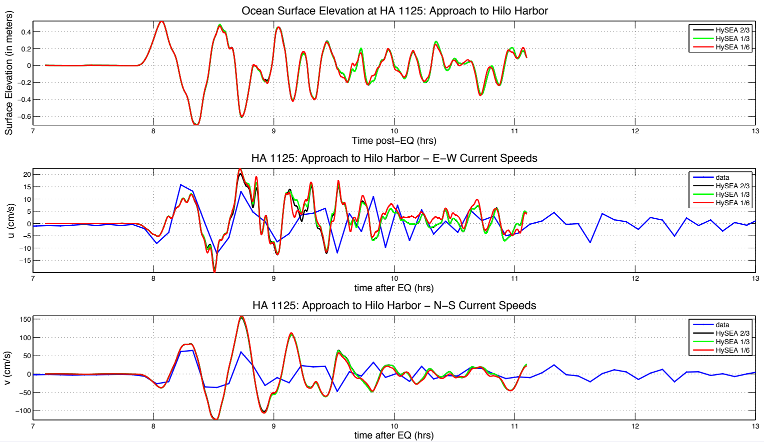
Hilo Tide Station - [lat,lon] = (19.7308,204.9447)



Benchmark Problem 2 - Complete scenario -Time series at HA1125

1. Sensitivity to mesh refinement - Inner Mesh

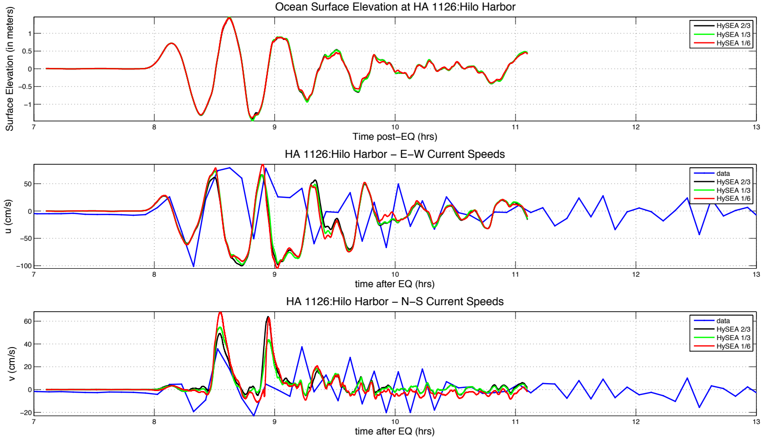
HA1125, Harbour entrance - [lat,lon] = (19.7452,204.9180)



Benchmark Problem 2 - Complete scenario -Time series at HA1126

1. Sensitivity to mesh refinement - Inner Mesh

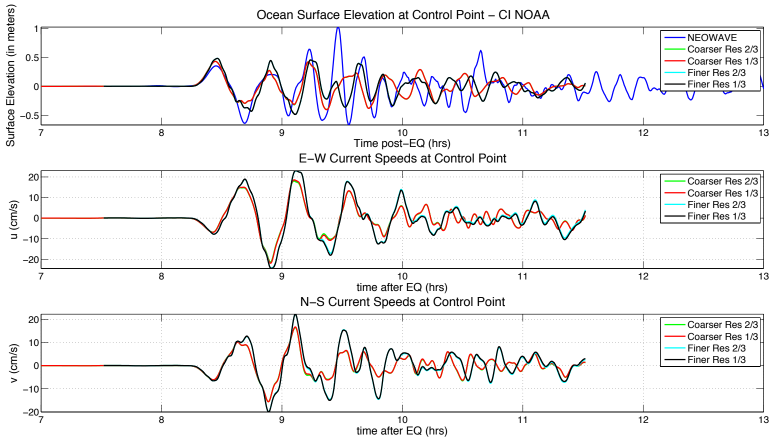
HA1126, Inside Harbour - [lat,lon] = (19.7417,204.9300)



Benchmark Problem 2 - Complete scenario -Time series at control point

2. Sensitivity to mesh refinement - Ambient and Intermediate Meshes

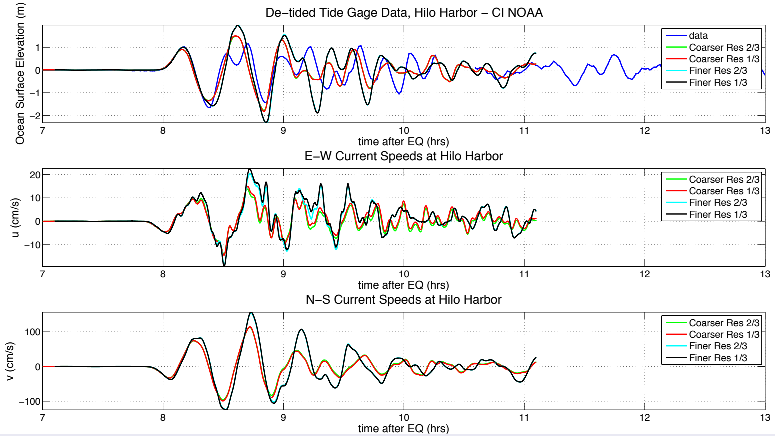
Control Point - [lat,lon] = (19.7576,204.93)



Benchmark Pb 2 - Complete scenario -Time series at the tidal station

2. Sensitivity to mesh refinement - Ambient and Intermediate Meshes

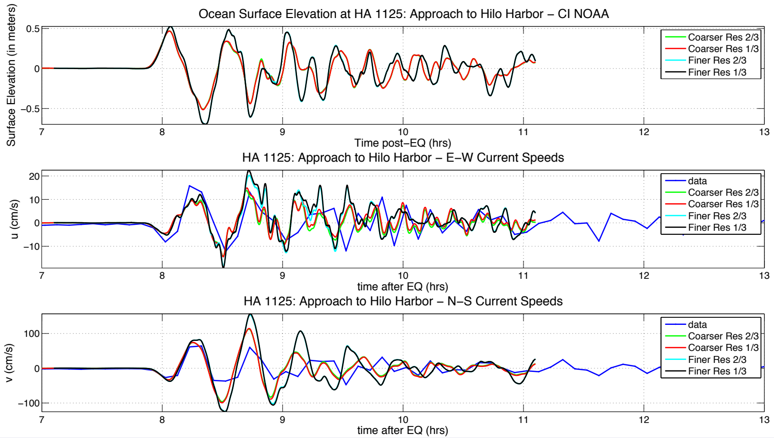
Hilo Tide Station - [lat,lon] = (19.7308,204.9447)



Benchmark Problem 2 - Complete scenario -Time series at HA1125

2. Sensitivity to mesh refinement - Ambient and Intermediate Meshes

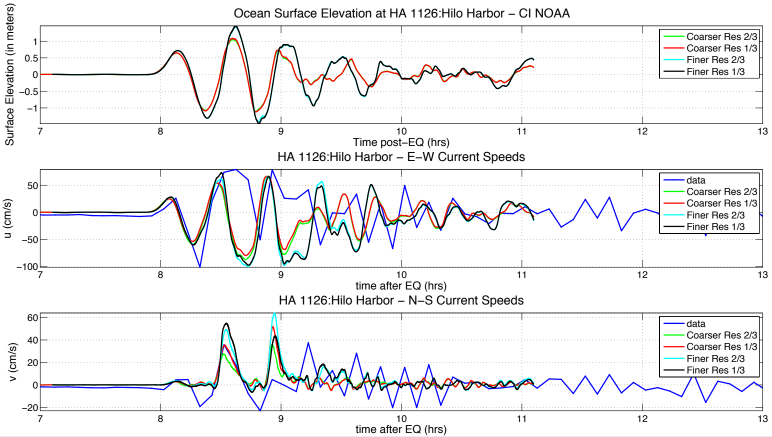
HA1125, Harbour entrance - [lat,lon] = (19.7452,204.9180)



Benchmark Problem 2 - Complete scenario -Time series at HA1126

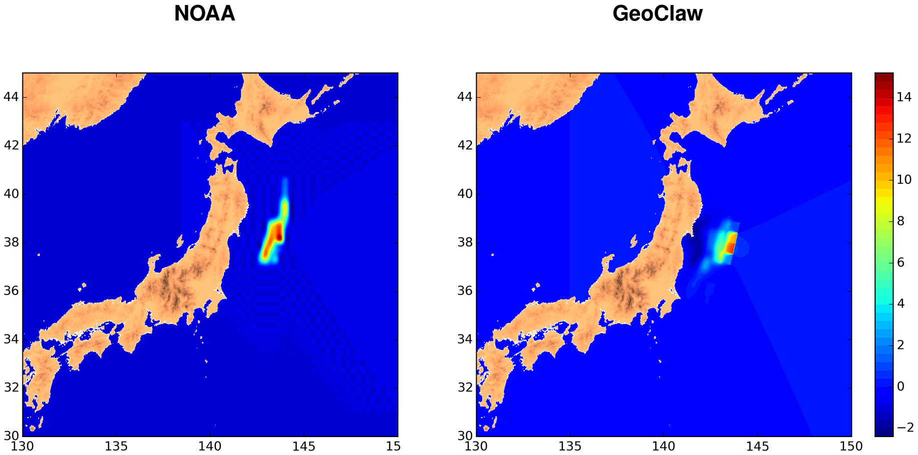
2. Sensitivity to mesh refinement - Ambient and Intermediate Meshes

HA1126, Inside Harbour - [lat,lon] = (19.7417,204.9300)



Benchmark Problem 2 - Complete scenario - Initial Conditions

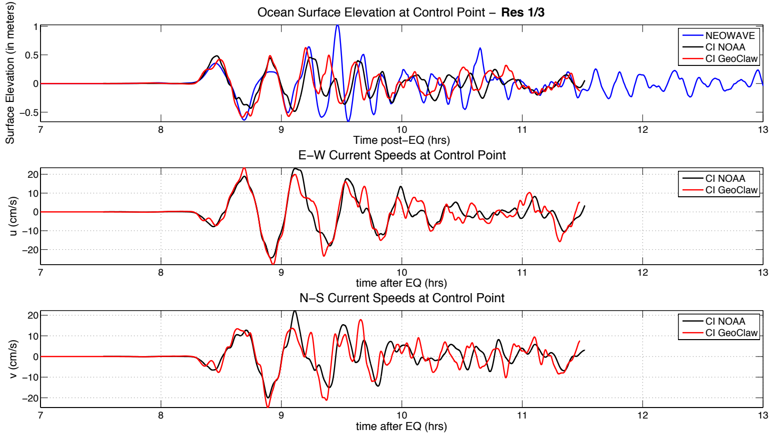
3. Two Sources as Initial Condition (NOAA and GeoClaw)



Benchmark Problem 2 - Complete scenario - Time series at control

3. Two Sources as Initial Condition (NOAA and GeoClaw)

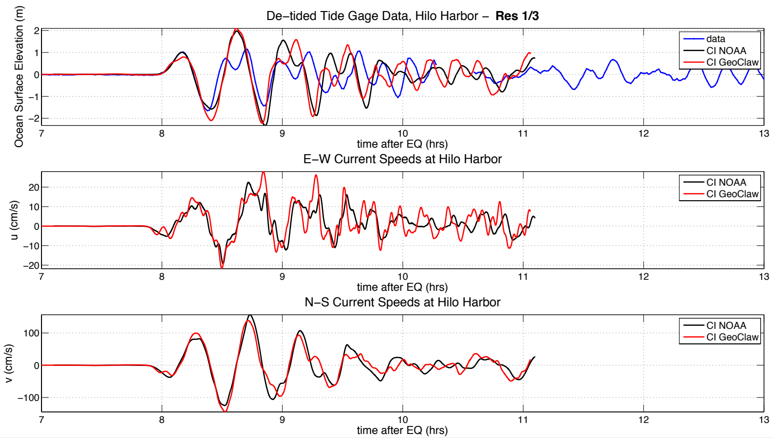
Control Point - [lat,lon] = (19.7576,204.93)



Benchmark Pb 2 - Complete scenario - Time series at the tidal station

3. Two Sources as Initial Condition (NOAA and GeoClaw)

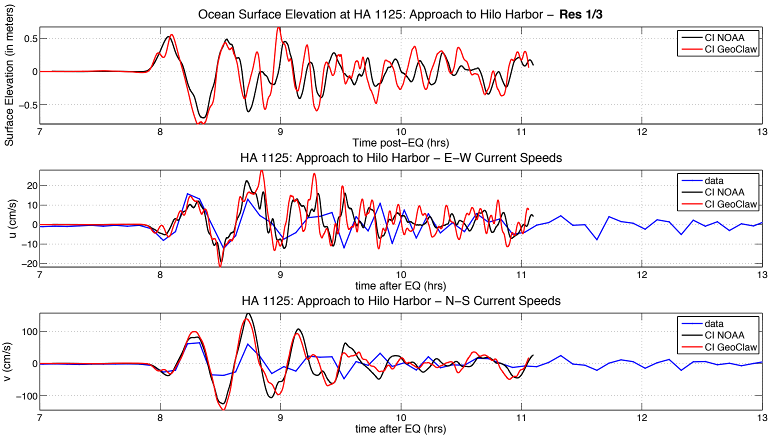
Hilo Tide Station - [lat,lon] = (19.7308,204.9447)



Benchmark Problem 2 - Complete scenario - Time series at HA1125

3. Two Sources as Initial Condition (NOAA and GeoClaw)

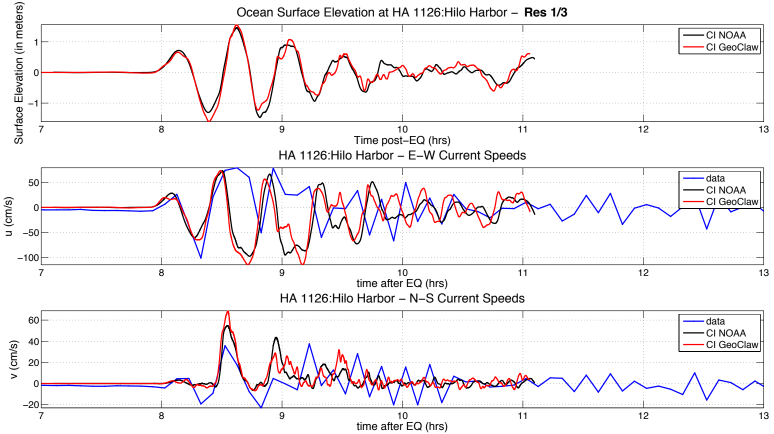
HA1125, Harbour entrance - [lat,lon] = (19.7452,204.9180)



Benchmark Problem 2 - Complete scenario - Time series at HA1126

3. Two Sources as Initial Condition (NOAA and GeoClaw)

HA1126, Inside Harbour - [lat,lon] = (19.7417,204.9300)



Benchmark Problem 3 - Tauranga Harbour

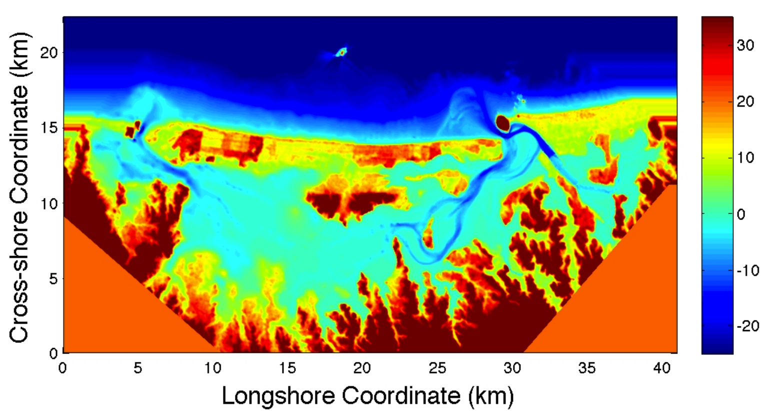
Description and Aim

- **Field dataset** - Japan 2011 in Tauranga Habour (New Zealand)
- Aim: **Attempt to include effects of tides**

Observed Data

Benchmark Problem 3 - Tauranga Harbour

Setup - Bathymetry



Benchmark Problem 3 - Tauranga Harbour

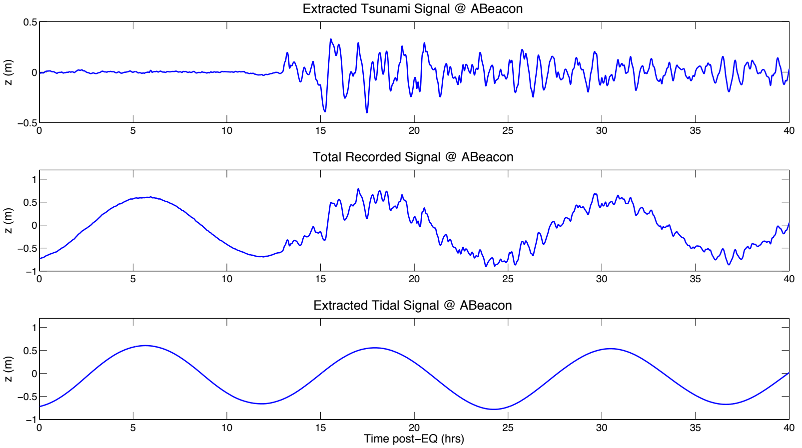
Setup

- Domain: $[0, 40000] \times [0, 20000]$ in meters (rotated) - 40 km $\times$ 20 km
- Data Resolution: 10 m
- Numerical resolution: 20 m (a$\times$b)

Benchmark Problem 3 - Tauranga Harbour

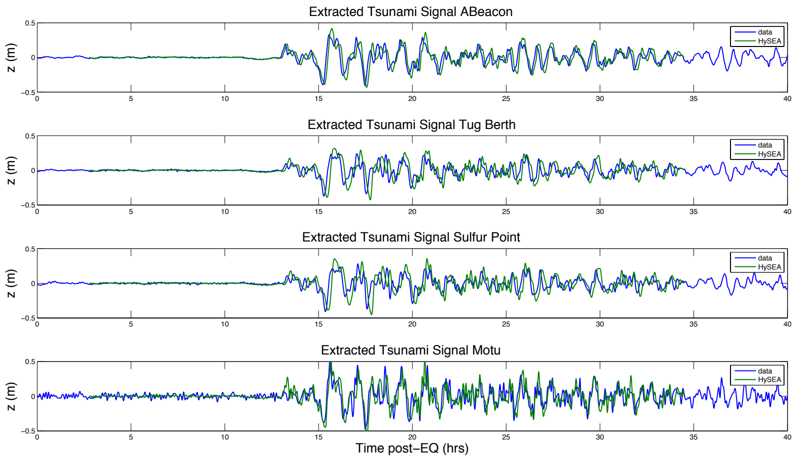
Setup - Boundary Condition

- Use most offshore measured free surface elevation data (ABeacon tide gage)



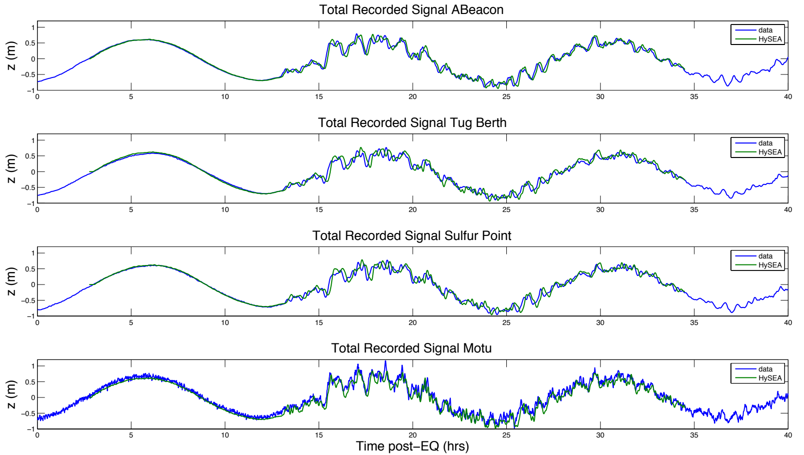
Benchmark Problem 3 - **Free surface elevation at the 4 tidal stations**

Tsunami-Only signal



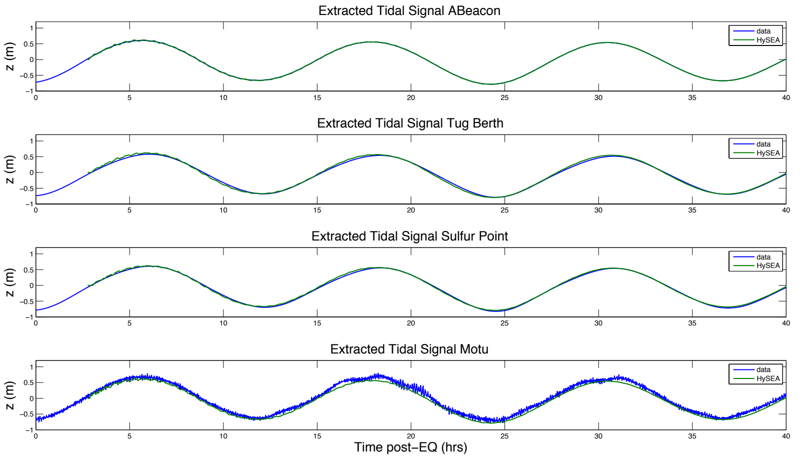
Benchmark Problem 3 - **Free surface elevation at the 4 tidal stations**

Tsunami + Tide signal



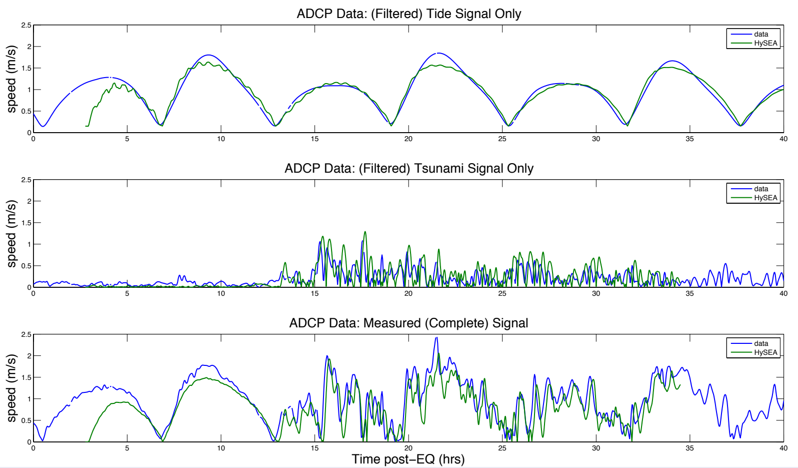
Benchmark Problem 3 - **Free surface elevation at the 4 tidal stations**

Tide-Only signal



Benchmark Problem 3 - **Depth-Average Horizontal Velocity data**

ADCP: [lat,lon] = (-37.6307,176.18377) - [x,y] = (29250,14660) (rotated)

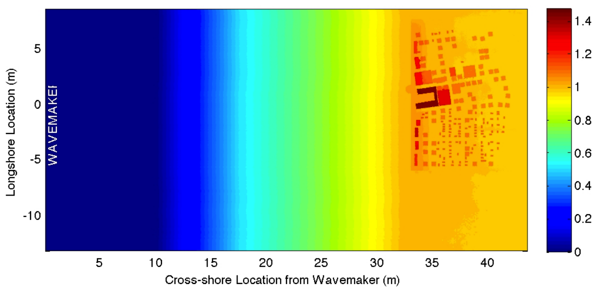


Benchmark Problem 4 - Seaside (Oregon)

Description

- Single long-period wave
- Piecewise linear slope and small scale model of Seaside (Oregon)
- Free surface information
- Velocity information

Setup - Bathymetry

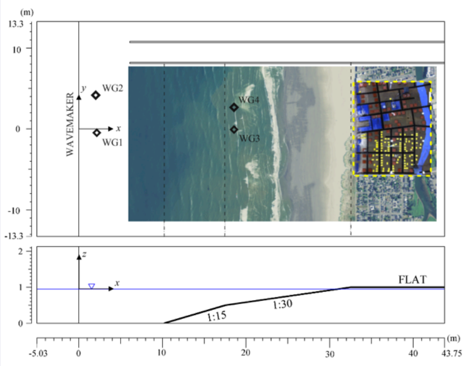


Benchmark Problem 4 - Seaside (Oregon)

Setup

- Domain: $[0.012, 43.633] \times [-13.261, 8.549]$ in meters (43.621×21.81 meters)
- Data Resolution: 0.01 m
- Mesh: 4363×2182

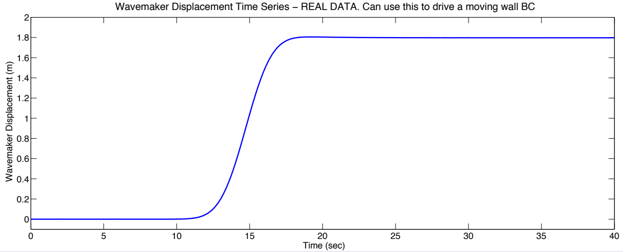
Physical Model



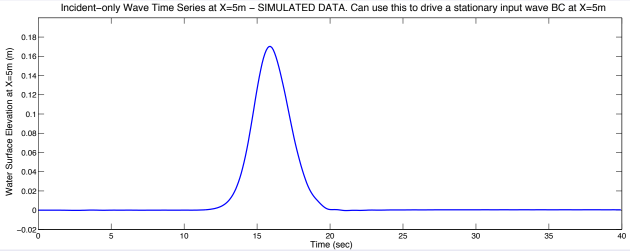
Benchmark Problem 4 - Seaside (Oregon)

Setup - Boundary Condition

- Wavemaker

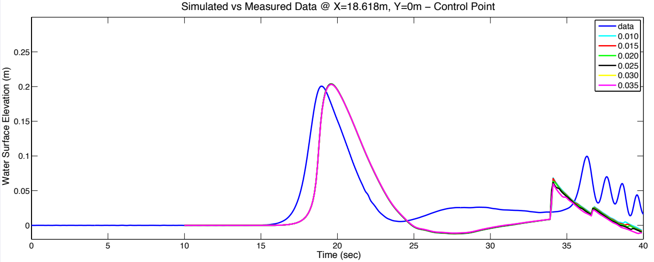


- **Incident wave time series at x=5 m**



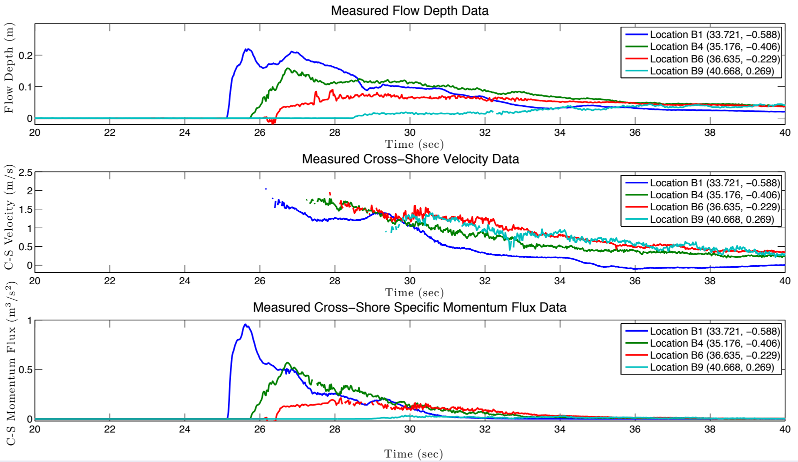
Benchmark Problem 4 - Seaside (Oregon)

Water surface elevation at WG3



Benchmark Problem 4 - Seaside (Oregon)

Measured Data at B1, B4, B6, B9 (Flow Depth - Velocity - Specific Momentum Flux)

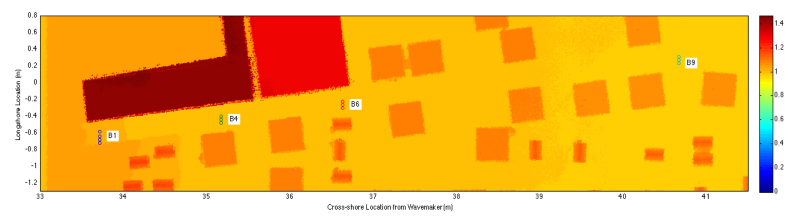


Benchmark Problem 4 - Seaside (Oregon)

What we have done

- Numerical Resolution: 1 and 2 cm
- Numerical scheme: Order 1, 2 and WAF (Order 2 presented)
- Varying friction (from 0.01 to 0.035)
- Spatial variability (4 cm distance)

Spatial Variability



Benchmark Problem 4 - Seaside (Oregon)

What we have done

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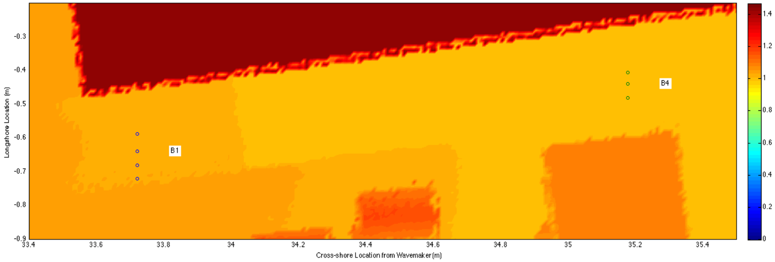
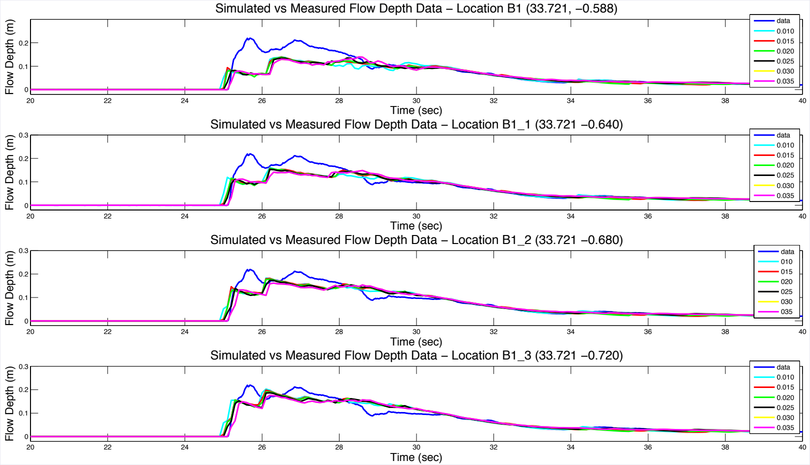
Spatial Variability



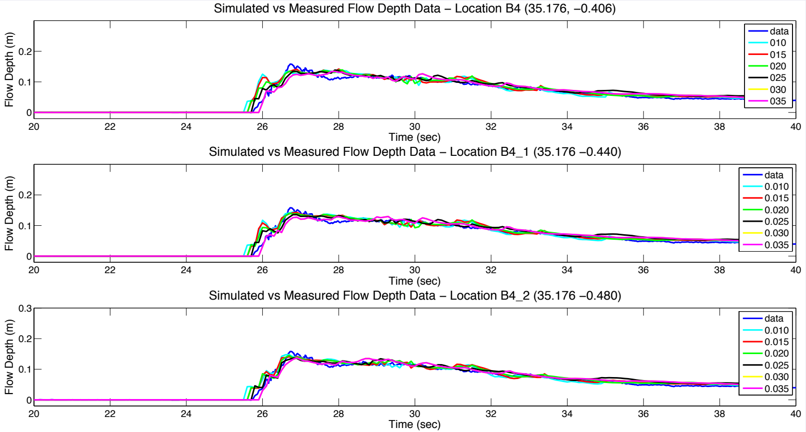
Benchmark Problem 4 - Seaside (Oregon)

Flow Depth Spatial Variability for all the “B1” points



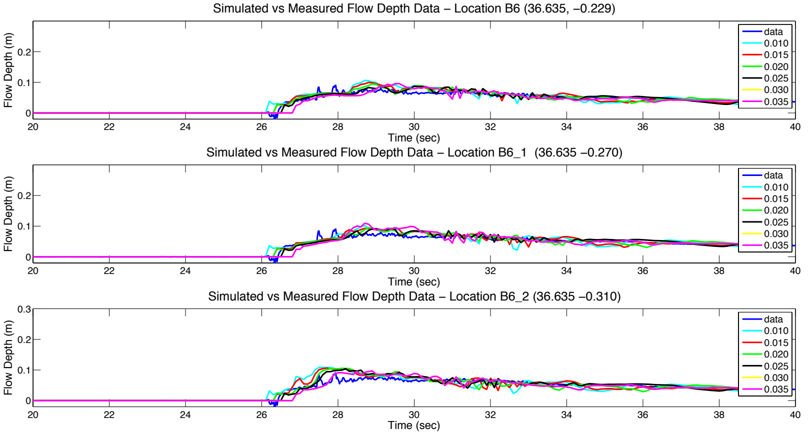
Benchmark Problem 4 - Seaside (Oregon)

Flow Depth Spatial Variability for all the “B4” points



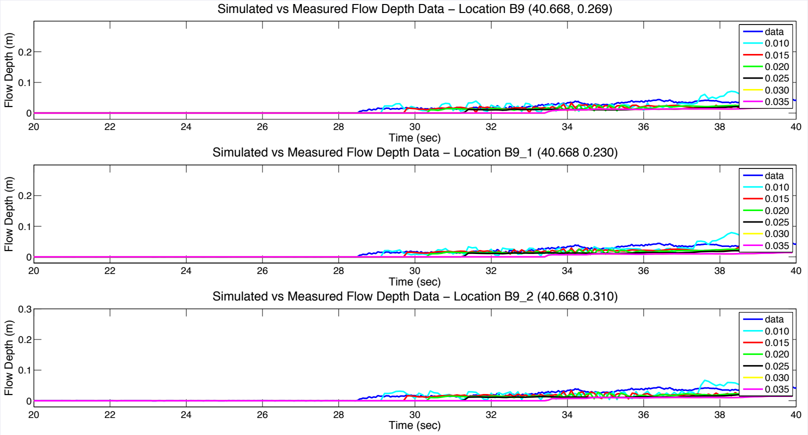
Benchmark Problem 4 - Seaside (Oregon)

Flow Depth Spatial Variability for all the "B6" points



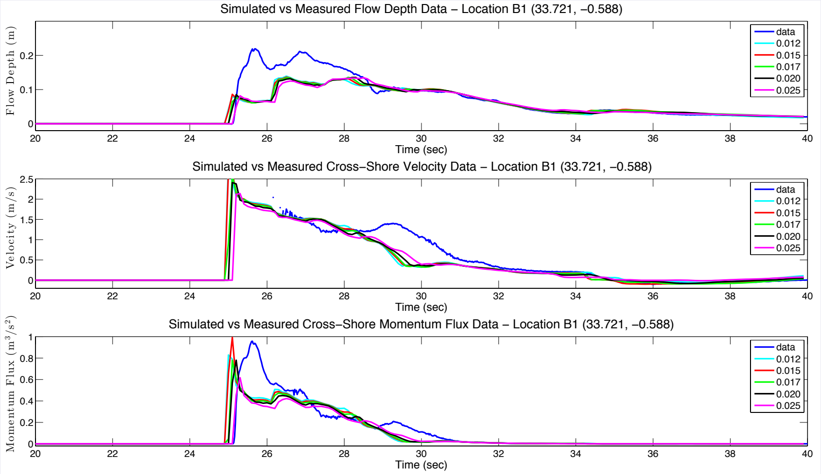
Benchmark Problem 4 - Seaside (Oregon)

Flow Depth Spatial Variability for all the “B9” points



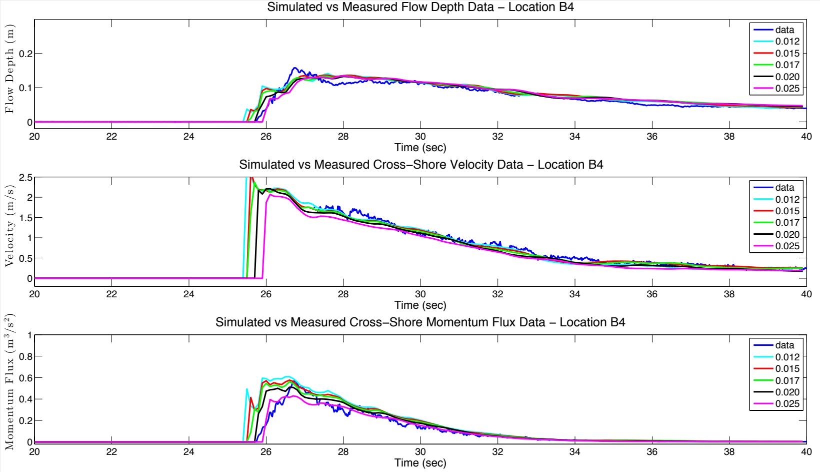
Benchmark Problem 4 - Seaside (Oregon)

Simulated vs Measured Data comparison at B1



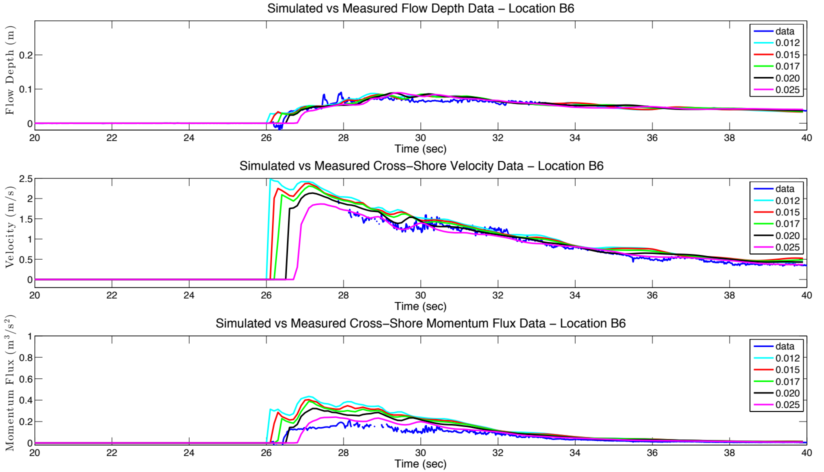
Benchmark Problem 4 - Seaside (Oregon)

Simulated vs Measured Data comparison at B4



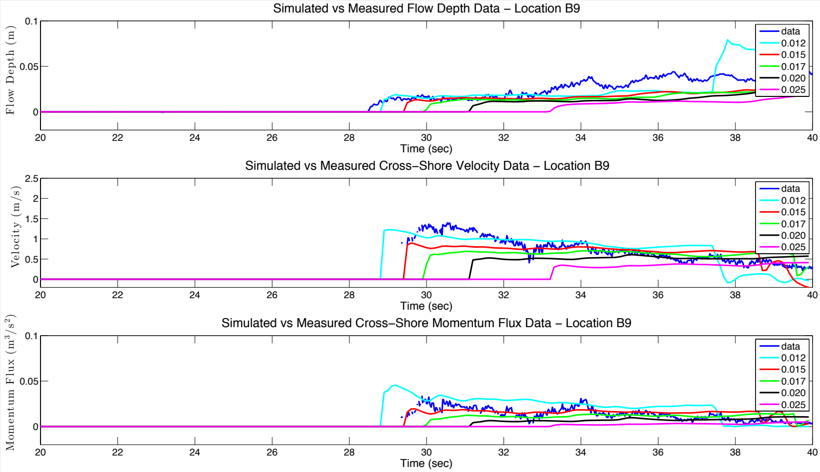
Benchmark Problem 4 - Seaside (Oregon)

Simulated vs Measured Data comparison at B6



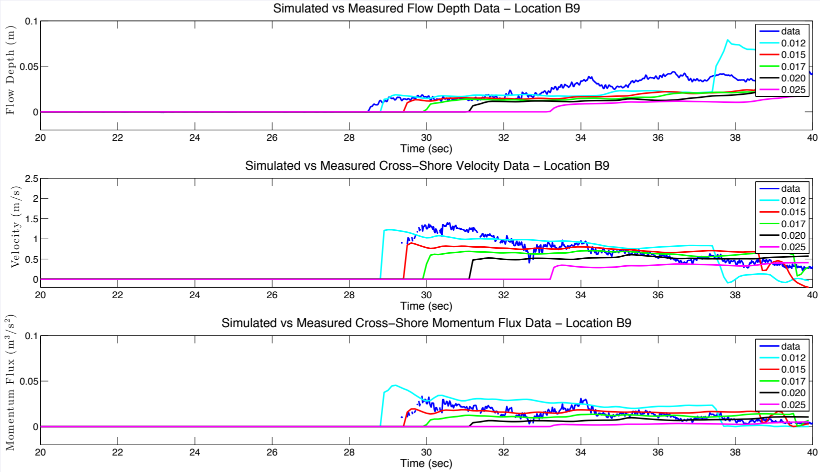
Benchmark Problem 4 - Seaside (Oregon)

Simulated vs Measured Data comparison at B9



Benchmark Problem 4 - Seaside (Oregon)

Simulated vs Measured Data comparison at B9



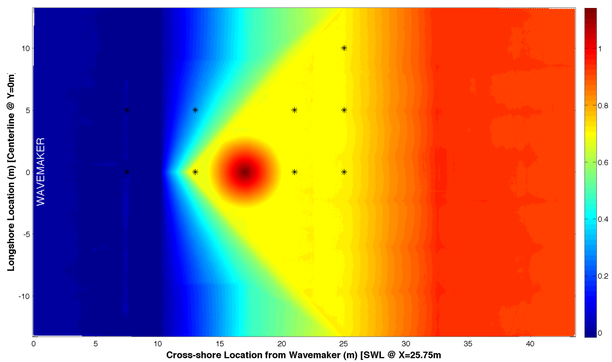
Benchmark Problem 5

Setup

- Single solitary wave
- Triangular shaped shelf with an island
- Free surface information
- Velocity information

Benchmark Problem 5

Setup - Bathymetry



Bathymetric Data

- Approx. Domain: $[-0.1, 44.6] \times [-13, 13]$ in meters (43.744×26.554 m)
- Data Resolution: $\Delta x = 0.0438$ m - $\Delta y = 0.0266$ m
- Mesh: $1,000 \times 1,000$

Benchmark Problem 5

Model Set-up

- Extended domain $[-9, 44.6] \times [-13, 13]$
- Initial Condition:
  - Imposed surface elevation (soliton) from Tonelli and Petti (2009):

$$\eta(x, t = 0) = A \, \text{sech} \left[(x - x_0) \sqrt{3A/(4H^3)} \right]$$

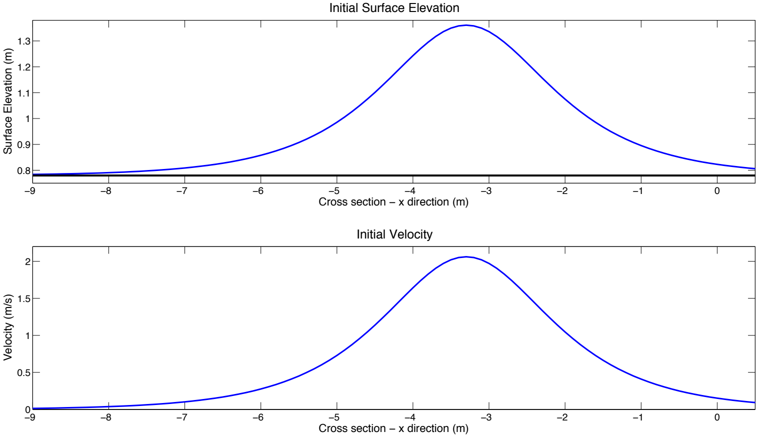
  - Velocity Correction:

$$u(x, 0) = \eta(x, 0) \sqrt{gH}/H$$

  with $x_0 = -3.3$ m; $A = 0.39$ m; $H = 0.78$ m; $g = 9.81$ m/s.
- Initial condition:
  - $h(x, y, 0) = \eta(x, 0) + 0.78$,
  - $q_x(x, y, 0) = h(x, y, 0)\, u(x, 0)$
  - $q_y = 0.0$
- Time of simulation: 20 s

Benchmark Problem 5

Setup - Initial Condition



Benchmark Problem 5

What we have done

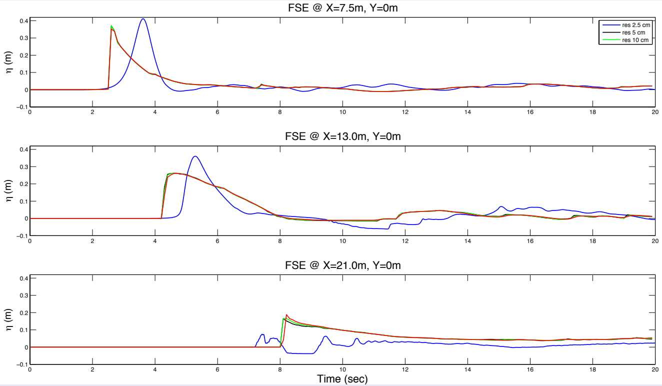
- SW non-dispersive
  - Test order (2^{nd} and 3^{rd})
  - Mesh resolution (2.5 cm, 5 cm, 10 cm)
  - Friction (from 0.005 to 0.035)
- SW Dispersive (beta version)
  - 3^{rd} order
  - Resolution 10 cm (490×260)
  - Friction (from 0.005 to 0.035)

Some preliminary conclusions

- Dispersion is mandatory
- Friction is mostly felt in the points behind the obstacle (more if just behind)

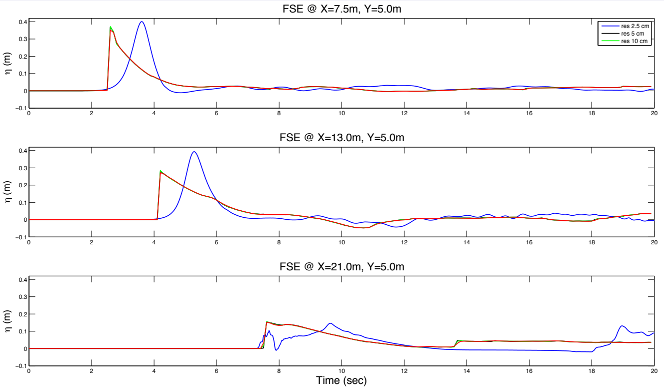
Benchmark Problem 5. Mesh resolution

SW non-dispersive - **Three resolutions** (2.5 cm, 5 cm, 10 cm) - 3rd order - Fric 0.025



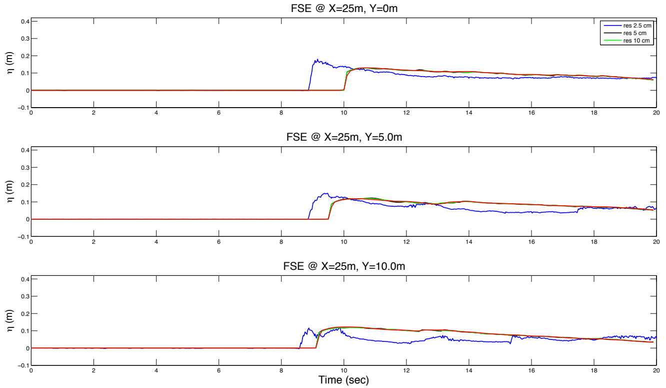
Benchmark Problem 5. Mesh resolution

SW non-dispersive - **Three resolutions** (2.5 cm, 5 cm, 10 cm) - 3rd order - Fric 0.025



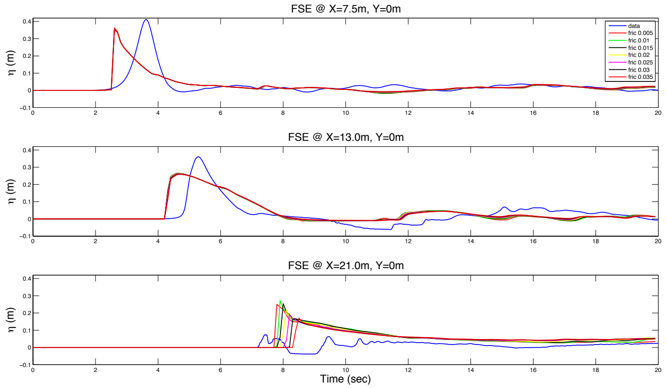
Benchmark Problem 5. Mesh resolution

SW non-dispersive - **Three resolutions** (2.5 cm, 5 cm, 10 cm) - 3rd order - Fric 0.025



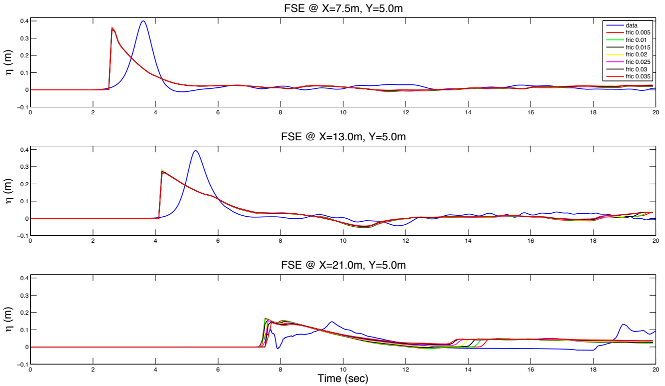
Benchmark Problem 5 - **Sensitivity to friction**

SW non-dispersive - 3rd order - Res 10 cm - Varying friction



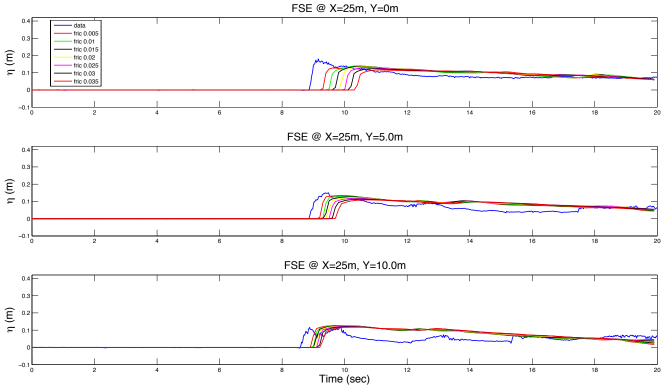
Benchmark Problem 5 - **Sensitivity to friction**

SW non-dispersive - 3rd order - Res 10 cm - Varying friction



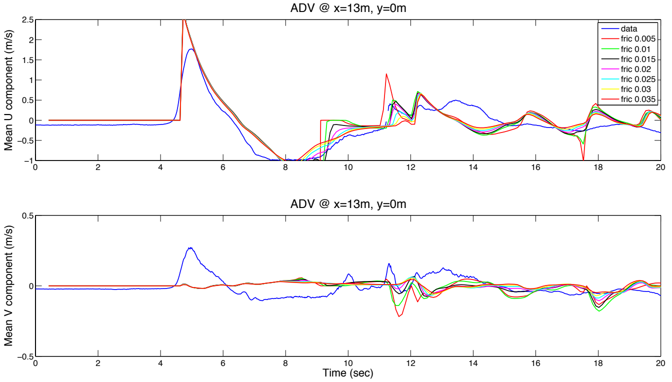
Benchmark Problem 5 - **Sensitivity to friction**

SW non-dispersive - 3^{rd} order - Res 10 cm - Varying friction



Benchmark Problem 5. Dispersion - **Sensitivity to friction**

SW non-dispersive - 3rd order - Res 10 cm - Varying friction



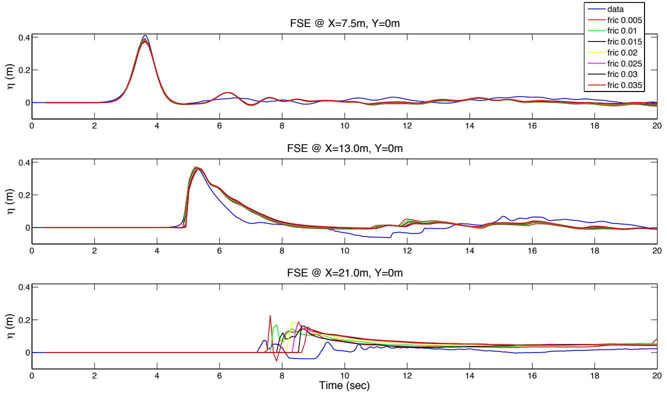
Benchmark Problem 5 - SW Dispersive

Dispersion model - Madsen and Sorensen (1992)

- Dispersion coefficient: 1/21
- Breaking wave criteria (based on Kazolea, Delis and Synolakis, 2014). Dispersion is locally applied when:
  - $h_i > h_{eps}$ and
  - $|\partial_t \eta_i| < \gamma \sqrt{g\, h_i}$ with $\gamma = 0.65$
  - $(\partial_x \eta_i)^2 + (\partial_y \eta_i)^2 < \tan^2(\phi_c)$ with $\phi_c = 33^\circ$

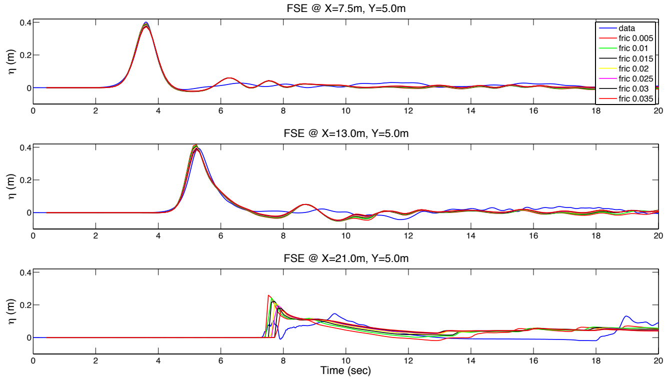
Benchmark Problem 5. Dispersion - Sensitivity to friction

Dispersive SW - 3rd order - Res 10 cm - Varying friction



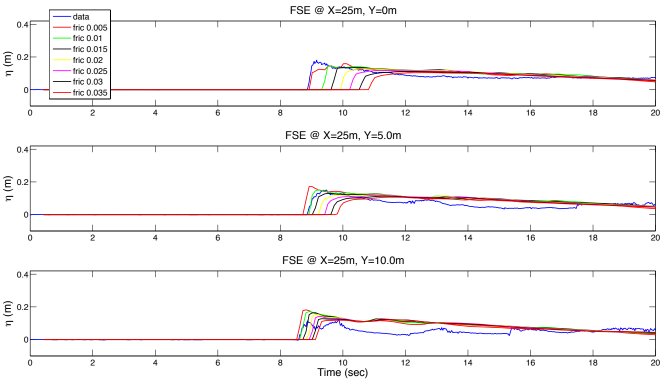
Benchmark Problem 5. Dispersion - Sensitivity to friction

Dispersive SW - 3rd order - Res 10 cm - Varying friction



Benchmark Problem 5. Dispersion - Sensitivity to friction

Dispersive SW - 3rd order - Res 10 cm - Varying friction



Benchmark Problem 5. Dispersion - Varying friction

Dispersive SW - 3rd order - Res 10 cm - Varying friction