ICCE 2018

36TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING 2018

Baltimore, Maryland | July 30 – August 3, 2018

The State of the Art and Science of Coastal Engineering

ICCE 2018

36TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING 2018

Baltimore, Maryland | July 30 – August 3, 2018

The State of the Art and Science of Coastal Engineering

EFFECT OF FRICTION IN TSUNAMI INUNDATION MODELLING

Deniz Velioglu Sogut, Dr.

Department of Civil Engineering, Stony Brook University, Stony Brook, NY

Ahmet Cevdet Yalciner, Prof.

Ocean Engineering Research Center, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

INTRODUCTION

Numerous numerical codes to be used for simulating flood and inundation

- Flow 3D simulates linear and nonlinear propagating surface waves as well as long waves by solving three-dimensional Navier-Stokes (3D-NS) equations

FLOW-3D®
THEORETICAL FRAMEWORK

The VOF technique:

The fractional volume is represented by a quantity F → $0 < F < 1$

$F = 1$: interior regions of liquid

$F = 0$: the liquid-free regions

Any element having an F value between 0 and 1 contains a surface

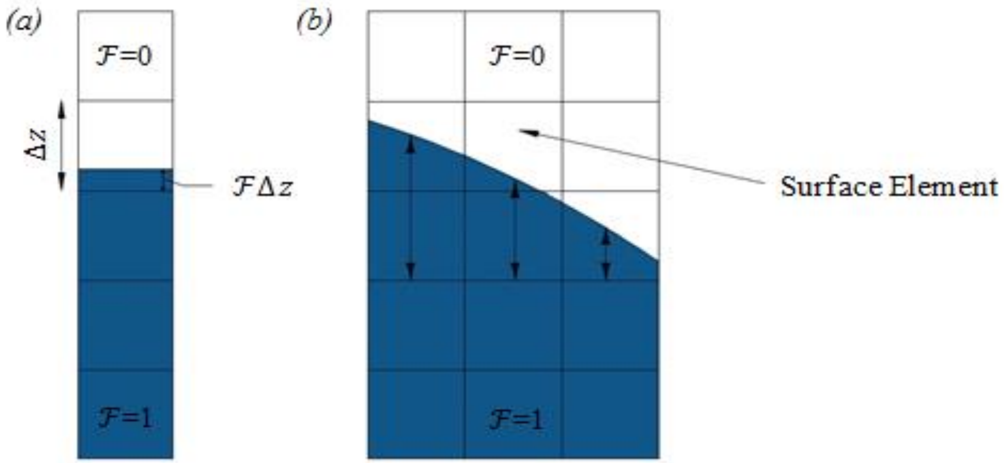


Figure 1. Details of the VOF technique: *(a)* surface in one-dimensional column of elements; *(b)* surface in two-dimensional grid of elements (Flow Science, 2002)

FLOW-3D®
THEORETICAL FRAMEWORK

Structured Mesh

<u>Multiple mesh blocks</u>

- *Linked mesh blocks:*

Mesh the areas of interest and limit the total number of computational cells

- *Nested mesh blocks:*

Enhance the resolution around an area of interest

- *Conforming and partially overlapping mesh blocks:*

Resolve irregularly shaped features with sharp changes in scale

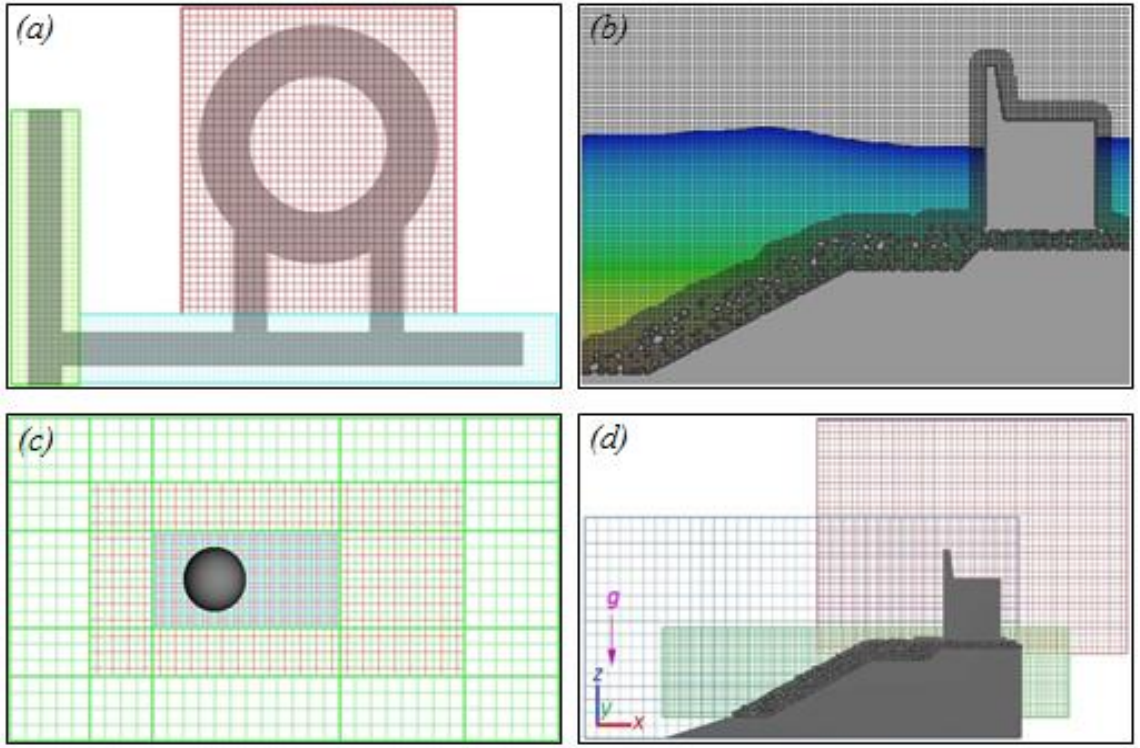


Figure 2. FLOW-3D® meshing techniques: (a) linked mesh; (b) conforming mesh, (c) nested mesh; (d) partially overlapping mesh (Flow Science, 2002)

FLOW-3D®
THEORETICAL FRAMEWORK

Solids → STereoLithography (STL) format

The STL files are produced using various types of Computer-aided Design (CAD) software

Terrain data → Raster file format known as the ESRI ASCII

To describe fluid motion:

- 3D mass continuity and momentum (Navier–Stokes) equations
- Finite difference/Finite volume method
- Cartesian coordinate system (x, y, z)

FLOW-3D®
THEORETICAL FRAMEWORK

Continuity equation for incompressible fluids - ρ is constant:

$$\frac{\partial}{\partial x}(uA_x)+\mathcal{R}\frac{\partial}{\partial y}(vA_y)+\frac{\partial}{\partial z}(wA_z)+\xi\frac{uA_x}{x}=\frac{R_{SOR}}{\rho}$$

The *equations of motion* for the fluid velocity components (u,v,w) in x, y and z directions:

$$\frac{\partial u}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x}+vA_y\mathcal{R}\frac{\partial u}{\partial y}+wA_z\frac{\partial u}{\partial z}\right\}-\xi\frac{A_y v^2}{xV_F}$$
$$=-\frac{1}{\rho}\frac{\partial P}{\partial x}+G_x+\mathrm{f}_x-b_x-\frac{R_{SOR}}{\rho V_F}(u-u_w-\Delta u_s)$$

$$\frac{\partial v}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial v}{\partial x}+vA_y\mathcal{R}\frac{\partial v}{\partial y}+wA_z\frac{\partial v}{\partial z}\right\}+\xi\frac{A_y uv}{xV_F}$$
$$=-\frac{1}{\rho}\left(\mathcal{R}\frac{\partial P}{\partial y}\right)+G_y+\mathrm{f}_y-b_y-\frac{R_{SOR}}{\rho V_F}(v-v_w-\Delta v_s)$$

$$\frac{\partial w}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial w}{\partial x}+vA_y\mathcal{R}\frac{\partial w}{\partial y}+wA_z\frac{\partial w}{\partial z}\right\}$$
$$=-\frac{1}{\rho}\frac{\partial P}{\partial z}+G_z+\mathrm{f}_z-b_z-\frac{R_{SOR}}{\rho V_F}(w-w_w-\Delta w_s)$$

where

u, v and w are the water particle velocities

P is pressure

V_F is the fractional volume open to flow

A_x, $A_y$and A_z are the fractional areas

R_{SOR} is a mass source

G_x, G_y and G_z are body accelerations

f_x, f_y and f_z are viscous accelarations

b_x, b_y and b_z are the flow losses across porous media

u_w, v_w and w_w are the velocity of the mass source component

u_s, v_s and w_s are the fluid velocities at the surface of the mass source

ξ is a coefficient and $\xi = 0$ in Cartesian geometry

$\mathcal{R}$ is a coefficient and is unity in Cartesian coordinate system

FLOW-3D®
THEORETICAL FRAMEWORK

- Time history of water surface fluctuation data
- An initial wave profile at the boundary
- Generate periodic linear and nonlinear waves such as cnoidal wave, Stokes' wave and solitary wave

Wave generation modules:

i. Periodic Linear Waves → Airy's linear wave theory

ii. Stokes' Wave → 5th order Stokes' wave theory (Fenton, 1985)

iii. Cnoidal Wave → Fenton's Fourier series method (Fenton, 1999)

iv. Random Wave → *Pierson-Moskowitz (P-M)* and *JONSWAP spectrums*

v. Solitary Wave → McCowan's theory (McCowan, 1891)

FLOW-3D®
THEORETICAL FRAMEWORK

STABILITY

FLOW-3D® automatically adjusts the time step size to be as large as possible without exceeding any of the stability limits and affecting accuracy

The time step size stability condition:

- Surface waves should not propagate more than one cell in one time step
- In case of shallow water flows, the time step stability limit is controlled by the surface wave speed, which is evaluated from the depth of the fluid, $F\Delta z$:

$$\Delta t < 0.5 \frac{min\{\Delta x_{\mathrm{i}}, \Delta y_{\mathrm{j}}\}}{\sqrt{F \Delta z_k G_z}}$$

where F is the fluid fraction in the cell and G_z is the acceleration in z direction

FLOW-3D®
THEORETICAL FRAMEWORK

FRICTION

- FLOW-3D® uses a Nikuradse type of surface roughness, k_s

- The Manning's roughness coefficient, n, may be converted to k_s *by (Yen, 1991):*

$$k_s = \left(\frac{n}{0.038921}\right)^6$$

- k_s is set manually as the Surface Roughness coefficient

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

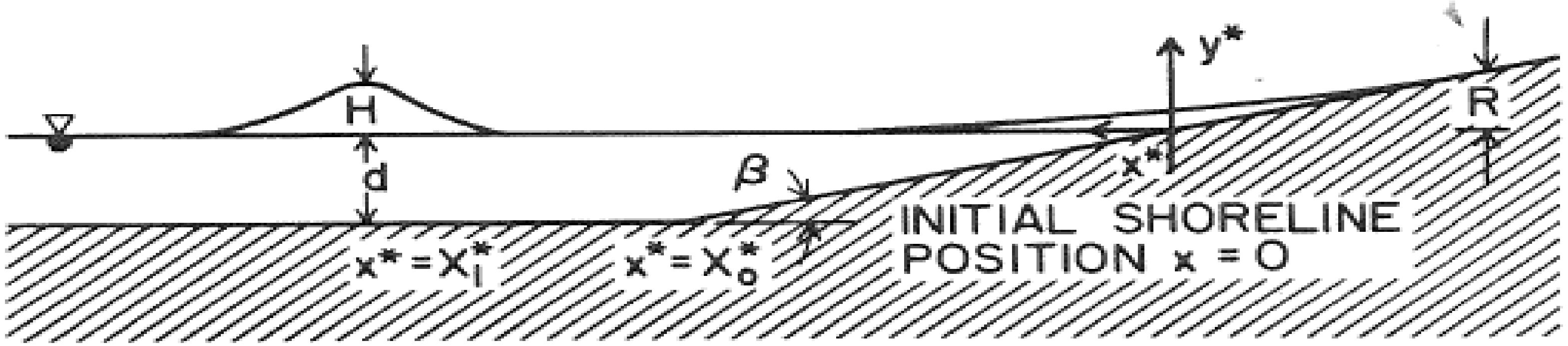


Figure 3. A definition sketch for a solitary wave climbing up on a sloping beach (Synolakis, 1986)

Maximum Run-up of nonbreaking solitary waves on plane beaches is given by the runup law (Analytical Solution) (Synolakis,1986):

$$\frac{R}{d} = 2.831\sqrt{\cot\beta}\,\left(\frac{H}{d}\right)^{5/4}$$

where:

R is maximum run up

d is undisturbed water depth

H is wave height

β is beach slope angle

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

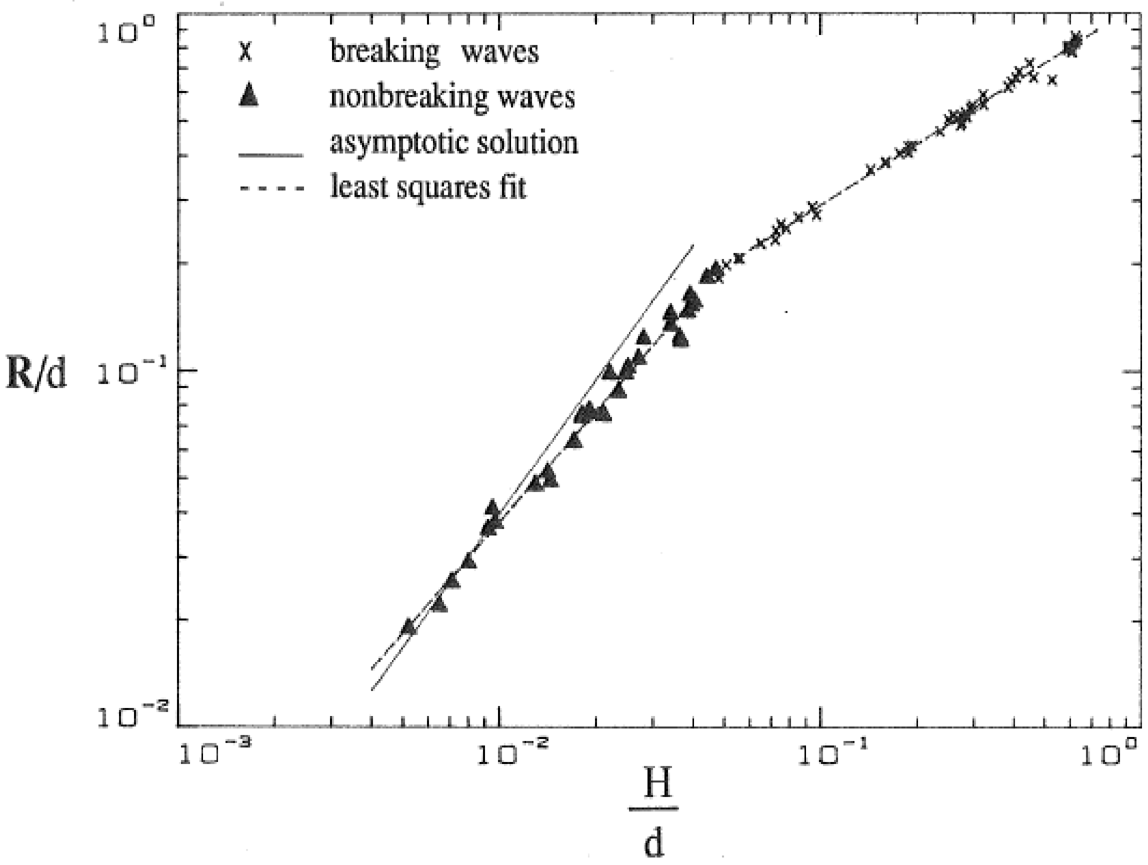


Figure 4. The maximum runup of solitary waves climbing up a 1:19.85 beach. Comparison between laboratory and the analytical result (Synolakis, 1986)

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

Model Domain

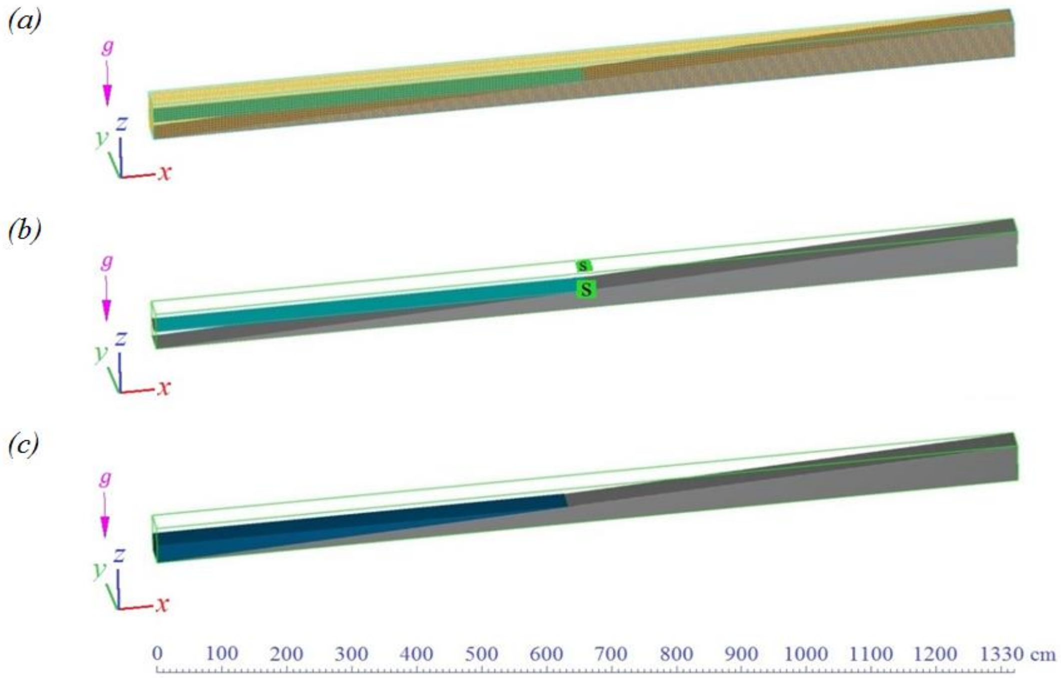


Figure 5. FLOW-3D® computational domain of an experimental run with H⁄d=0.005: (a) meshing; (b) boundary conditions; (c) after using FAVOR™

Bathymetry: 1352 cm in x-direction

40 cm in y-direction

Slope = 1:19.85

$\Delta x = \Delta y = \Delta z = 1$ cm

$n_{Manning}$ = 0.00, 0.01 and 0.03

Undisturbed Flow Depth = 6.5 ~ 38 cm

Simulation Time = 60 seconds

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

Incident Wave

The *solitary wave generator module of FLOW-3D®*

↓

water depth (d) and wave height (H) values are used as given in Synolakis (1986)

The minimum x boundary is defined as the wave boundary where solitary waves are reproduced(left) d. It is important to note that FLOW-3D® initiates the motion of solitary waves at a distance, expressed as $L/2$, from the mesh boundary as default. Therefore, the FLOW-3D® computational domain starts from the toe of the slope (ramp).

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

Spatial Discretization

- The finer the grid size, the closer are the computed results to the exact solutions
- No considerable change is observed $\Delta x < 1.0$ cm (spatial grid size)
- The analytically and numerically computed maximum runup values and free surface profiles differ about ~1% for $\Delta x \leq 1.0$ cm

The previous numerical model validations that used BMP 1 (NTHMP, 2011) are taken into account in the determination of the grid size

After a careful analysis, the grid size is selected as $\Delta x = \Delta y = \Delta z = 1$ cm

Variable time stepping is employed

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

Friction Analysis

Three different Manning’s roughness coefficients are used to assess the effect of friction on the maximum runup values are:

$n = 0$ (i.e. frictionless bottom)

$n = 0.01$ (i.e. neat cement/concrete/smooth glass beach)

$n = 0.03$ (i.e. fine particles along the channel bottom)

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

Friction Analysis

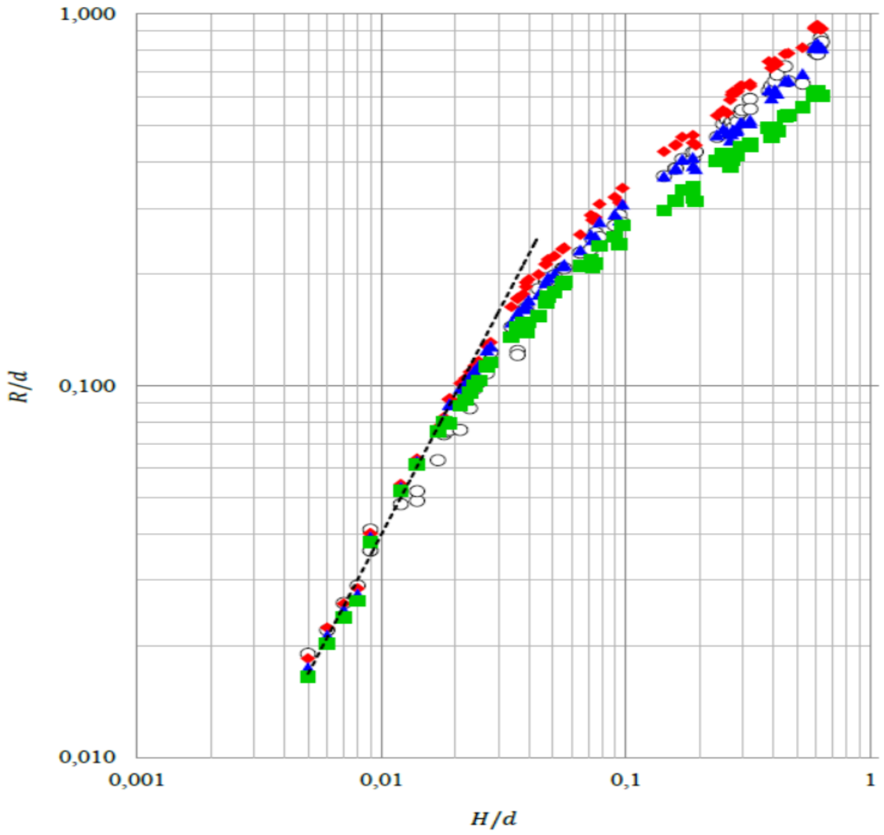


Figure 6: FLOW-3D model results for different Manning's roughness coefficients. The dashed black line and circles represent the runup law and experimental data of Synolakis (1986), respectively, the red diamonds represent the results when n = 0; the blue triangles represent the results when n = 0.01; the green squares represent the results when n = 0.03.

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

Friction Analysis

- $H/d \leq 0.01$

The computed maximum runup values do not depend on n for small non-breaking waves

- $0.01 < H/d < 0.044$

The computed runup heights are found to be slightly affected by the bottom friction

BENCHMARK problem #1

Solitary Wave Run-up on a Uniformly Sloped Beach

Friction Analysis

- $H/d \geq 0.044$

The maximum runup strongly depends on n

[similar results were reported by Lynett et. al. (2002)]

The maximum runup values of *breaking solitary waves:*

8 %, 4 % and 20 % less than the laboratory measurements for

$n = 0$, $n = 0.01$ and $n = 0.03$, respectively

BENCHMARK problem #2

Solitary Wave on a Conical Island

Problem Description

- The wave conditions on the south side of Babi Island are usually calm even when there are strong wind waves and swells of the Flores Sea attacking from the north
- The south shore of Flores island was prone to the December 12, 1992 tsunami attack, although it was usually protected from wind waves and swells

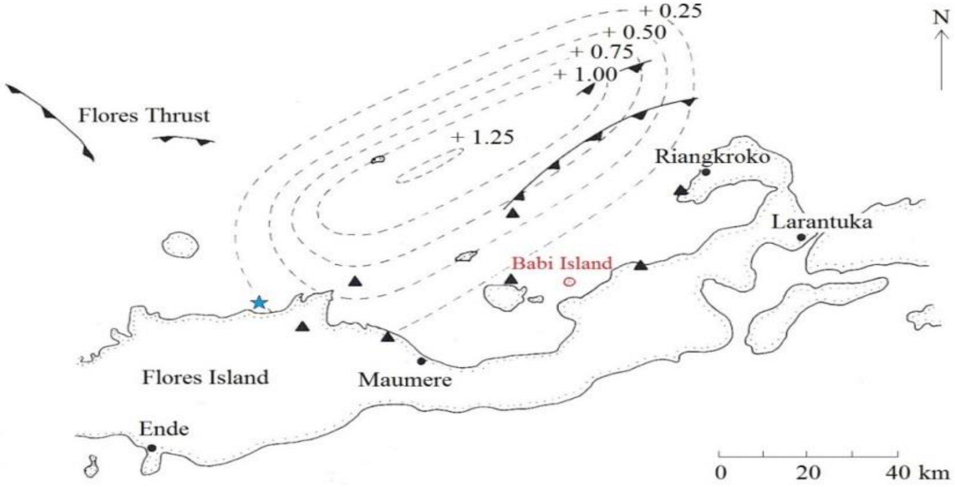


Figure 7: Map of Flores Island. The star represents the epicenter of the main shock; the triangles show the aftershock locations; the dashed contour lines indicate the predicted vertical seafloor displacement in meters, which is directly translated to the initial tsunami condition (Yeh et al., 1994)

BENCHMARK problem #2

Solitary Wave on a Conical Island

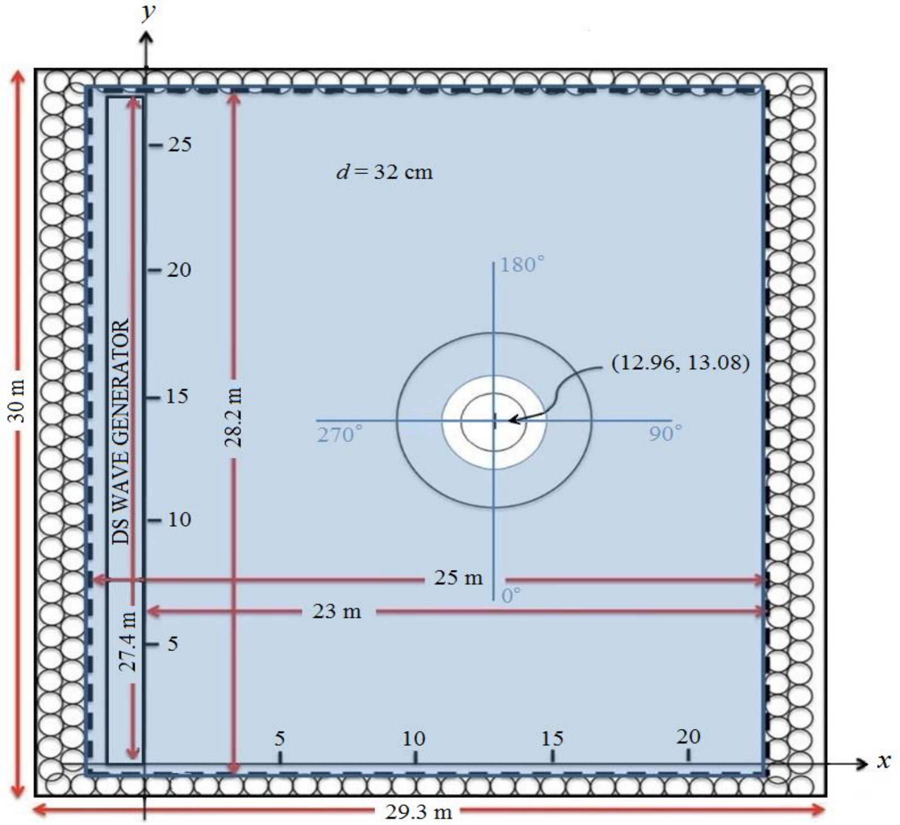
Problem Description

The fact that the tsunami attacked the conically shaped Babi Island from the north, but an extremely high inundation was observed in the south (back or lee side of the island), suggests that there is a need for a better understanding of the important physical parameters involved in a three-dimensional tsunami runup

BENCHMARK problem #2

Solitary Wave on a Conical Island

Problem Description



- The basin dimensions 29.3 m x 30 m
- The surface of the basin and the conical island were made of smooth concrete.
- Directional Spectral Wave Generator:
  - ➢located at *x=12.96* m from the island
  - ➢waves having solitary wave-like profiles

Figure 8: Basin geometry, coordinate system and location of gauges (Credit: Frank Gonzalez) (Horrillo et al., 2015)

BENCHMARK problem #2

Solitary Wave on a Conical Island

Problem Description

- The island was shaped like a truncated, right circular cone with diameters of 7.2 m at the toe and 2.2 m at the crest
- The vertical height of the island was approximately 0.625 m, with 1V:4H beach face
- The water depth in the basin 0.32 m

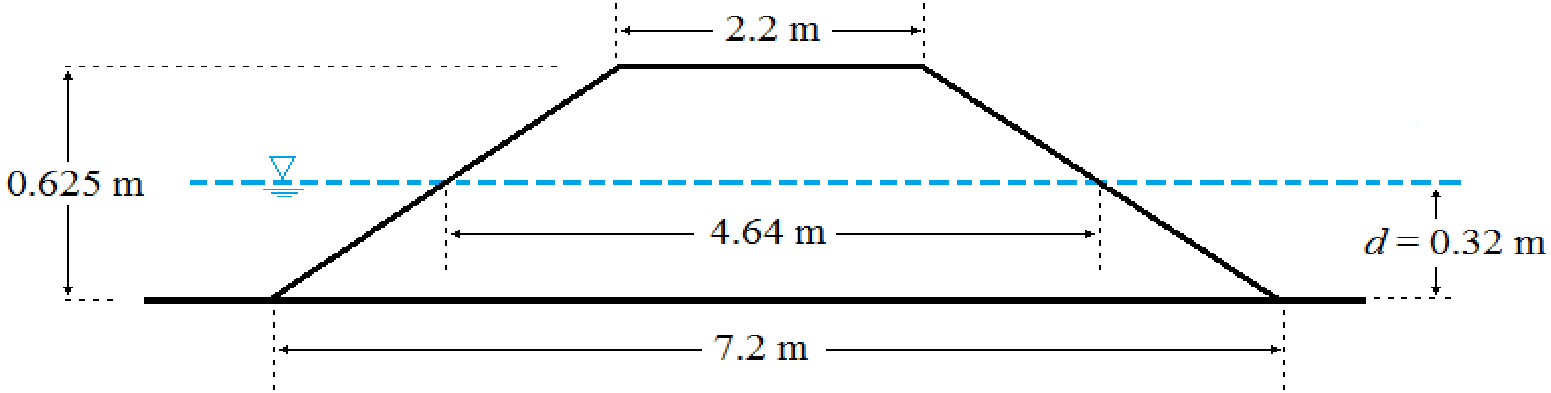


Figure 9: Cross Sectional sketch for the conical island (not to scale)

BENCHMARK problem #2

Solitary Wave on a Conical Island

Problem Description

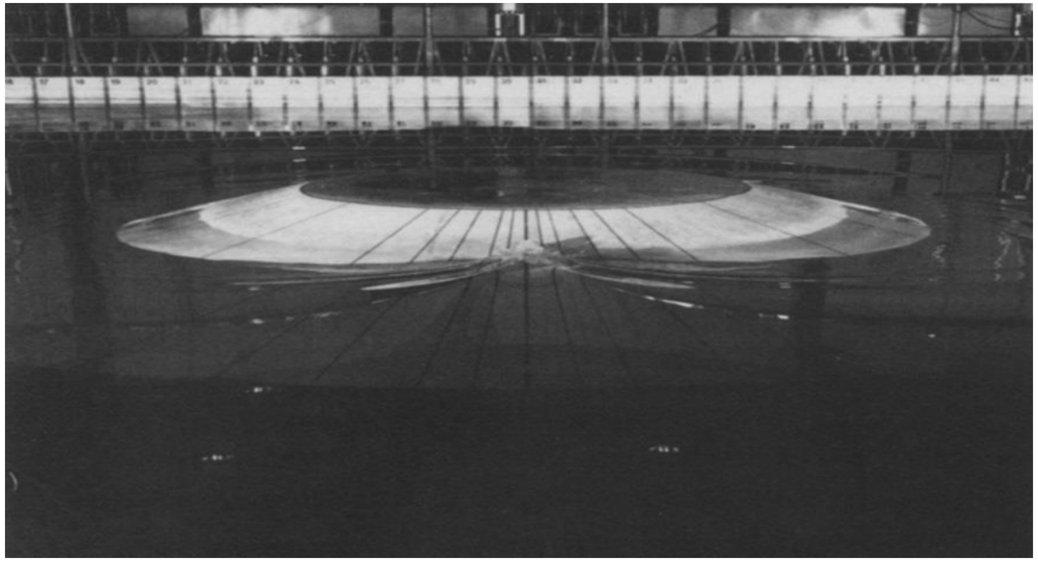


Figure 10: A view of the conical island and the directional spectral wave generator from the back side of the island (Briggs et al., 1995)

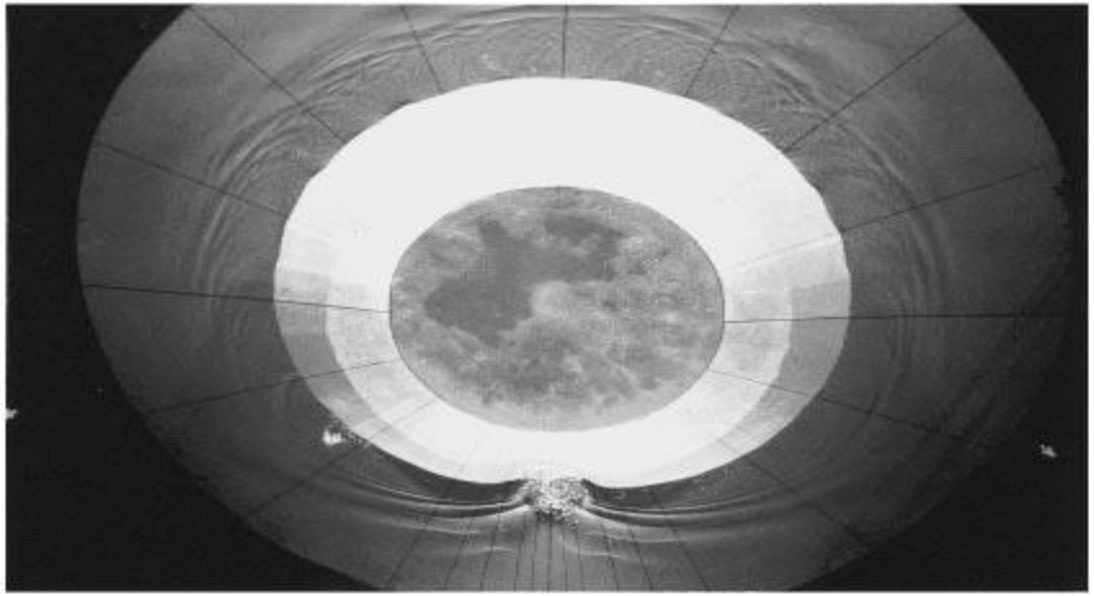


Figure 11: An overhead photograph of the wave runup on the lee side of the island (Briggs et al., 1995)

BENCHMARK problem #2

Solitary Wave on a Conical Island

Problem Description

Three different cases:

- Case A: the initial H/d ratio is 0. 045
- Case B: the initial H/d ratio is 0. 091
- Case C: the initial H/d ratio is 0. 181

Incident Wave: Gauge 2 data

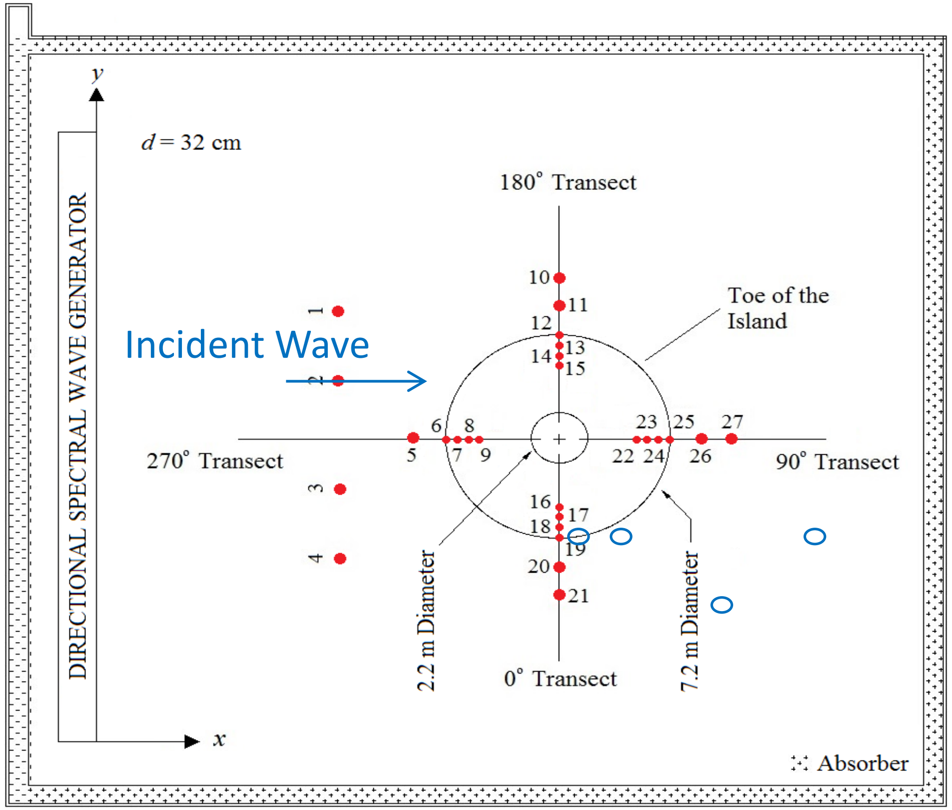
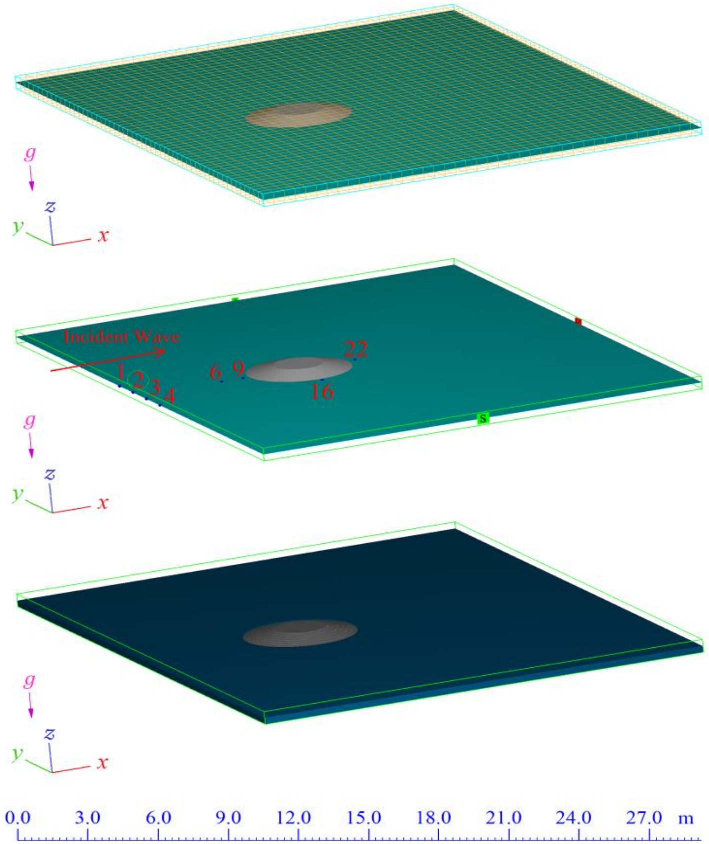


Figure 12. Schematic showing the gauge locations around the conical island (not to scale)

BENCHMARK problem #2

Solitary Wave on a Conical Island

Model Domain



Bathymetry: 27.6 m in x-direction

25.0 m in y-direction

$\Delta x = \Delta y = \Delta z = 5$ cm

Undisturbed Flow Depth = 32 cm

$n_{Manning}$ = 0.00, 0.01 and 0.03

Simulation Time = 40 seconds

(The computations are terminated after the first reflection of the wave from the island)

Figure 13. FLOW-3D computational domain: meshing (enlarged for clarity), boundary conditions and gauge locations and after using FAVOR™

BENCHMARK problem #2

Solitary Wave on a Conical Island

Incident Waves

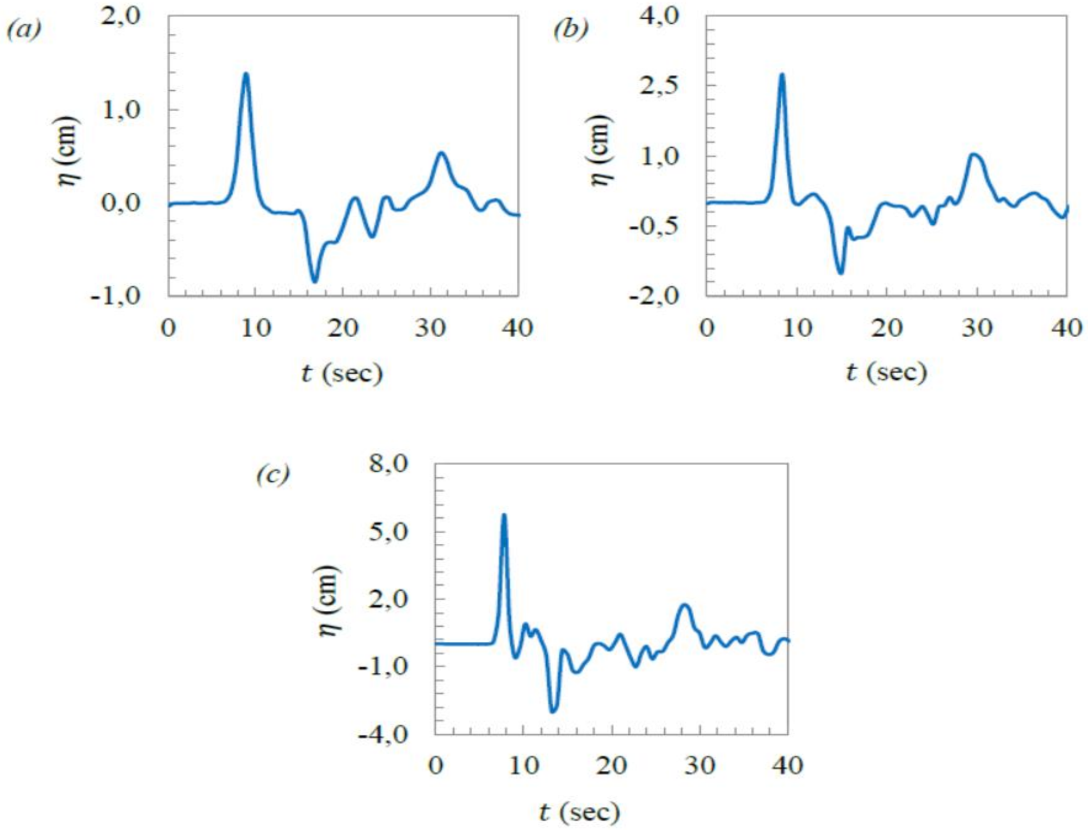


Figure 14. The free surface elevation time series recorded at Gauge 2 for (a) Case A, (b) Case B and (c) Case C (Briggs et al., 1995)

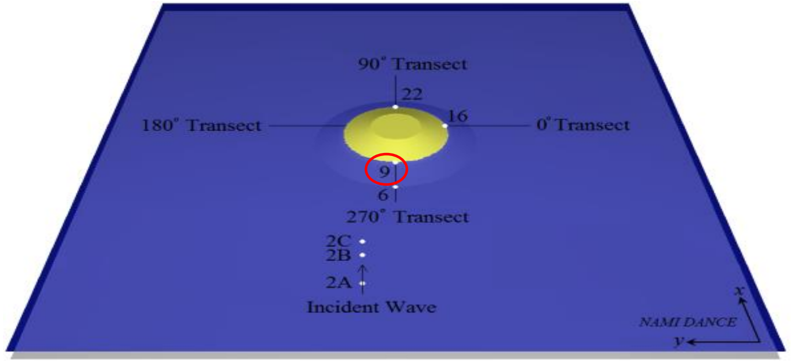
BENCHMARK problem #2

Solitary Wave on a Conical Island

Spatial Discretization

Table 1 FLOW-3D: Computed runup values at Gauge 9 for different Δx values values and H/d conditions (n=0.01)

Grid Size Δx **(m)**	**Maximum Runup (cm)**		
	$H/d = 0.045$	$H/d = 0.091$	$H/d = 0.181$
0.01	2.28	5.64	9.60
0.05	2.28	5.64	9.60
0.1	2.27	5.63	9.58
0.5	2.23	5.60	9.55
1.0	2.20	5.57	9.47



The grid size is selected as $\Delta x = \Delta y = \Delta z = 5$ cm

Variable time stepping is employed

BENCHMARK problem #2

Solitary Wave on a Conical Island

Friction Analysis

Manning’s roughness coefficients used to assess the effect of friction on the maximum runup values are:

$n = 0$ (i.e. frictionless bottom)

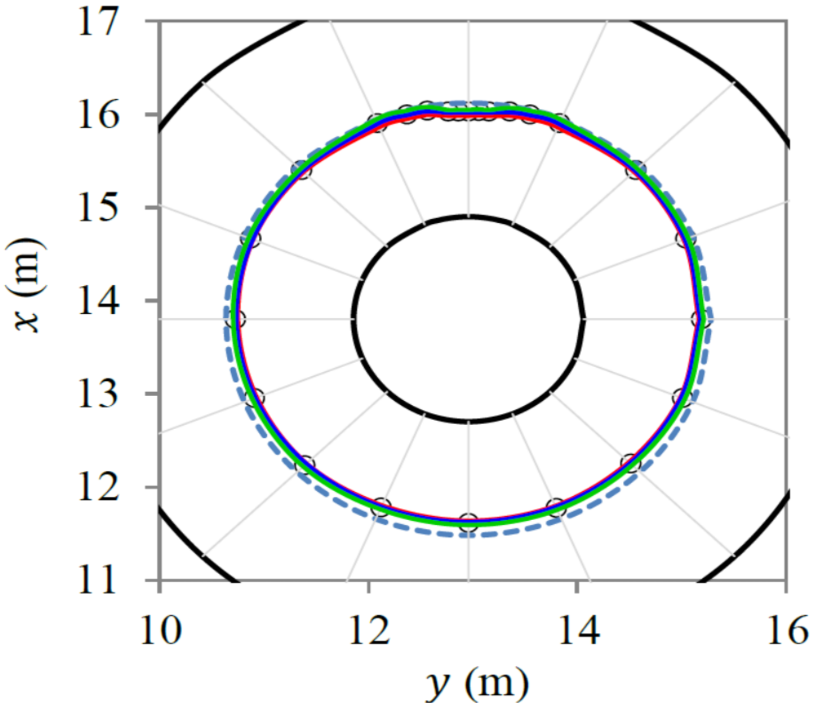
$n = 0.01$ (i.e. neat cement/concrete/smooth glass beach)

$n = 0.03$ (i.e. fine particles along the channel bottom)

BENCHMARK problem #2

Solitary Wave on a Conical Island

Friction Analysis



Case A: the initial H/d ratio is 0. 045

🟥 $n_{Manning} = 0$

🟦 $n_{Manning} = 0.01$

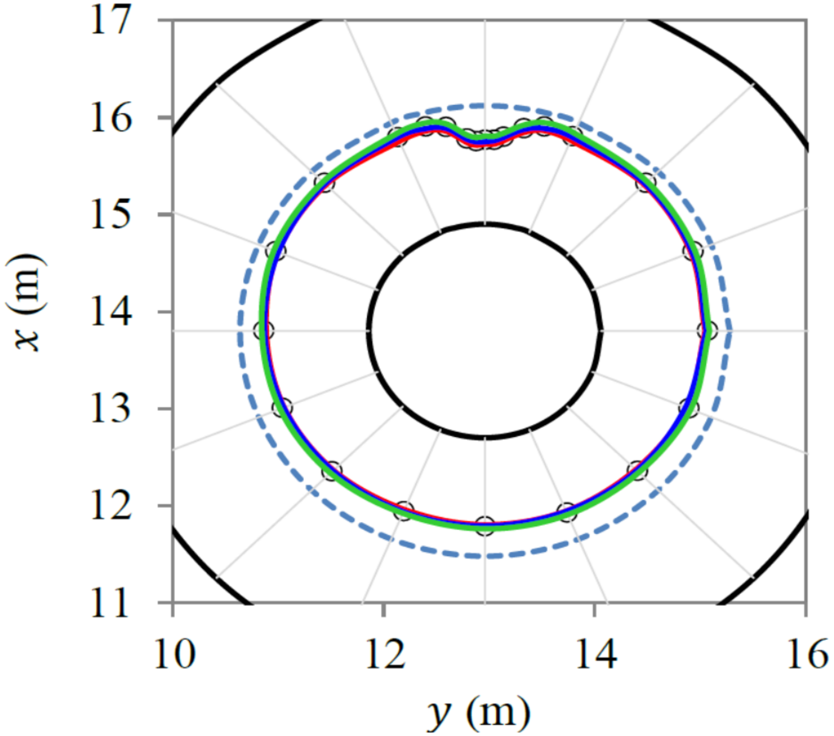
🟩 $n_{Manning} = 0.03$

Figure 15. FLOW-3D runup predictions according to different Manning's roughness coefficients for Case A. The dashed blue line represents the initial shoreline; the red line represents the results when n = 0; the blue line represents the results when n = 0.01; the green line represents the results when n = 0.03.

BENCHMARK problem #2

Solitary Wave on a Conical Island

Friction Analysis



Case B: the initial H/d ratio is 0. 091

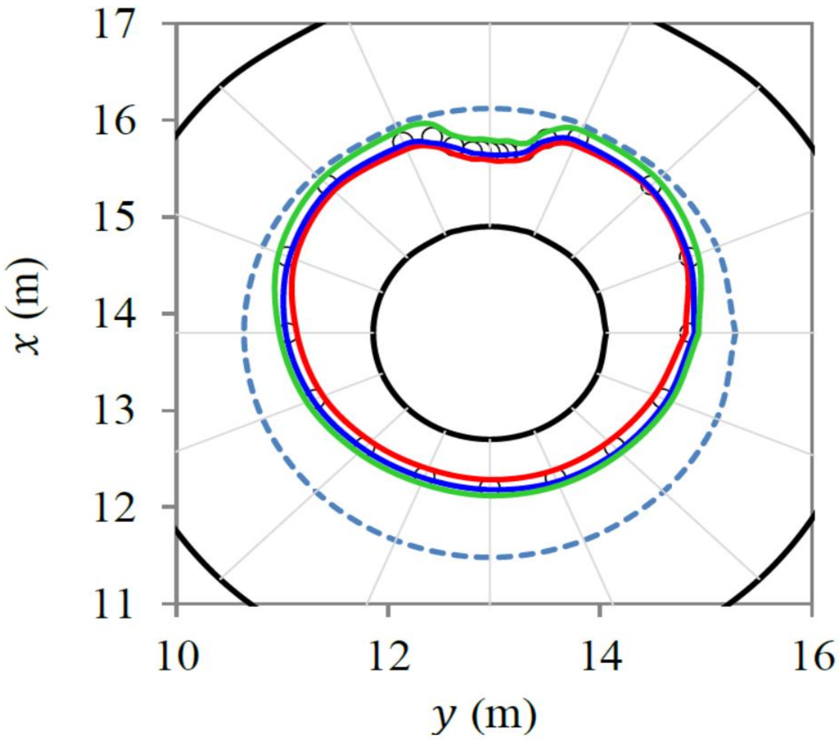
🟥 $n_{Manning} = 0$
🟦 $n_{Manning} = 0.01$
🟩 $n_{Manning} = 0.03$

Figure 16. FLOW-3D runup predictions according to different Manning's roughness coefficients for Case B. The dashed blue line represents the initial shoreline; the red line represents the results when n = 0; the blue line represents the results when n = 0.01; the green line represents the results when n = 0.03.

BENCHMARK problem #2

Solitary Wave on a Conical Island

Friction Analysis



Case C: the initial H/d ratio is 0. 181

🟥 $n_{Manning} = 0$

🟦 $n_{Manning} = 0.01$

🟩 $n_{Manning} = 0.03$

Figure 17. FLOW-3D runup predictions according to different Manning's roughness coefficients for Case C. The dashed blue line represents the initial shoreline; the red line represents the results when n = 0; the blue line represents the results when n = 0.01; the green line represents the results when n = 0.03.

BENCHMARK problem #2

Solitary Wave on a Conical Island

Friction Analysis

- The effect of friction varies spatially over the computational domain since the friction term is a function of water depth
- The computed and measured runup values match around the perimeter of the conical island when $n = 0.01$, including the extreme runup behind the conical island
- Cases B and C: the computed inundation levels on the frictionless surface are higher than the measured one
- Case A: the computed runup values are not significantly affected by n

BENCHMARK problem #3

Flow through a City Building Layout

Experiment

Physical model → 1:50 scale idealization of the town Seaside, Oregon

Water depth @ wavemaker : 0.97 m

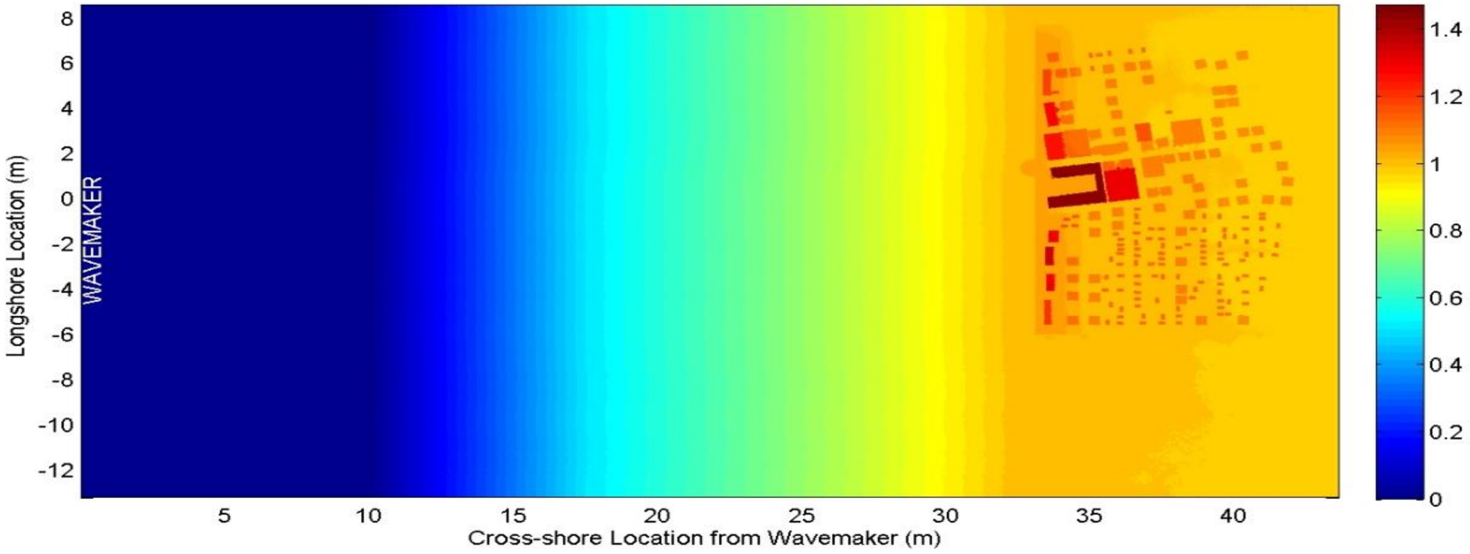


Figure 18. Piecewise linear slope and small-scale model of the town of Seaside, Oregon

BENCHMARK problem #3

Flow through a City Building Layout

Experiment

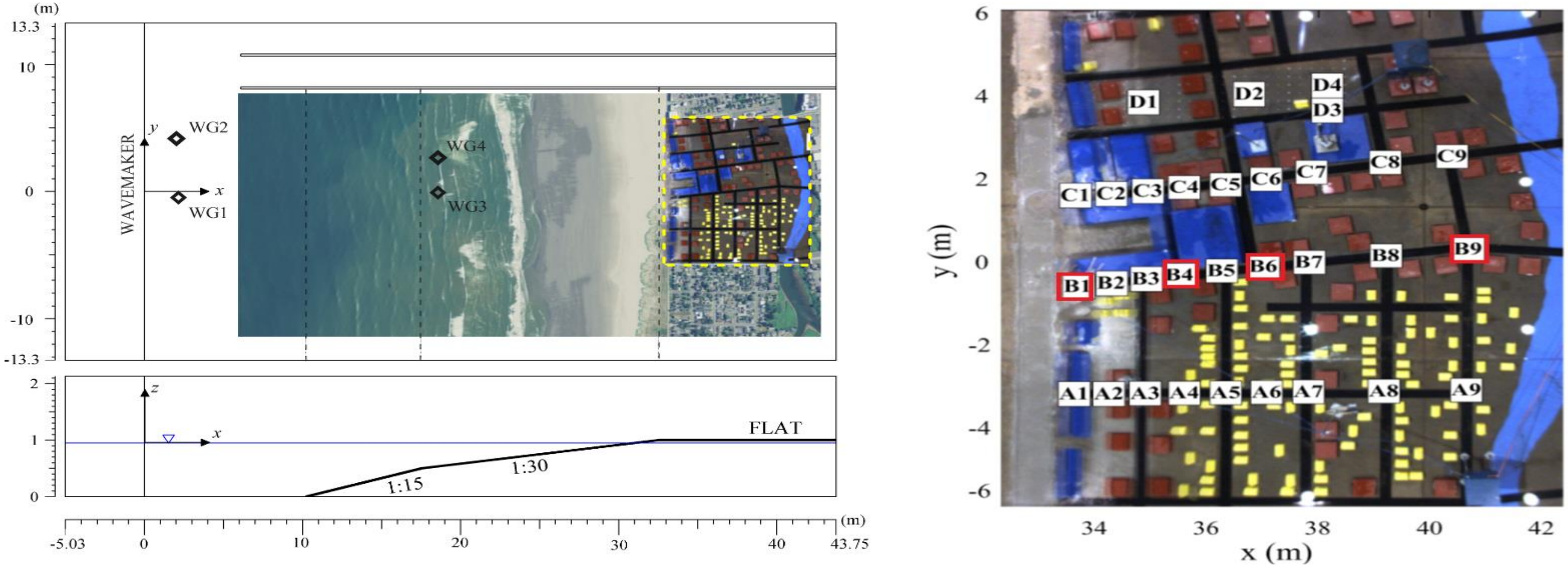


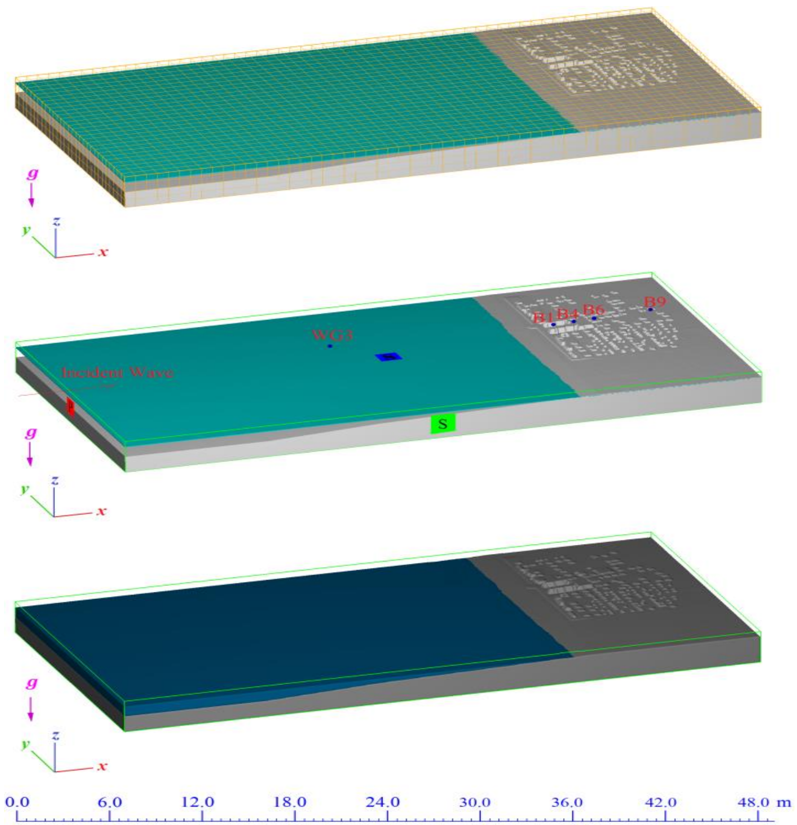
Figure 19. Points of measurement (Park H. et. al., 2013)

Overland flow depth , cross shore velocity and momentum-flux data comparisons are given at gauge points: B1, B4, B6 and B9

BENCHMARK problem #3

Flow through a City Building Layout

Model Domain



Bathymetry: 44 m in x-direction

22 m in y-direction

$\Delta x = 0.05$ m

$n_{Manning} = 0, 0.005, 0.01, 0.02, 0.03$

Undisturbed Flow Depth = 0.97 m

Simulation Time = 60 sec

Figure 20. FLOW-3D computational domain : meshing (enlarged for clarity), boundary conditions and gauge locations and after using FAVOR™

BENCHMARK problem #3

Flow through a City Building Layout

Incident Wave

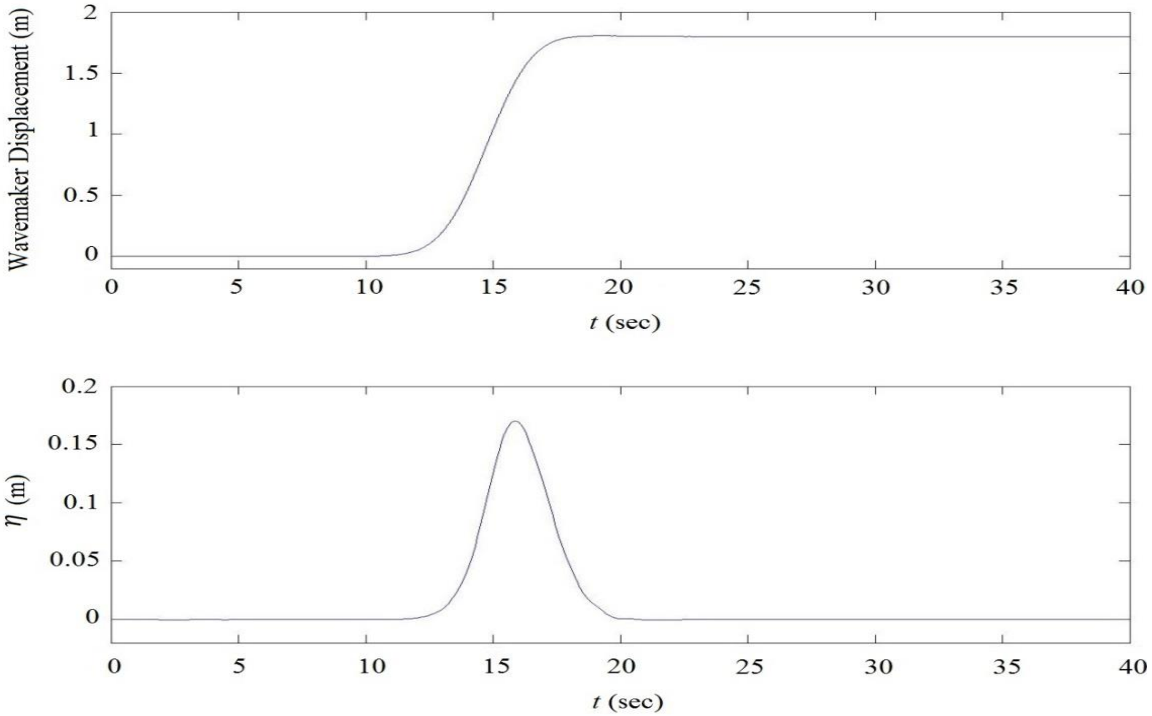


Figure 21. Wavemaker displacement time series – real data, which can be used to drive a moving wall boundary condition; incident-only wave time series at x= 5 m – simulated data, which can be used to drive a stationary input wave boundary condition at x= 5 m (NTHMP, 2015).

BENCHMARK problem #3

Flow through a City Building Layout

Incident Wave

Free surface elevation comparisons at WG3:

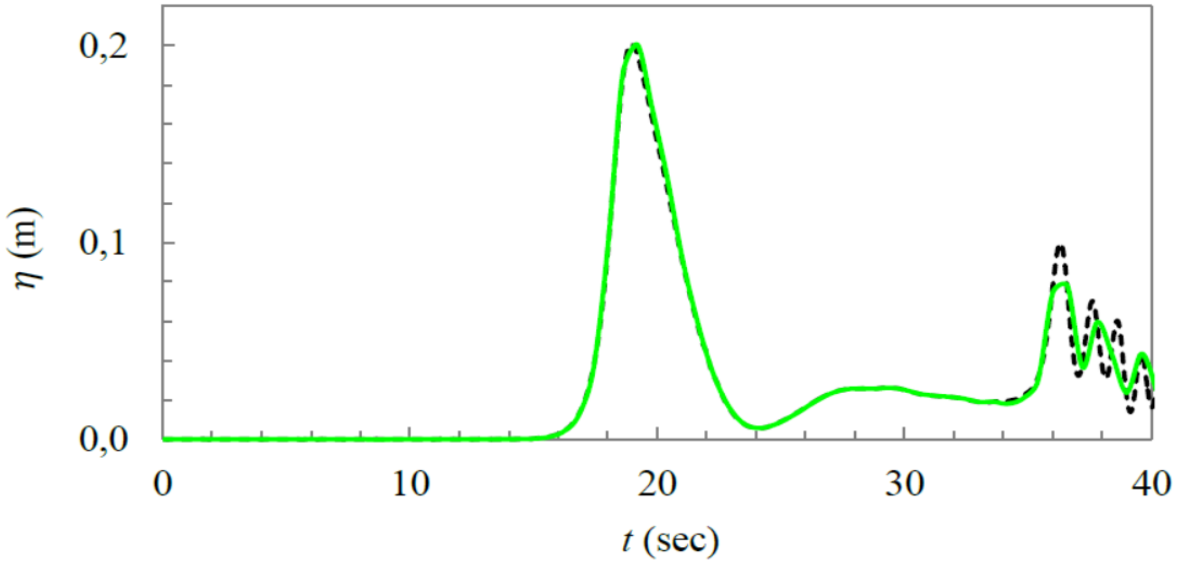


Figure 22. Comparison of computed and recorded free surface elevation at the control point, WG3. The green line represents the FLOW-3D® computation; the black line represents the recorded free surface elevation at WG3.

BENCHMARK problem #3

Flow through a City Building Layout

Spatial Discretization

- Proper modeling of macro-roughness elements: $\Delta x \leq 0.1$ m
- After $\Delta x = 0.05$ m, the results are insensitive to grid size
- The effect of grid size is negligible offshore

- Previous studies: Adaptive mesh refinement, the coarsest grid having a resolution of approximately 0.1 m and the finest grid, which only covered the town of Seaside model region, having a 0.01 m resolution (NTHMP, 2015)

After a careful analysis, the grid size is selected as $\Delta x = \Delta y = \Delta z = 5$ cm

Variable time stepping is employed

BENCHMARK problem #3

Flow through a City Building Layout

Friction Analysis

Manning's roughness coefficients used to assess the effect of friction on the maximum runup values are:

$n = 0$ (i.e. frictionless bottom)

$n = 0.005$

$n = 0.01$

$n = 0.02$

$n = 0.03$

BENCHMARK problem #3

Flow through a City Building Layout

Friction Analysis – Overland Flow Depth

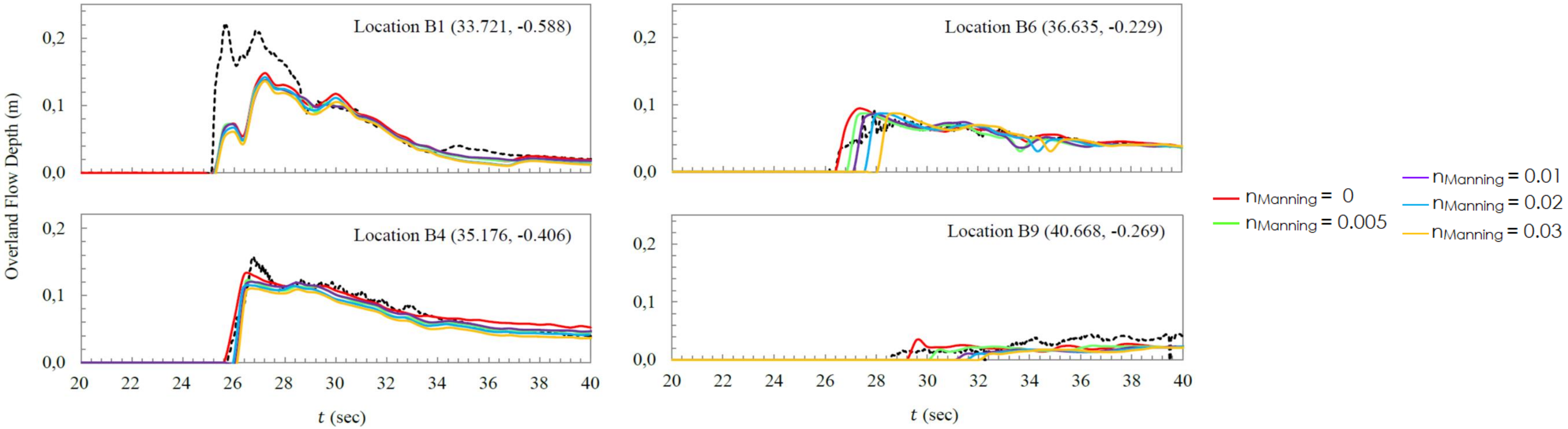


Figure 23. Comparison of computed and measured overland flow depth for locations B1, B4, B6 and B9, respectively. The dashed black line represents the measured data; the red, green, purple, blue and orange lines represent the FLOW-3D computations when n =0 , n =0.005, n =0.01, n =0.02 and n =0.03, respectively.

BENCHMARK problem #3

Flow through a City Building Layout

Friction Analysis – Cross shore Velocity

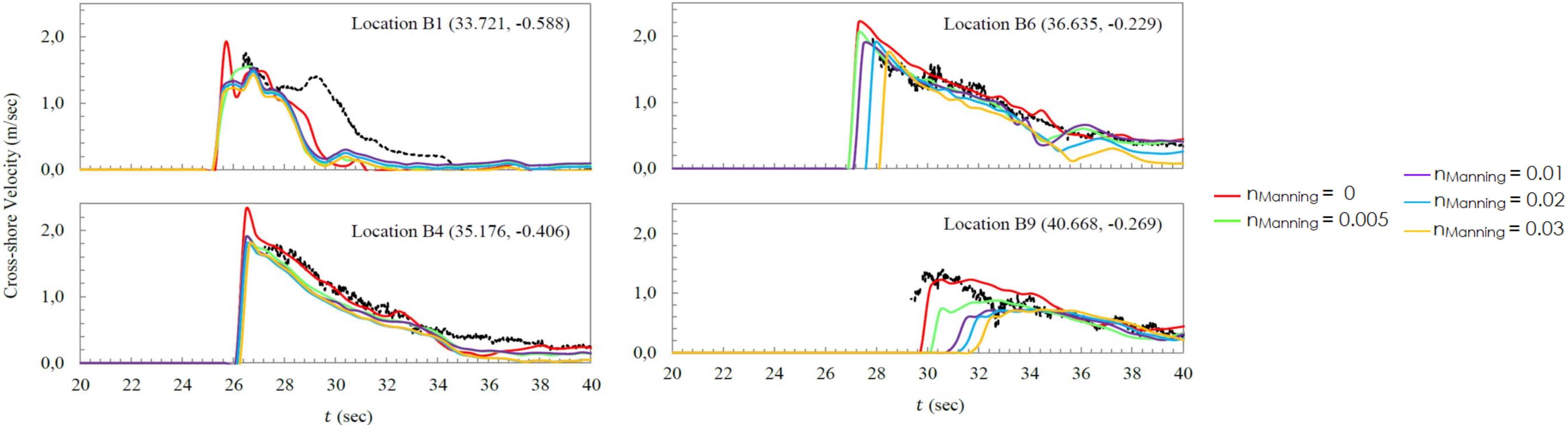


Figure 24. Comparison of computed and measured cross-shore velocity for locations B1, B4, B6 and B9, respectively. The dashed black line represents the measured data; the red, green, purple, blue and orange lines represent the FLOW-3D computations when n =0 , n =0.005, n =0.01, n =0.02 and n =0.03, respectively.

BENCHMARK problem #3

Flow through a City Building Layout

Friction Analysis – Momentum Flux

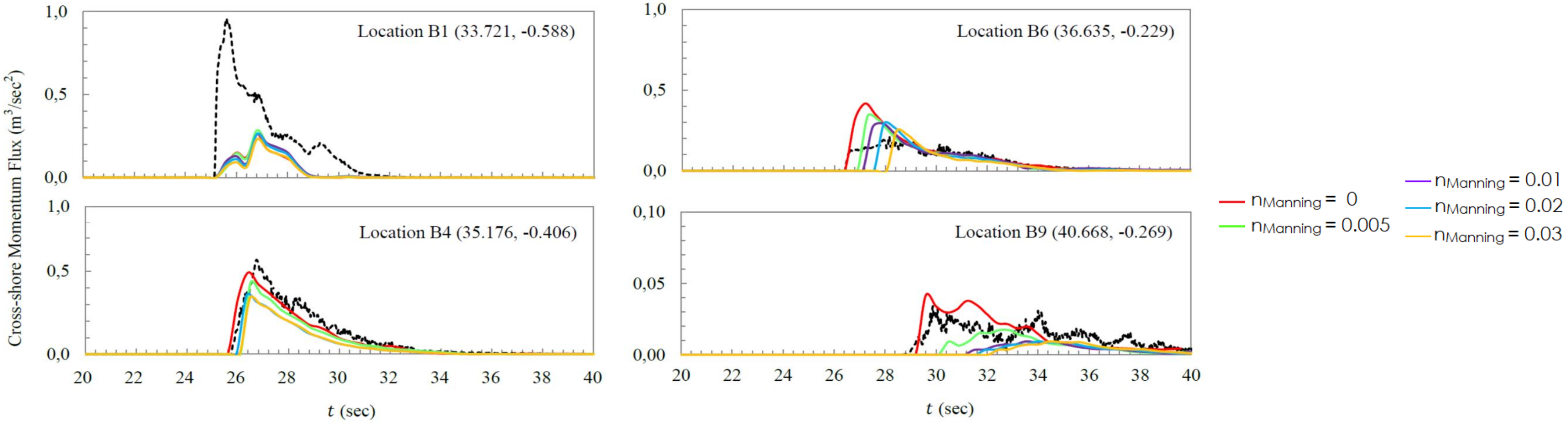


Figure 25. Comparison of computed and measured cross-shore momentum flux for locations B1, B4, B6 and B9, respectively. The dashed black line represents the measured data; the red, green, purple, blue and orange lines represent the FLOW-3D computations when n =0 , n =0.005, n =0.01, n =0.02 and n =0.03, respectively.

BENCHMARK problem #3

Flow through a City Building Layout

Friction Analysis

- The overland flow depth and cross-shore velocity values decrease as the friction factor is increased
- The effect of varying friction is stronger in more inland areas
- When the bottom surface conditions are very rough, in the furthest areas inland, there is a decrease in the overland flow depth by 20%, in the cross-shore velocity by 60%, and in the specific momentum flux by 80%
- The arrival time of the inundation wave is earliest when no friction is set in the odel
- Dominancy of friction on the arrival times is increased as the flow moves towards inland areas

CONCLUSION

- Bottom friction is effective on the wave runup height and wave propagation distance on land

- The bottom characteristics of the study area should be investigated and proper friction values (not only a constant value but also different friction values depending on the ground conditions must be determined in tsunami numerical modeling before developing reliable

ACKNOWLEDGEMENT

The authors wish to thank Dr. Andrey Zaytsev due to his undeniable contributions to the development of in-house numerical model, NAMI DANCE.

The Turkish branch of Flow Science, Inc. are also acknowledged.

The National Tsunami Hazard Mitigation Program (NTHMP), who provided most of the benchmark data, is appreciated.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

THANK YOU...

Great Wave off Kanagawa, by Hokusai, color woodblock print first published between 1826 and 1833. The waves depicted are sometimes mistakenly referred to as tsunami (津波), but they are okinami (沖波), or giant offshore waves.
Source: Library of Congress/Wikimedia Commons