NTHMP Benchmarking of NHWAVE for Propagation and Inundation

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Outline

- Need for benchmarking NHWAVE
- NTHMP-related Background
- Model Description
- Basic Hydrodynamic Considerations
- Analytical Benchmarks
- Laboratory Benchmarks

Need for benchmarking NHWAVE

- NHWAVE is used extensively by US East Coast component of NTHMP to model landslide sources on the continental slope margin (Currituck, etc). As such it falls within the family of models needing benchmarking under TWEA/NTHMP guidance.
- NHWAVE is not typically used to model inundation for East Coast events, which affects choice of benchmarks below. However…
- For studies of slides in confined regions, NHWAVE is often used for entire problem to avoid model nesting issues.

Nat Hazards (2015) 76:705–746
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ORIGINAL PAPER

Modeling of SMF tsunami hazard along the upper US East Coast: detailed impact around Ocean City, MD

Stephan T. Grilli · Christopher O'Reilly · Jeffrey C. Harris · Tayebeh Tajalli Bakhsh · Babak Tehranirad · Saeideh Banihashemi · James T. Kirby · Christopher D. P. Baxter · Tamara Eggeling · Gangfeng Ma · Fengyan Shi

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Abstract With support from the US National Tsunami Hazard Mitigation Program (NTHMP), the authors have been developing tsunami inundation maps for the upper US

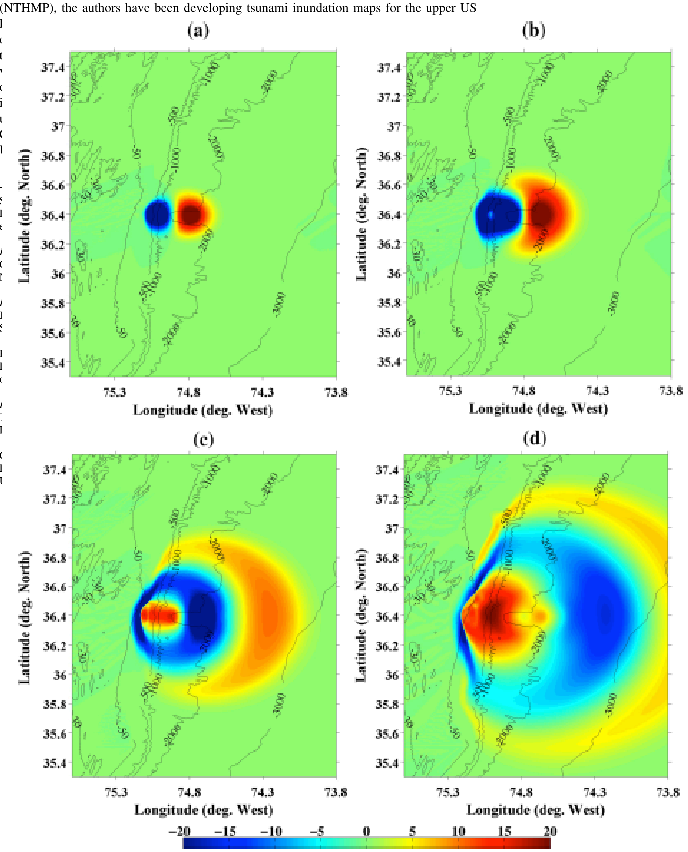

Fig. 7 Currituck SMF tsunami source generation in NHW ($C_d = 0$; 500-m resolution grid, 3 σ-layers). Instantaneous surface elevation (*color scale* is in meter) at: **a** 125 s; **b** 250 s; **c** 500 s; and **d** 800 s (13.3 min.) after SMF triggering (see Fig. 8 for E-W transects through these results). Bathymetric contours are marked in *meters*

Landslides manuscript No.
(will be inserted by the editor)

The 27 April 1975 Kitimat, British Columbia submarine landslide tsunami: A comparison of modeling approaches

James T. Kirby · Fengyan Shi · Dmitry Nicolsky · Shubhra Misra

Received: date / Accepted: date

Abstract We present nu
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and with two approaches
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slide based on Newtonian
are capable of reproducin
tation of slide geometry is
obtained using estimates
that are within reasonabl

Keywords landslide · tsu

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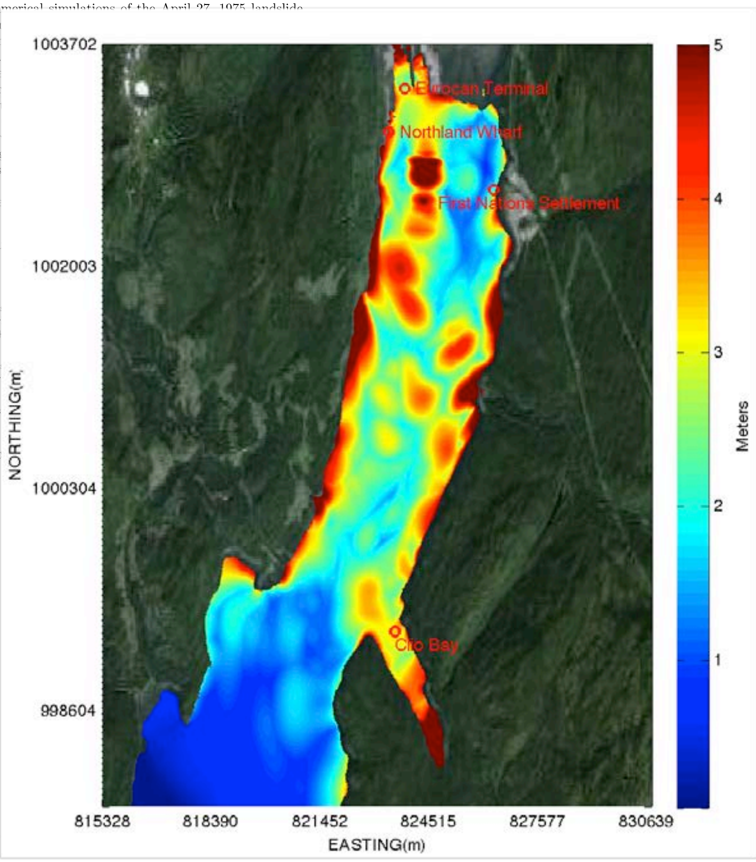

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NOAA Technical Memorandum OAR PMEL-135

STANDARDS, CRITERIA, AND PROCEDURES FOR NOAA EVALUATION OF TSUNAMI NUMERICAL MODELS

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UNITED STATES DEPARTMENT OF COMMERCE
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Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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Under Secretary for Oceans and Atmosphere/Administrator

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NOAA Special Report

PROCEEDINGS AND RESULTS OF THE 2011 NTHMP MODEL BENCHMARKING WORKSHOP

National Tsunami Hazard Mitigation Program

July 2012

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

Texas A&M University at Galveston

Table 1-4: Current benchmark tests for model verification and validation

Benchmark Test	Category	Description
BP1*	Analytical Solution	Single Wave on a Simple Beach
BP2		Solitary Wave on a Composite Beach
BP3		Sub-aerial Landslide on Simple Beach (2-D Landslide)
BP4*	Laboratory Experiment	Solitary Wave on a Simple Beach
BP5		Solitary Wave on a Composite Beach
BP6*		Solitary Wave on a Conical Island
BP7		Tsunami Runup onto a Complex Three-Dimensional Beach. Monai Valley
BP8		Tsunami Generation and Runup Due to Three-Dimensional Landslide
BP9*	Field Measurements	Okushiri Island Tsunami
BP10		Rat Island Tsunami

* Benchmark test used for NTHMP's model comparison

NTHMP Guidance

The NTHMP Tsunami Inundation Model Approval Process (created July 2015)

According to the 2006 Tsunami Warning and Education Act, all inundation models used in NTHMP projects must meet benchmarking standards and be approved by the NTHMP Mapping and Modeling Subcommittee (MMS). To this end, a workshop was held in 2011 by the MMS, and participating models whose results were approved for tsunami inundation modeling were documented in the "Proceedings and results of the 2011 NTHMP Model Benchmarking Workshop".

Since then, other models have been subjected to the benchmark problems used in the workshop, and their approval and use subsequently requested for NTHMP projects. **For those currently wishing to benchmark their tsunami inundation models, this document details how approval from MMS can be achieved.**

Steps for achieving MMS approval for tsunami inundation models

1 Preliminary requirements

- All models being used by U.S. federal, state, territory, and commonwealth governments should be provided to the public as "open source."
- Through professional papers and/or other accessible publications (university, government, etc.), there should be adequate documentation for others who are qualified to test and/or use the model.

2Using the Benchmark Methods for Tsunami Model Validation and Verification provided by NOAA's National Center for Tsunami Research, complete the following Benchmark Problems:

- BP1 - Solitary wave on a simple beach (nonbreaking – analytic)
- BP4 – Solitary wave on a simple beach (breaking – lab)
- BP6 – Solitary wave on a conical island (lab)
- BP7 - Runup on Monai Valley Beach (lab)
- BP9 – Okushiri Island tsunami (field), if intended to model not from local source

3 Document the experiments and results

- The following Matlab program should be used for standardized analysis of benchmark problem results and to facilitate ease of comparison with other benchmarked models
  - Zipped file of MATLAB scripts for benchmark problems including a README document (provided by Juan Horrillo)
- A paper should be written and submitted to MMS for review in advance of presenting the results.

4Present results to the MMS

- Contact the MMS co-chairs to arrange a presentation to the group – presentations can be done in person at the NTHMP/MMS semi-annual meetings or scheduled separately and done via webinar to the group
- After the presentation and discussion with MMS, the modelers can decide if they would like the MMS members to vote on acceptance, or request a delay to make corrections to their model.

5 MMS votes on acceptance.

- If approved by MMS, the new model will be documented as such (no significant modifications to the tsunami runup algorithm may be introduced, following the benchmarking process)
- A summary of the model information will be added to the "NTHMP Benchmarked tsunami models" document posted on the MMS website
- The model results and paper will be added to the "Addendum to the 2011 NTHMP Model Benchmarking Workshop Proceedings" document, accessible through the MMS website.

NHWAVE Model Description

- NHWAVE is a fully nonlinear, non-hydrostatic, 3D solver for surface wave motion developed by Ma et al (2012).
- NHWAVE solves either the Euler equations or Reynolds-averaged Navier-Stokes (RANS) equations in a time-dependent, surface- and terrain-following σ coordinate system.
- In Navier-Stokes applications, turbulent stresses are represented through use of a $k-\varepsilon$ closure.
- In tsunami applications, the model is used to compute water column response to initial ground motion as well as near field propagation and runup.

Governing Equations

- The incompressible Navier-Stokes equations in Cartesian coordinates (x^*_1, x^*_2, x^*_3, where $x^*_1 = x^*$, $x^*_2 = y^*$ and $x^*_3 = z^*$) and time t^* are given by

$$\frac{\partial u_i}{\partial x_i^*} = 0$$

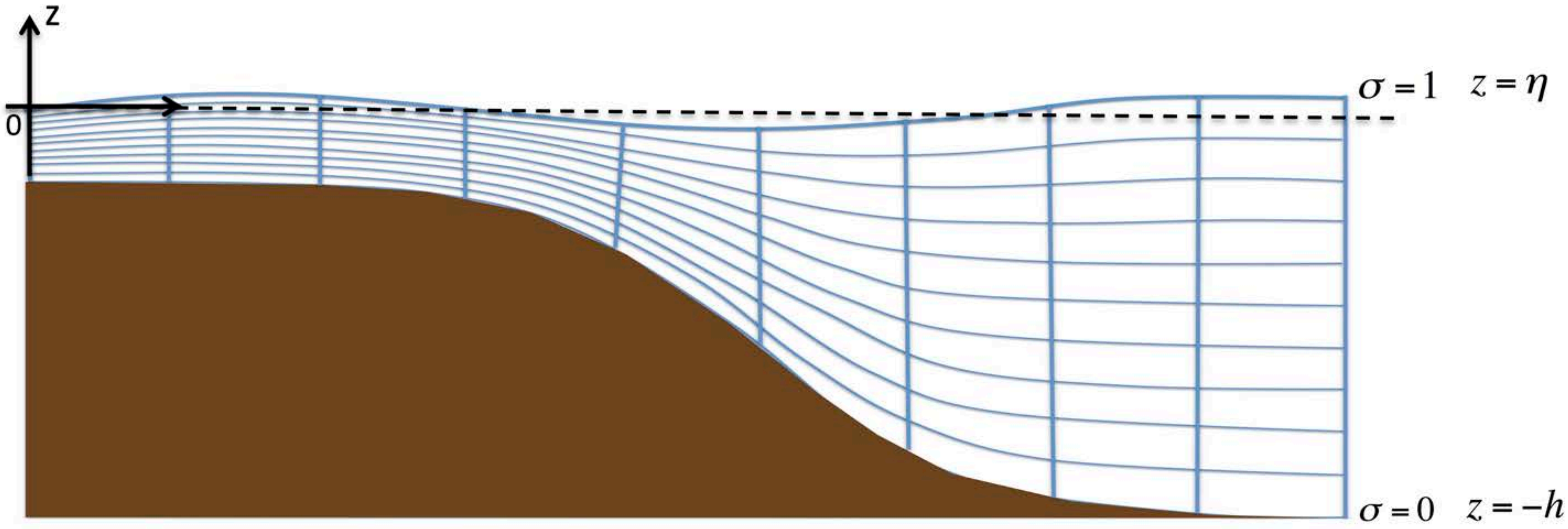
$$\frac{\partial u_i}{\partial t^*} + u_j \frac{\partial u_i}{\partial x_j^*} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i^*} + g_i + \frac{\partial \tau_{ij}}{\partial x_j^*}$$

- These equations are augmented by kinematic constraints given at the surface and bottom boundaries given by

$$\begin{aligned} \frac{\partial \eta}{\partial t^*} + u\frac{\partial \eta}{\partial x^*} + v\frac{\partial \eta}{\partial y^*} &= w; \qquad z^* = \eta \\ \frac{\partial h}{\partial t^*} + u\frac{\partial h}{\partial x^*} + v\frac{\partial h}{\partial y^*} &= -w; \qquad z^* = -h \end{aligned}$$

- And dynamic constraints on surface ($p=0$) and bottom

Fitting model domain to moving surface and bottom using sigma coordinates



Governing Equations In σ Coordinates

- A σ coordinate transformation is used in NHWAVE to map the bottom and surface onto constant boundaries of a strip of unit thickness.

$$t = t^* \quad x = x^* \quad y = y^* \quad \sigma = \frac{z^* + h}{D}$$

where D = h + η is total local depth.

Continuity equation:

$$\frac{\partial D}{\partial t} + \frac{\partial Du}{\partial x} + \frac{\partial Dv}{\partial y} + \frac{\partial \omega}{\partial \sigma} = 0$$

$$\omega = D\left(\frac{\partial \sigma}{\partial t^*} + u\frac{\partial \sigma}{\partial x^*} + v\frac{\partial \sigma}{\partial y^*} + w\frac{\partial \sigma}{\partial z^*}\right)$$

- Momentum equations:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} + \frac{\partial \mathbf{H}}{\partial \sigma} = \mathbf{S}_h + \mathbf{S}_p + \mathbf{S}_\tau \qquad \mathbf{U} = (Du, Dv, Dw)^T$$

- Fluxes and source terms:

$$\mathbf{F} = \begin{pmatrix} Duu + \frac{1}{2}gD^2 \\ Duv \\ Duw \end{pmatrix} \quad \mathbf{G} = \begin{pmatrix} Duv \\ Dvv + \frac{1}{2}gD^2 \\ Dvw \end{pmatrix} \quad \mathbf{H} = \begin{pmatrix} u\omega \\ v\omega \\ w\omega \end{pmatrix}$$

$$\mathbf{S}_h = \begin{pmatrix} gD\frac{\partial h}{\partial x} \\ gD\frac{\partial h}{\partial y} \\ 0 \end{pmatrix} \quad \mathbf{S}_p = \begin{pmatrix} -\frac{D}{\rho}(\frac{\partial p}{\partial x} + \frac{\partial p}{\partial \sigma}\frac{\partial \sigma}{\partial x^*}) \\ -\frac{D}{\rho}(\frac{\partial p}{\partial y} + \frac{\partial p}{\partial \sigma}\frac{\partial \sigma}{\partial y^*}) \\ -\frac{1}{\rho}\frac{\partial p}{\partial \sigma} \end{pmatrix} \quad \mathbf{S}_\tau = \begin{pmatrix} DS_{\tau_x} \\ DS_{\tau_y} \\ DS_{\tau_z} \end{pmatrix}$$

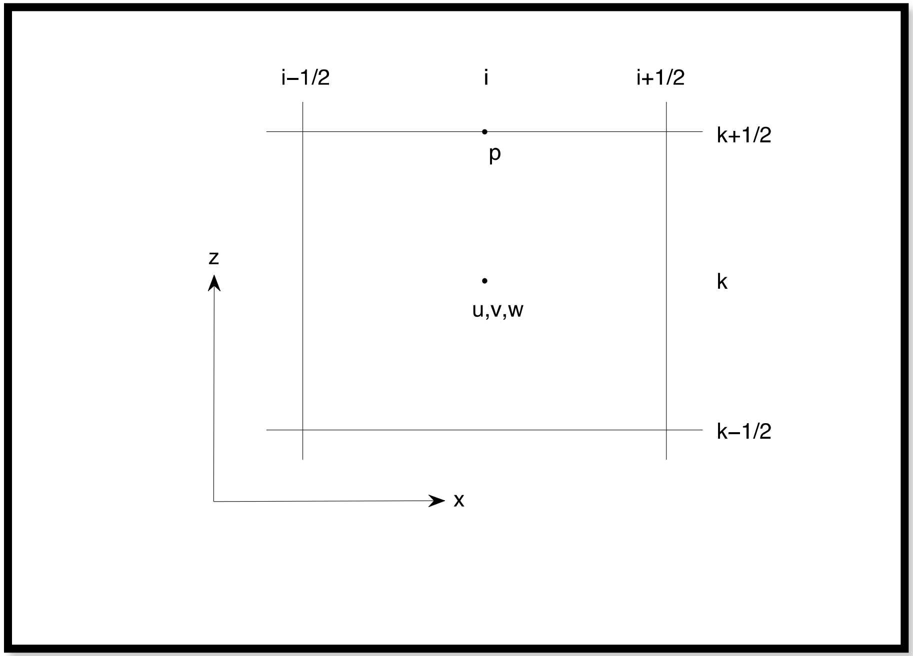
Grid Configuration

- Velocities are placed at the cell centers and the pressure is defined at vertically-facing cell faces

- The momentum equations are solved by a second-order Godunov-type finite volume method.

- The HLL approximate Riemann solver (Harten et al., 1983) is used to estimate fluxes at the cell faces.

- The pressure boundary condition at the free surface can be precisely assigned to zero.



Time Stepping and Spatial Finite Volume Scheme

- Time stepping using a Strong Stability Preserving (SSP) Runge-Kutta method. Time step Δt is adaptive during the simulation, following the Courant-Friedrichs-Lewy (CFL) criterion

$$\Delta t = C \min \left[\min \frac{\Delta x}{|u_{i,j,k}| + \sqrt{gD_{i,j}}}, \min \frac{\Delta y}{|v_{i,j,k}| + \sqrt{gD_{i,j}}}, \min \frac{\Delta \sigma D_{i,j}}{|w_{i,j,k}|} \right]$$

- Equations are discretized using a second-order Godunov-type finite volume method.

- Fluxes based on the conserved variables are calculated at the cell faces.

- Pressure-Poisson equation approximated using centered second-order finite differences. The linear system is solved using the high performance preconditioner HYPRE software library.

to download Manuscript: twolayermodel.tex

Click here to view linked References

age: www.elsevier.com/locate/ocemod

Shock-capturing non-hydrostatic model for fully dispersive surface wave processes

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ABSTRACT

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Landslide generated t
Longshore current

1. Introduction

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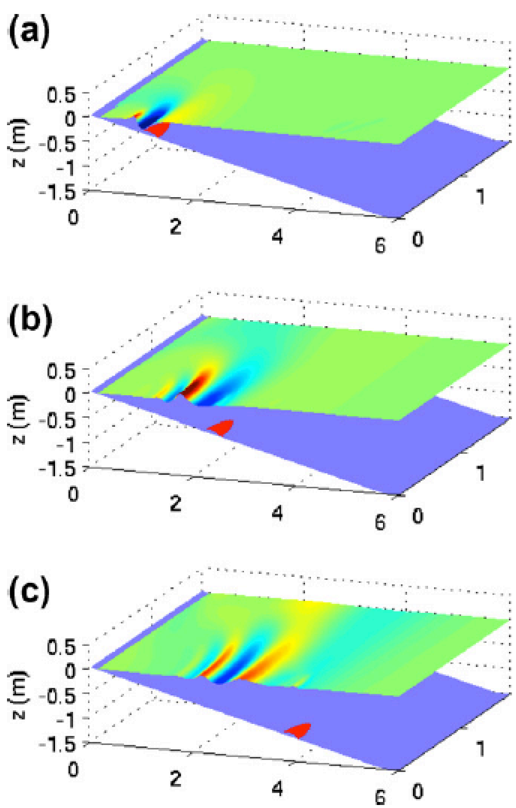

Fig. 14. Snapshots of landslide-generated waves simulated using nonhydrostatic model at times (a) $t = 1.0$ s; (b) $t = 2.0$ s and (c) $t = 3.0$ s after release of the sliding mass. The surface elevation is exaggerated 5 times.

A two-layer granular landslide model for tsunami wave generation: Theory and computation

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Abstract

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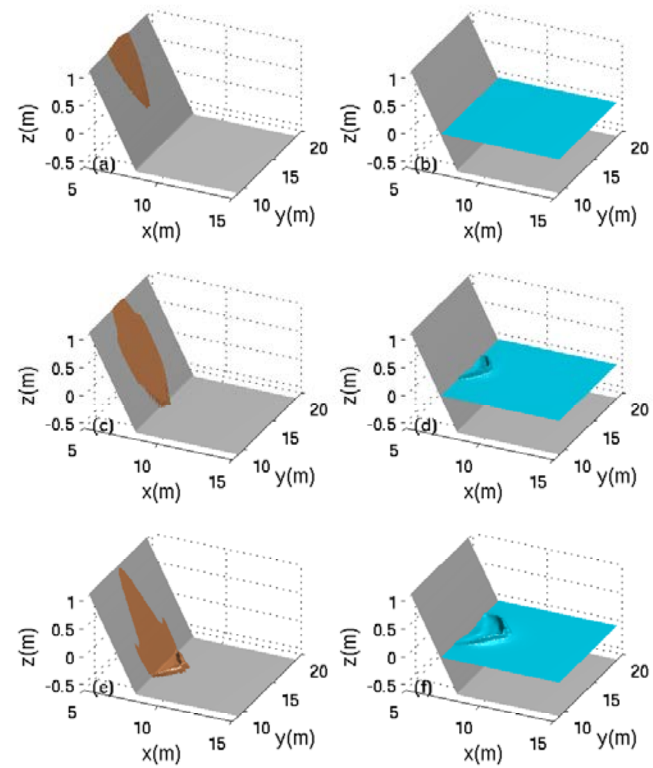

and (f) 1.0 s after slide impact.

Basic hydrodynamic considerations

1. **Mass Conservation**

$$V(t) = \int_{X_{max}}^{X_S} \int_{Y_{max}}^{Y_S} \eta(x, y, t) dx dy$$

Mass conservation were controlled for all of the benchmarks in this presentation. The total displaced volume V (t = T) was within 1% of the total displaced volume at the end of the computation V (t = T) where T represents the computation end time for each benchmark.

2, Convergence

For each benchmark test the grid steps Δx and Δy has been reduced to a a certain asymptotic limit to check the convergence of the model.
As recommended in literature, convergence of the code has been checked through the extreme runup and rundown.

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Analytic Benchmark

- BP1: Solitary wave on a plane slope

Laboratory Benchmarks

- BP4: Solitary wave on a plane slope
- BP6: Solitary wave on a conical island
- BP7: Monai Valley

~~Field Benchmark~~

- ~~BP9: Okushiri Island~~

Documentation provided to MMS

TSUNAMI BENCHMARK RESULTS FOR
NON-HYDROSTATIC WAVE MODEL NHWAVE
VERSION 1.1

BY
BABAK TEHRANIRAD, JAMES T. KIRBY,
GANGFENG MA, FENGYAN SHI

RESEARCH REPORT NO. CACR-12-03
MAY 2012

CENTER FOR APPLIED COASTAL RESEARCH

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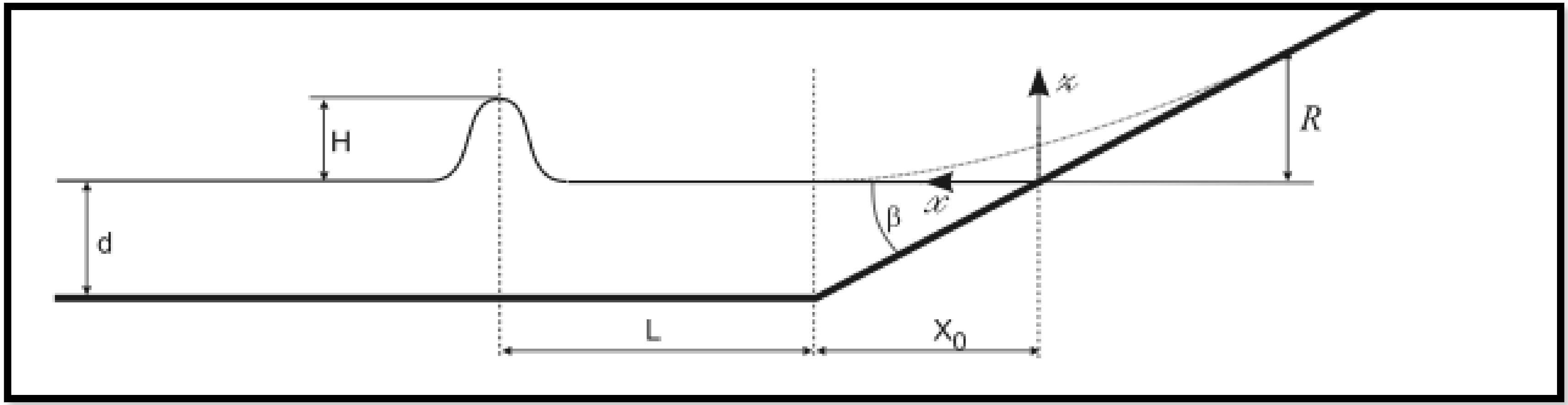
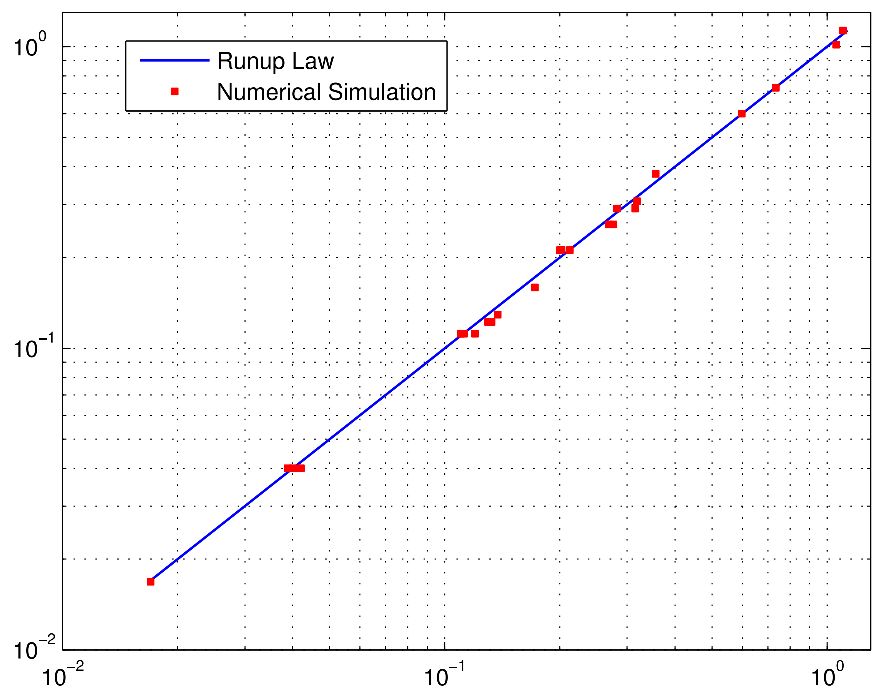
BP1: Solitary wave on a simple beach



$$R = 2.831\sqrt{\cot\beta}\,H^{\frac{5}{4}}$$

BP1: Solitary wave on a simple beach

- Cases studied here have different depths from 50cm to 100m.
- For each depth, different slopes and wave heights have been studied.



d(m)	$\Delta x(m)$	H/d	$Cot(\beta)$	R/d Runup Law	R/d Numerical Calculations	Error(%)
0.5	0.1	0.03	10.0	0.112	0.113	0.9
0.5	0.1	0.05	10.0	0.212	0.207	2.4
0.5	0.1	0.1	3.333	0.291	0.281	3.2
5.0	1.0	0.03	10.0	0.112	0.111	0.9
5.0	1.0	0.05	10.0	0.212	0.209	1.2
5.0	1.0	0.10	3.372	0.308	0.302	2.1
5.0	1.0	0.10	3.372	0.731	0.723	1.1
100	5.0	0.03	2.747	0.600	0.596	0.7
100	5.0	0.03	20.0	0.040	0.040	1.0

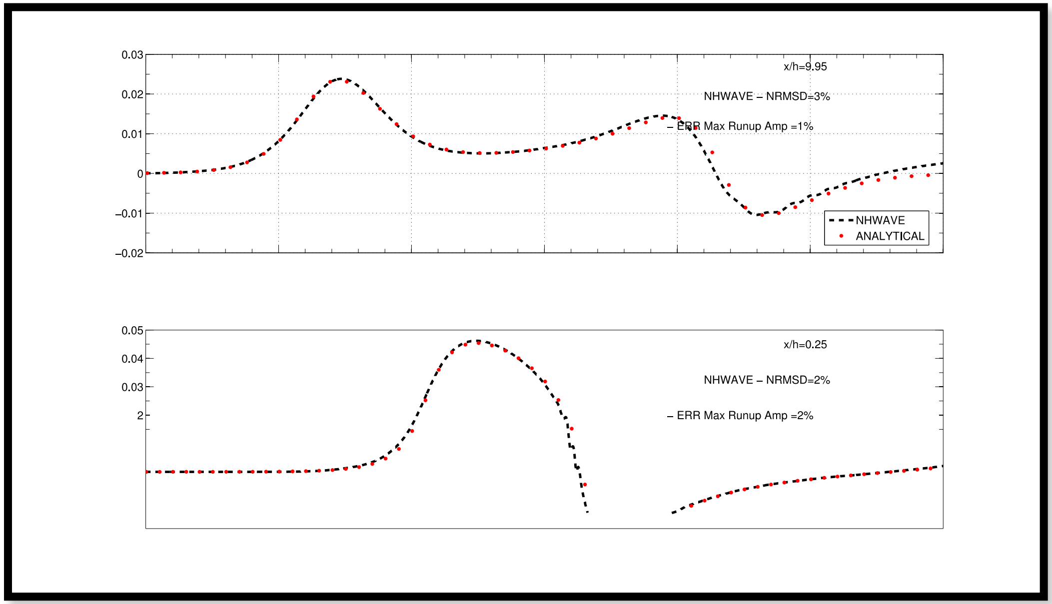
BP1: Solitary wave on a simple beach

- The analytical solution for different times is available for a specific case with $H/d = 0.0019$ and $\beta = \cot^{-1}(19.85)$.

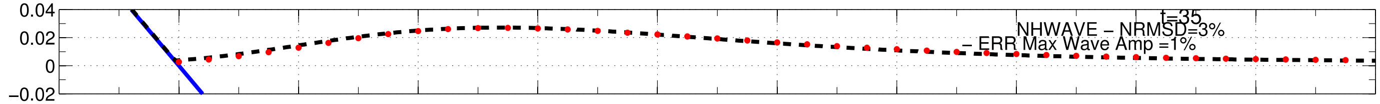
- To model this case, a grid size of $\Delta x = \Delta y = 0.05$ m and three vertical layers were used.

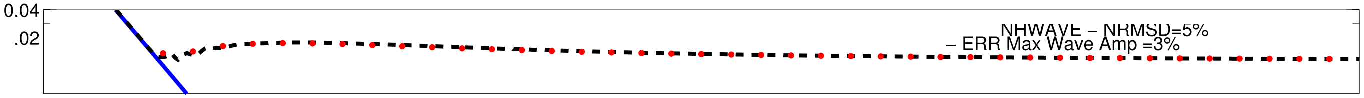
- The point $X/d = 0.25$, closer to initial shoreline, becomes temporarily dry during the process. The point $X/d = 9.95$ remains wet throughout the simulation.

The water level at two locations X/d = 0.25 and X/d = 9.95.



BP1: Solitary wave on a simple beach





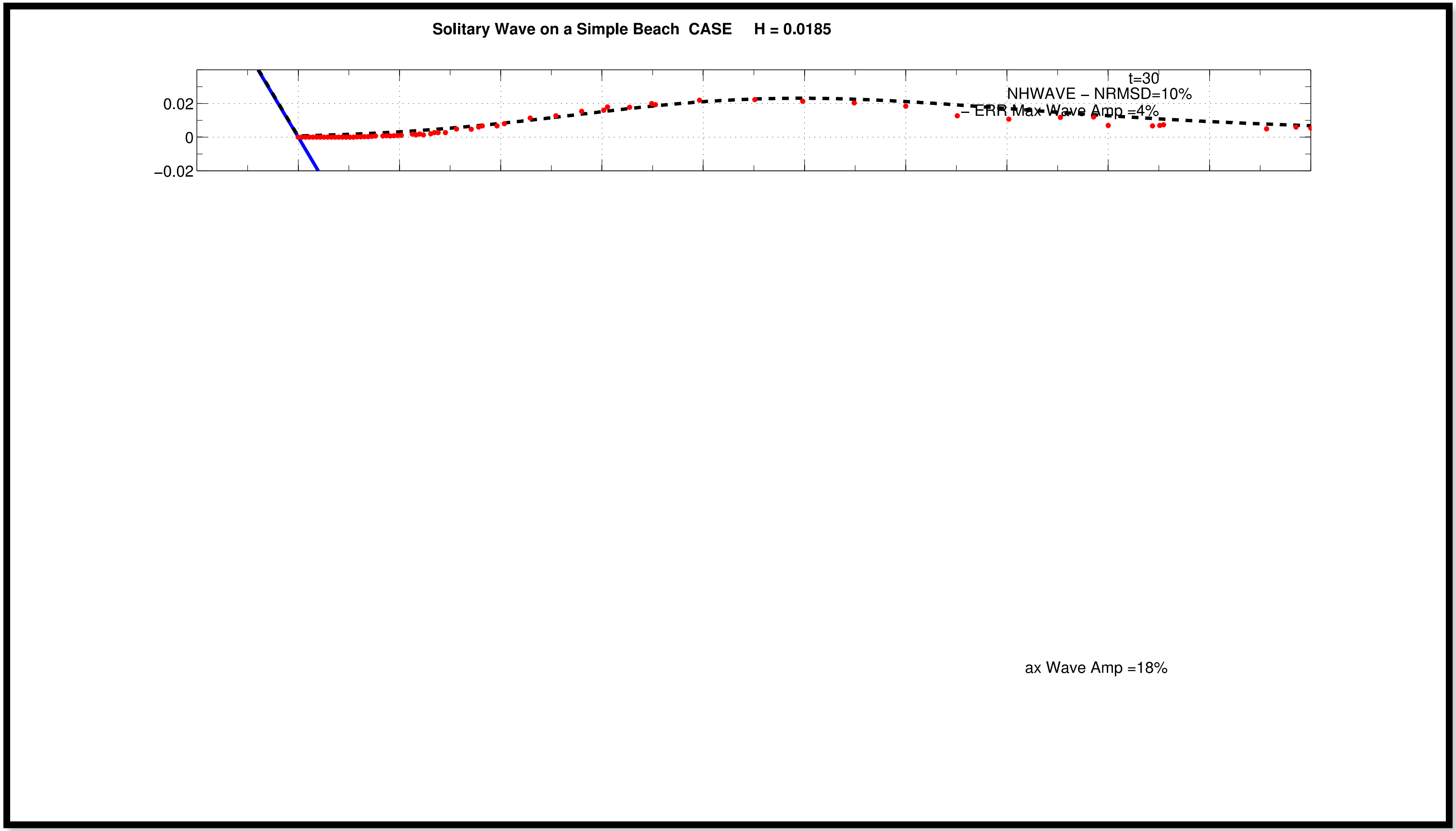
BP4: Solitary wave on a simple beach

- In this laboratory test, the 31.73 m-long, 60.96 cm-deep and 39.97 cm wide California Institute of Technology, Pasadena, California wave tank was used with water of varying depths.

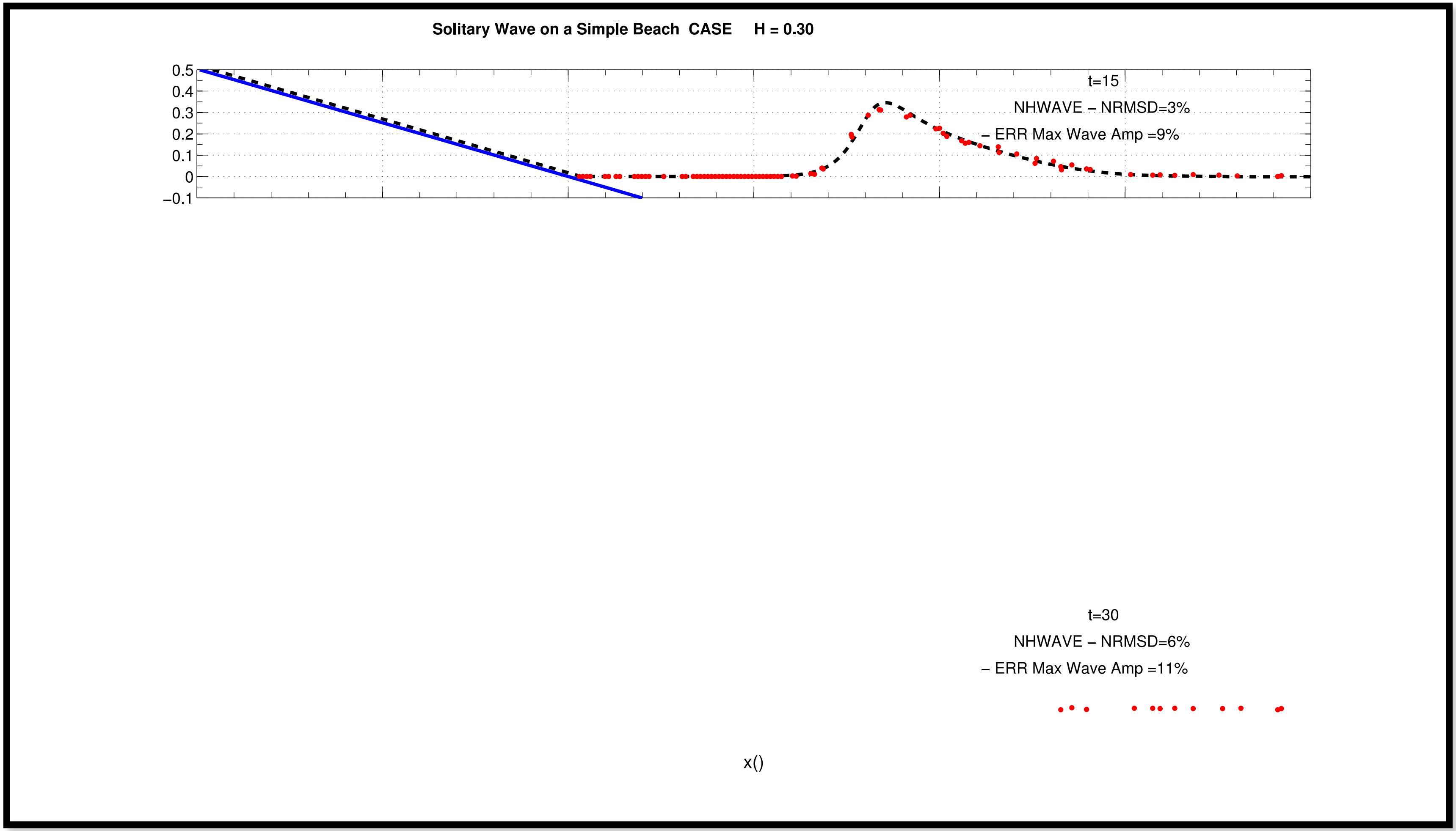
- This set of laboratory data has been used for many code validations. In this modeling test, the data sets for the **H/d=0.0185 nonbreaking** and **H/d=0.30 breaking** solitary waves are used.

- A grid size of $\Delta x = \Delta y = 0.05$ m and three vertical layers were used.

BP4: Solitary wave on a simple beach (nonbreaking)

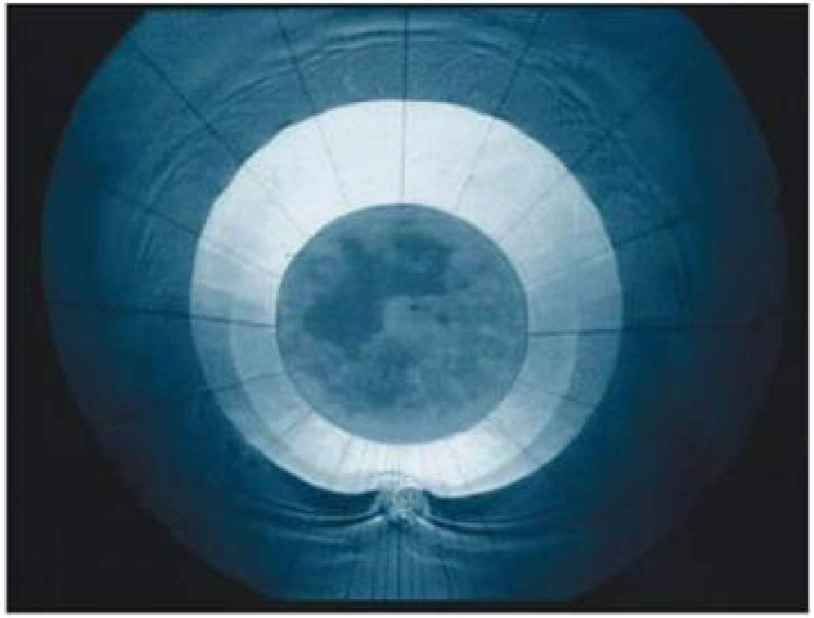


BP4: Solitary wave on a simple beach (breaking)



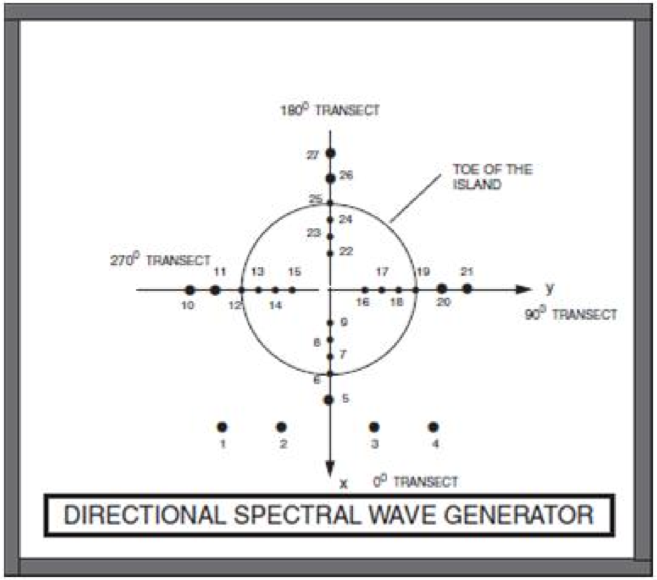
BP6: Solitary wave on a conical island

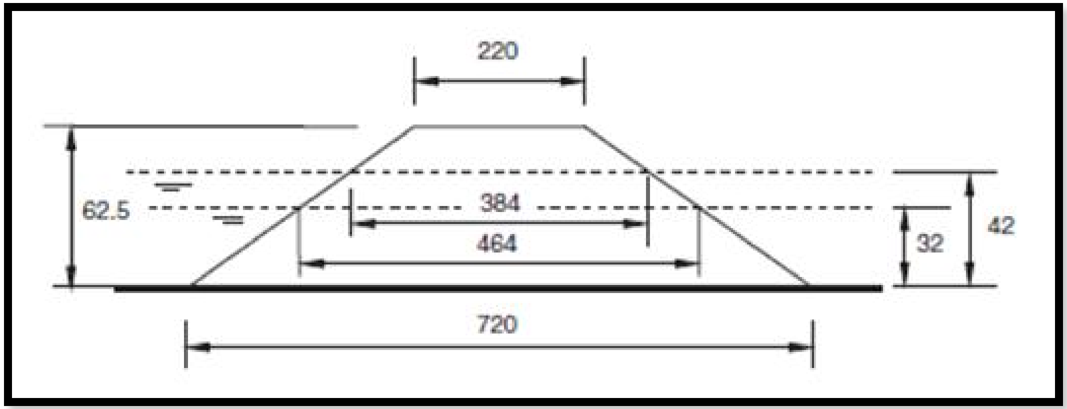
- Laboratory experiments on the interaction between solitary waves and a conical island were conducted by Briggs et al (1995).
- Large-scale laboratory experiments were performed at Coastal Engineering Research Center, Vicksburg, Mississippi, in a 30m-wide, 25m-long, and 60cm-deep wave basin
- In the physical model, a 62.5cm-high, 7.2m toe-diameter, and 2.2m crest-diameter circular island with a 1:4 slope was located in the basin



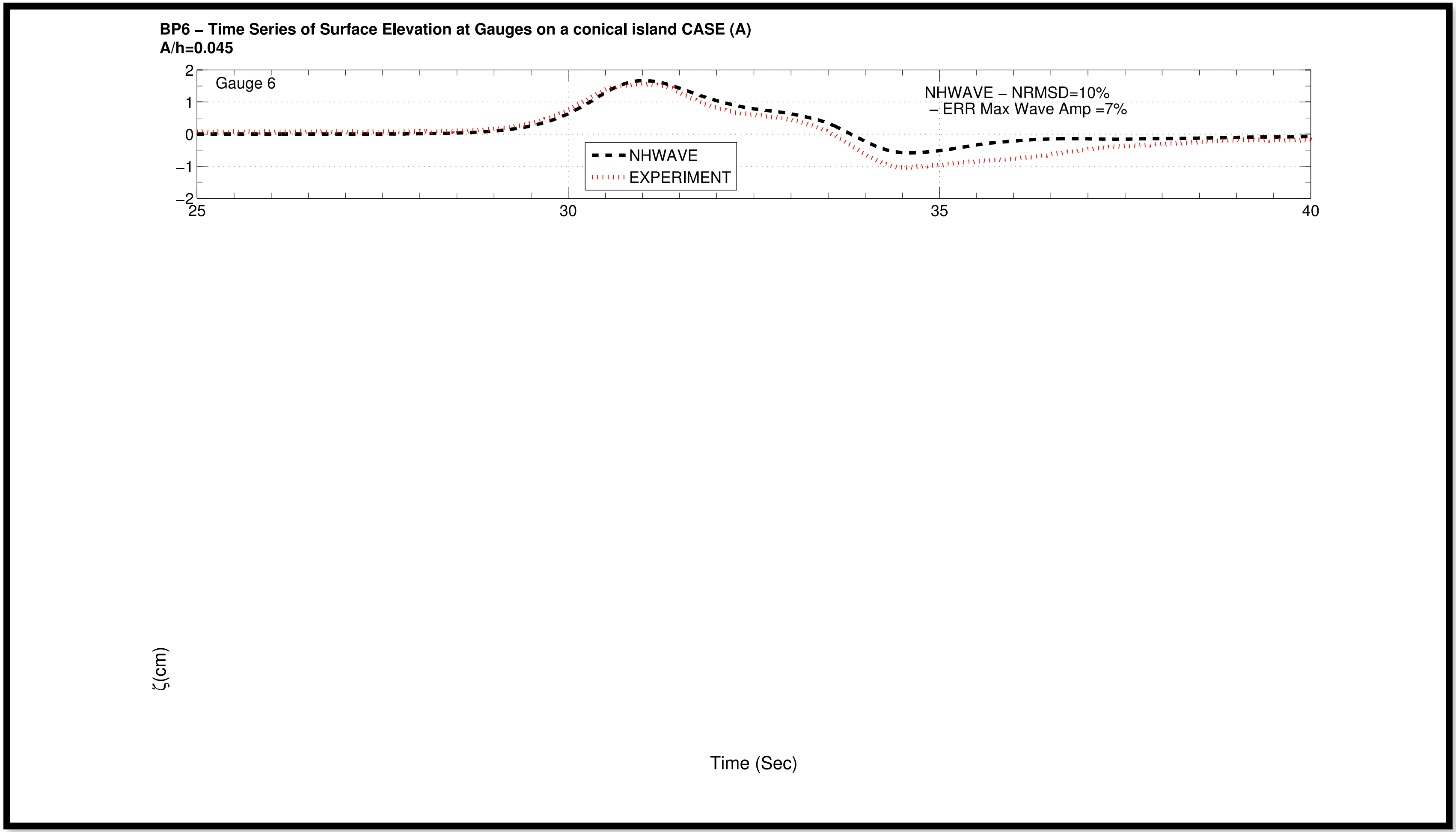
BP6: Solitary wave on a conical island

- Experiments were conducted at depth of 32cm, with three different solitary waves (H/d=0.045, 0.091, 0.181).
- Time histories of the surface elevation around the circular island are given at four locations, in the front of the island at the toe (Gauge 6) and gauges closest to the shoreline with the numbers 9, 16, and 22 located at the 0^o, 90^o, and 180^o radial lines.
- A grid size of Δx=Δy=0.10 m and three vertical layers were used.

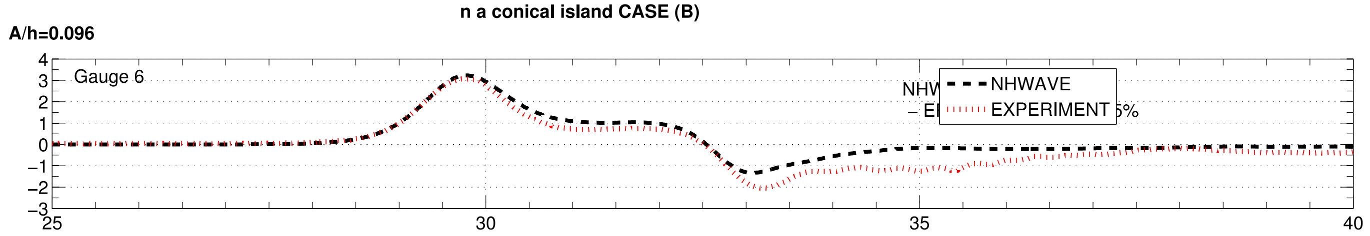




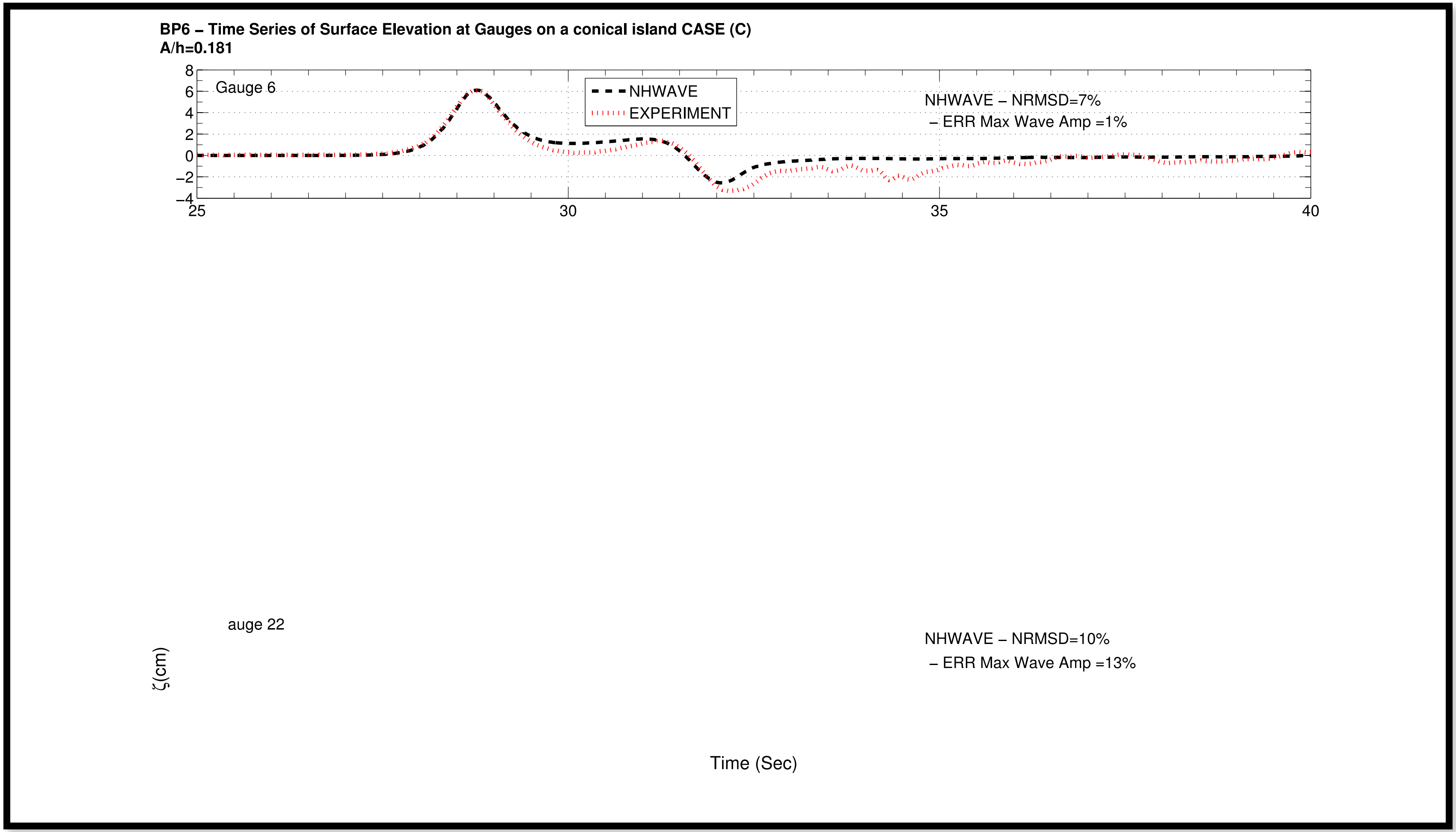
BP6: Solitary wave on a conical island (H/d=0.0045)



BP6: Solitary wave on a conical island (H/d=0.0096)



BP6: Solitary wave on a conical island (H/d=0.0181)

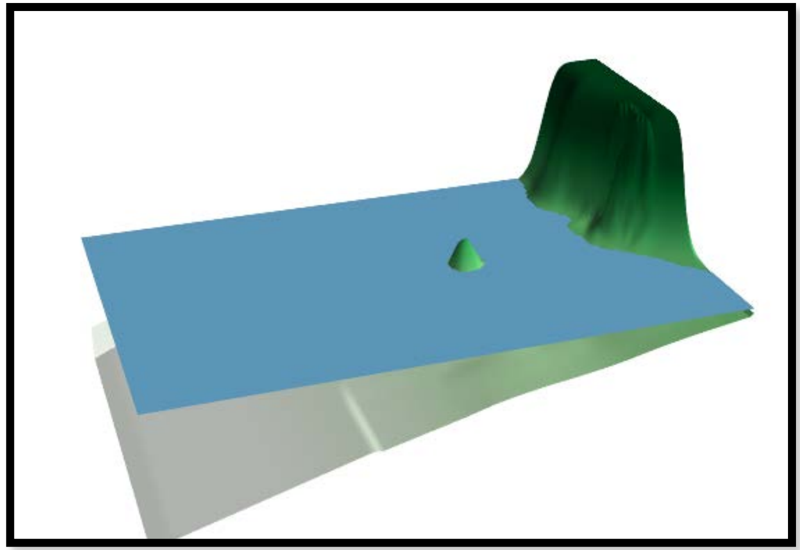


BP7: Monai Valley

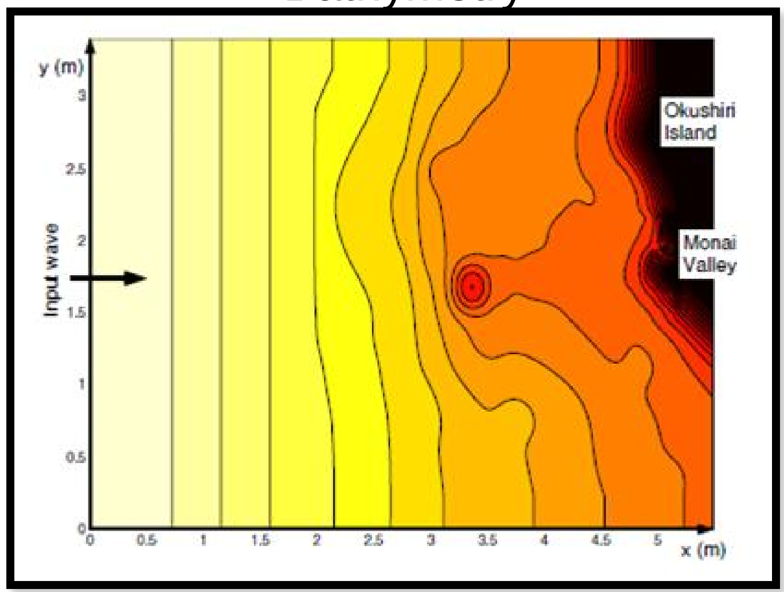
- A laboratory experiment, using a large-scale tank was focused on modeling runup of a long wave on a complex beach near the village of Monai.

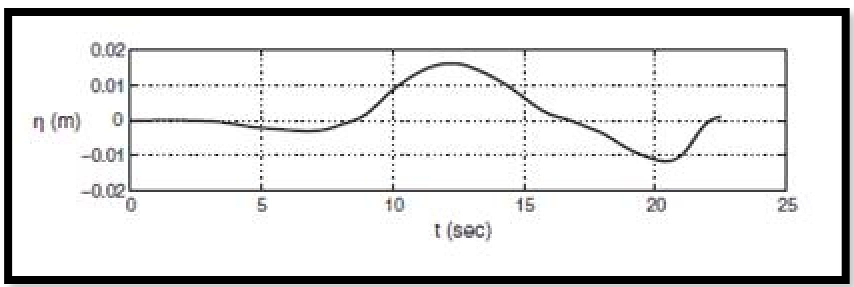
- The beach in the laboratory wave tank was a 1:400 scale model of the bathymetry and topography around a very narrow gully.

- The incoming wave in the experiment was created by wave paddles located away from the shoreline, and the water level elevations were recorded by several gauges.

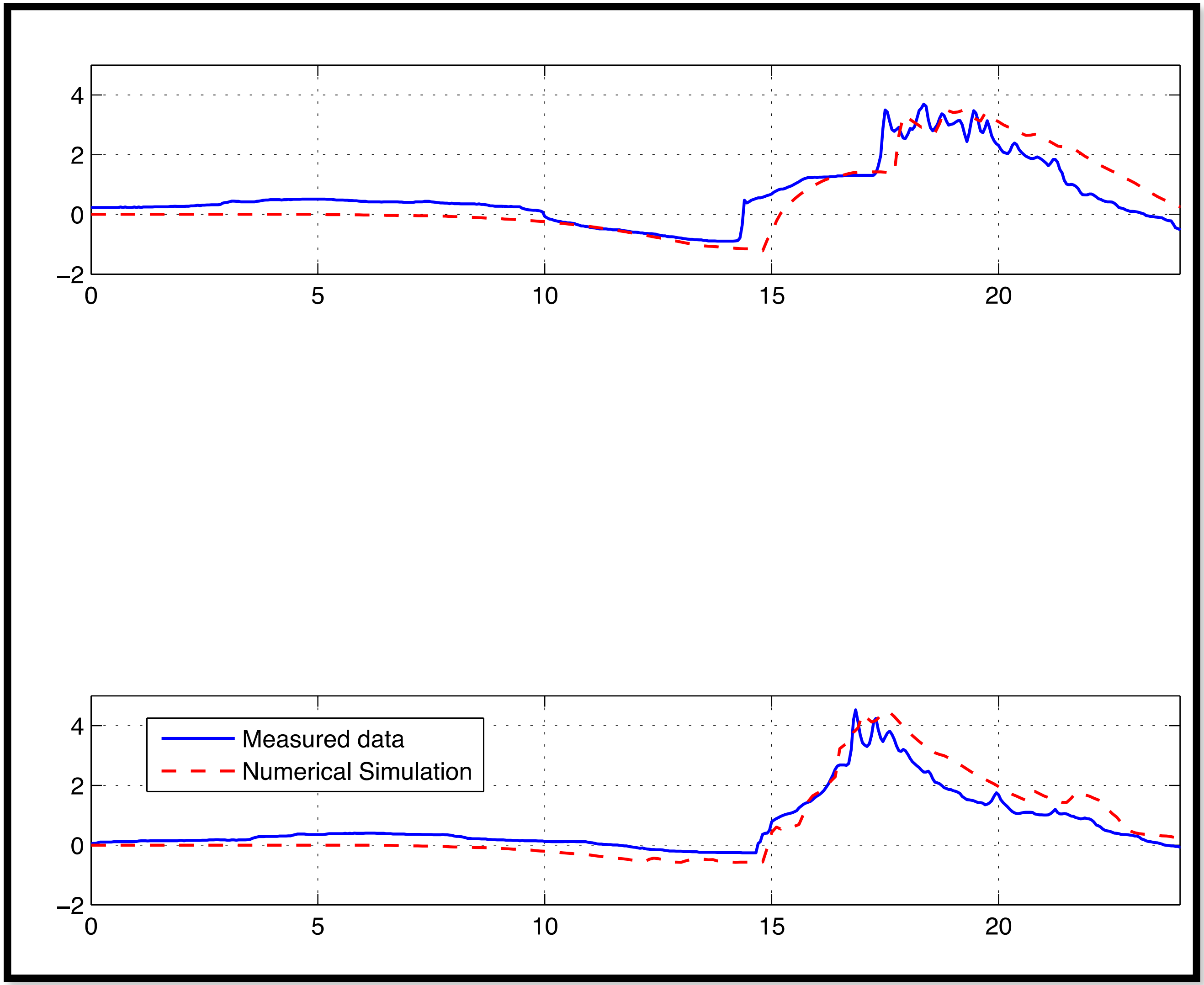


Bathymetry





BP7: Monai Valley

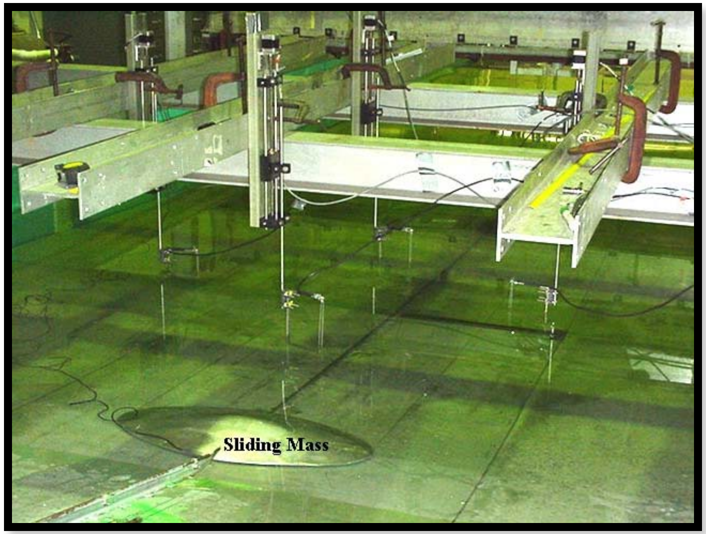


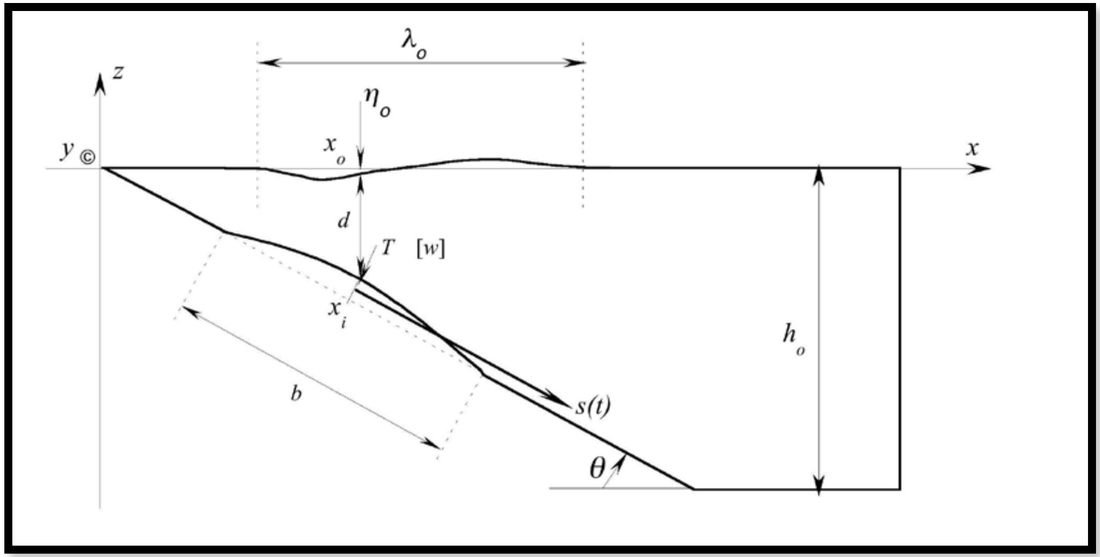
And, looking towards summer 2016 …

Enet-Grilli Landslide

- This benchmark test provide background information and details of available data for a three dimensional (3D) underwater landslide tsunami laboratory benchmark to validate landslide tsunami models (Enet and Grilli, 2007).

- These experiments are performed on a plane incline with angle θ = 15º, using a smooth stream- lined Gaussian-Shaped body, released at time t = 0 from different initial submergence depths





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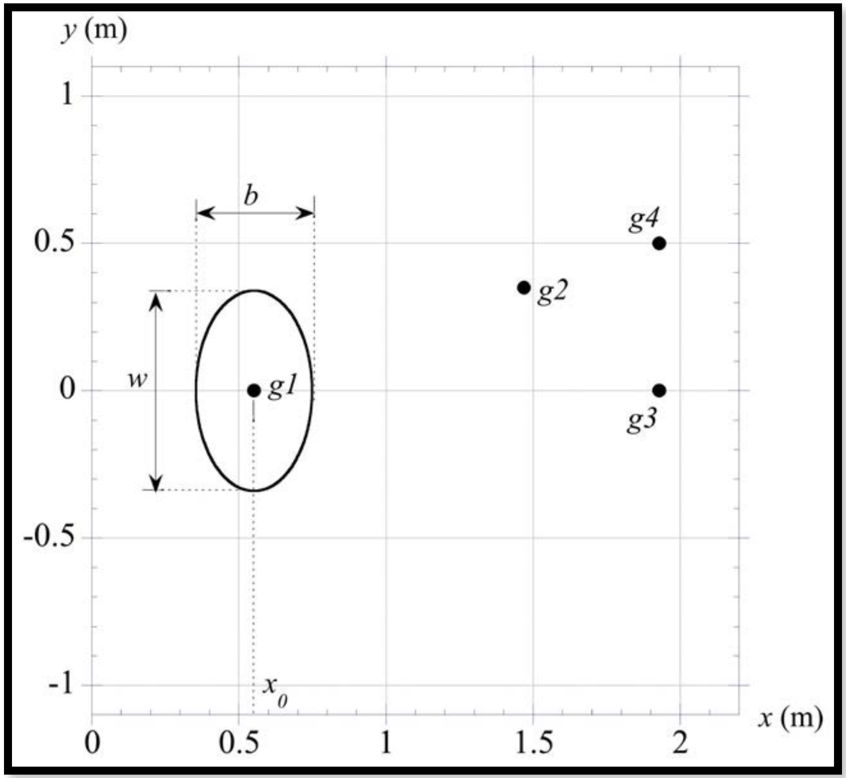
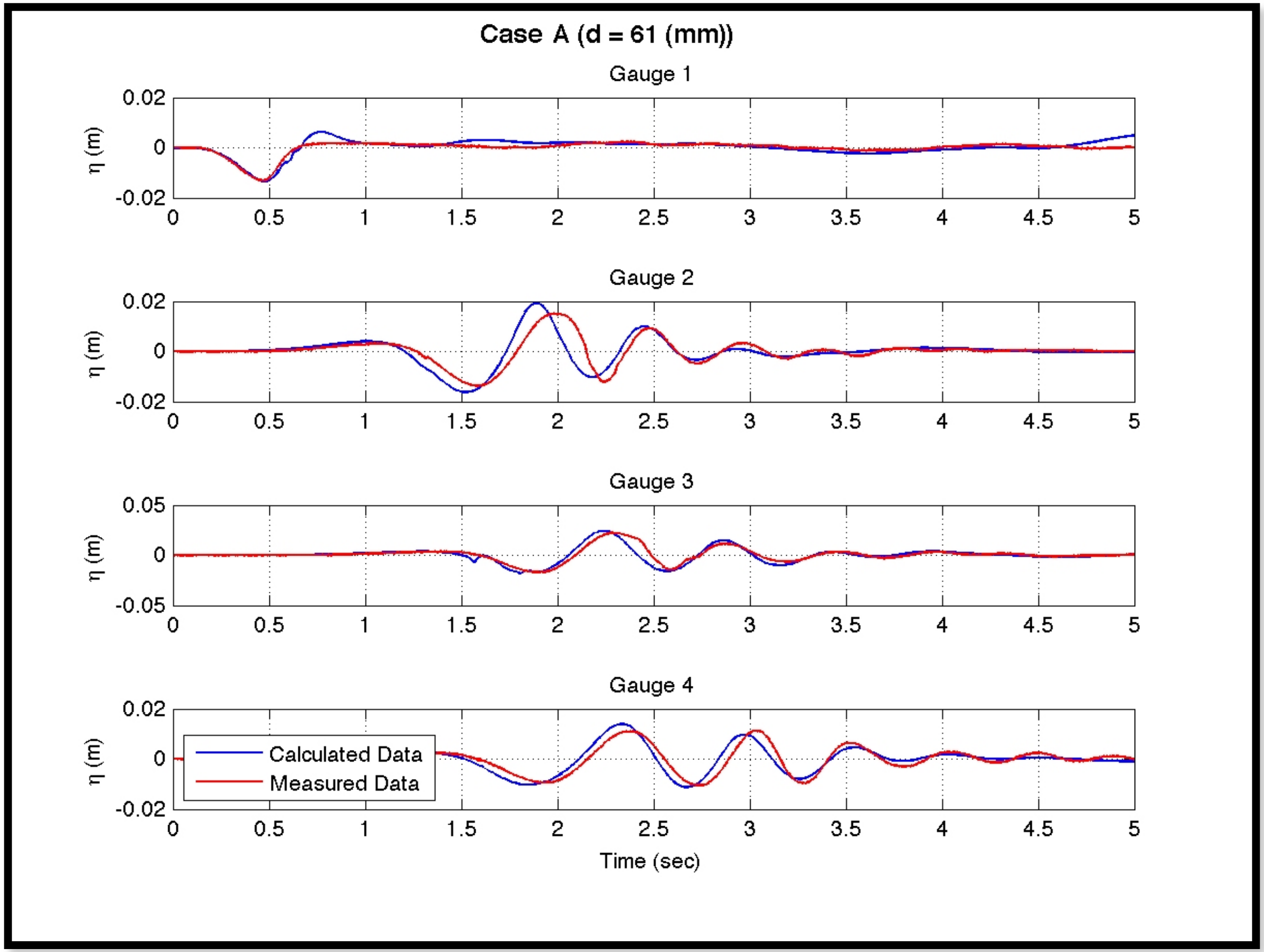
- Available measured includes slide kinematics, obtained from slide acceleration using a micro-accelerometer within the slide, time passage of the slide, and surface elevation for four gauges.

- Each experiments was repeated twice and both raw and averaged data was provided for each case.

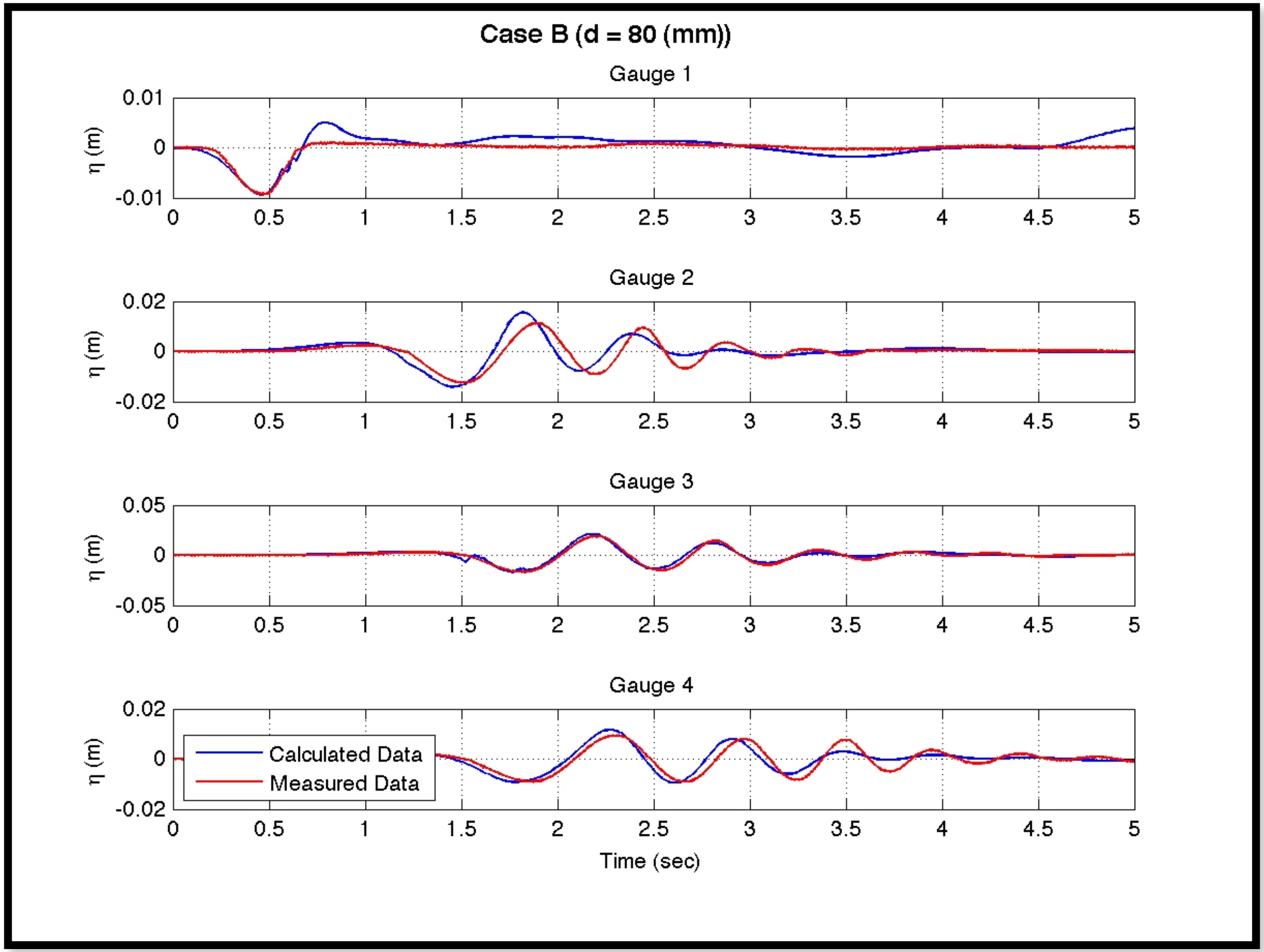
- The experimental parameters and measured data for seven different cases (Table below) exists for the four gauge shown in the figure.



Enet-Grilli Landslide (Case A)



Enet-Grilli Landslide (Case B)



Enet-Grilli Landslide (Case E)