Tsunamigenic landslide model benchmarking and validation workshop

By

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NTHMP-MMS

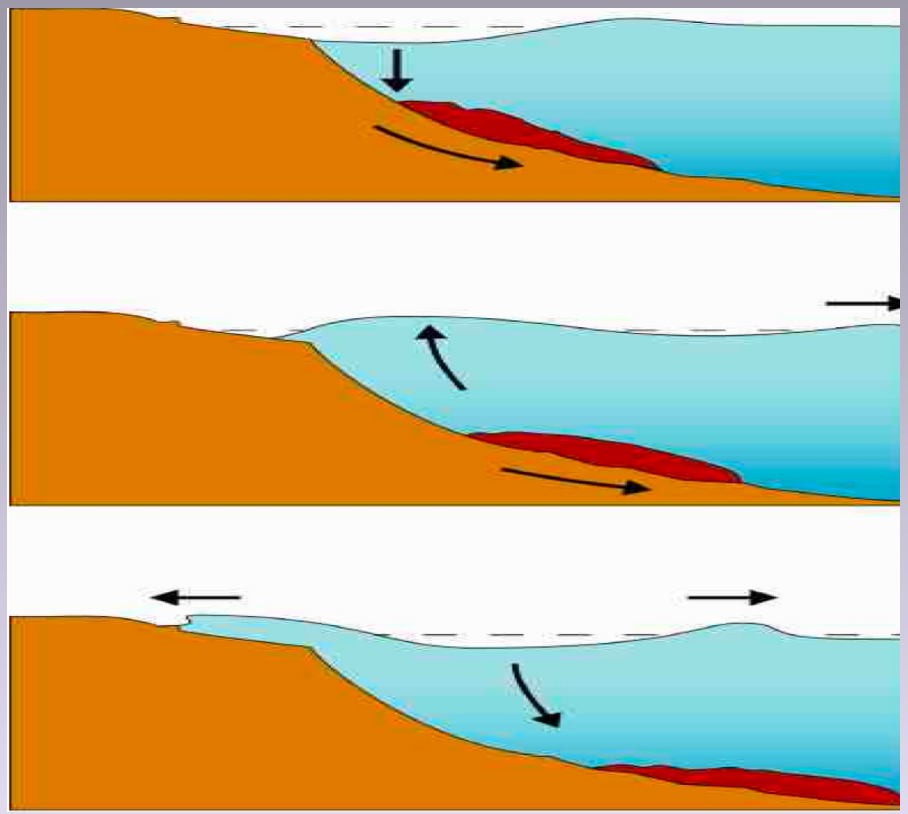
Landslide tsunami generation mechanism

-> Seismic triggering (as low as Mw = 6-7 ?) => ground acceleration (PHA), triggers landslide motion (Submarine Mass Failure; SMF)

=> tsunami source

-> SMF parameters and motion => tsunami generation and propagation (on- and offshore) (diff. co-seismic)

-> Tsunami => Coastal runup and inundation

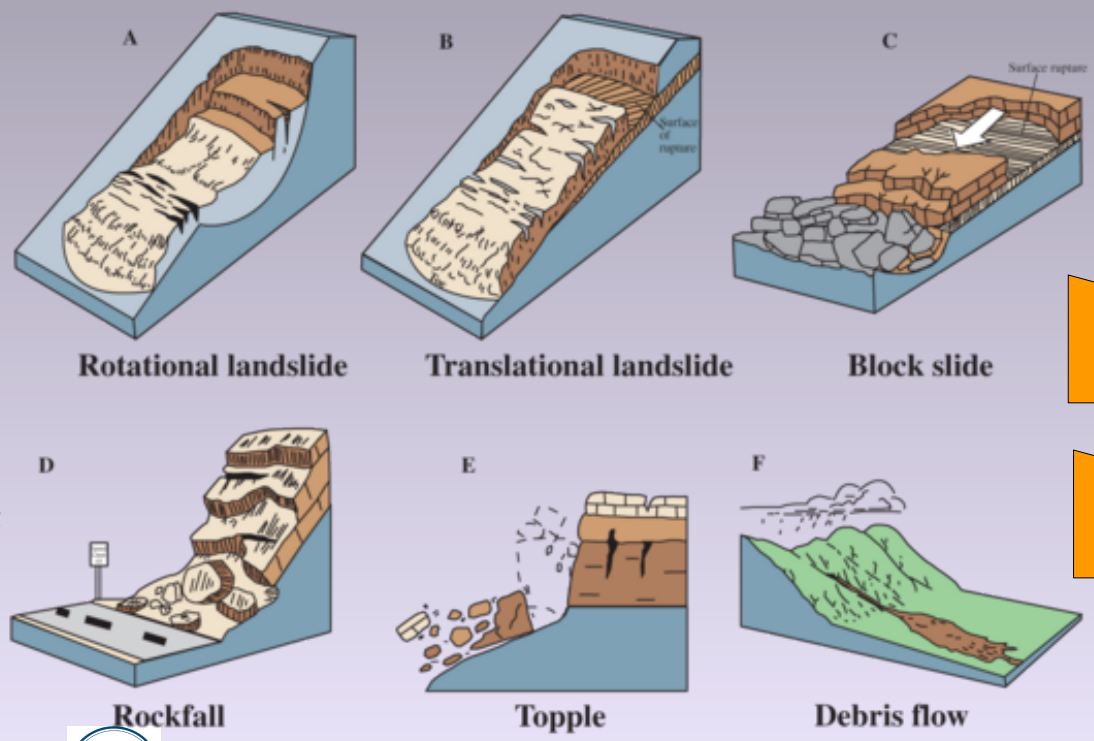


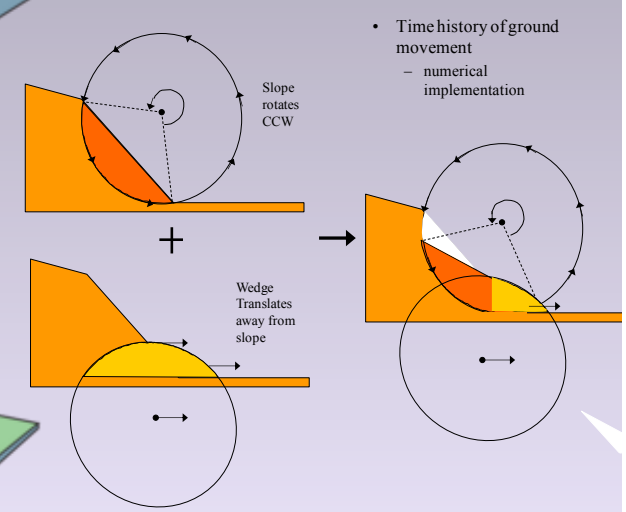
Landslide tsunami generation mechanism

-> Many types of slide failures => various mechanisms of tsunami source

-> Main parameters: volume, initial acceleration, depth/vertical motion

-> Worst case: rotational rigid slides (slumps) are the most tsunamigenic





(from USC;

P. Lynett)

URI UOD

Many observations of past underwater slides

- "Paleo-slides" off of Los Angeles : [Borrero et al., 2001]: complex shapes and material properties, variety of mechanisms

  => idealization for modeling and experimental purposes

Importance for NTHMP inundation mapping

- Many NTHMP "states" (regions) have significant tsunami hazard resulting rorm potential "landslide tsunamis" (this includes SMF, subaerial slides and volcano collapse/volcanic eruption):
  - -> Alaska/Aleutian (historical Lituya Bay, Skagway, Kitimat, Unimak)
  - -> Oregon/Washington (Cascadia induced SMFs)
  - -> California (Goleta, Big Sur,...)
  - -> Hawai (Kalapana,...)
  - -> Gulf of Mexico (Many sites, including off Mississipi Delta)
  - -> Puerto Rico (Mona Passage,...)
  - -> East Coast (Currituck and many others, Grand Bank,...)
- Many mechanisms => Many types of models are required in simulations
  => Need for model benchmarking

Workshop Rationale

-> Following earlier NTHMP model benchmarking workshops for *long wave model runup* (Galveston, 2011) and *long wave velocity* (Portland, 2015) => similar approach and goals for this workshop

-> Outcomes:

1. A set of *community accepted benchmark tests* for validating models for landslide tsunami generation (different classes)
2. A first set of *comparison of results of state-of-the-art landslide tsunami generation models* with the set of benchmarks => Develop acceptable accuracy thresholds
3. Recommendations for *future model/tests development* and *NTHMP set of criteria for acceptable landslide tsunami models*

Proposed Organization

- Committee of the two PIs plus MMS members to organize the workshop
  - -> Kick off meeting during the summer meeting + conf. calls
  - -> Initial benchmark selection and workshop agenda
  - -> Select venue (before/after summer meeting)
  - -> Preliminary list of potential benchmarks to follow
- Pre-workshop webpage will be built :
  - -> List and description of benchmarks data (a few months ahead of time)
  - -> Description/organization of workshop
  - -> Simulate benchmarks with a variety of models and compare results
  - -> Reach consensus on acceptable error threshold and models to use
- Invitation sent to potential participants with information to access site:
  - -> Ten supported participants from NTHMP modelers
  - -> Fifteen selected experts and graduate students ($20K of support)
  - -> Minimum set of benchmark to perform to receive financial support

Review of slide laboratory experiments

- Underwater rigid block slides (non- and streamlined) on a plane slope:
  - -> 2D (Watts, 1998 ; Watts, Grilli, Imamura, 2000; Grilli and Watts, 2005)
  - -> 3D (Enet and Grilli, 2003, 2005, 2007)
- Subaerial rigid block slides (non-streamlined) on a plane slope:
  - -> 2D Viroulet, Cébron, Kimmoun, Kharif, 2013)
  - -> 3D (Liu, Raichlen, Synolakis, Borrero, 2005)
- Subaerial granular slides (gravel, glass beads) on a plane slope:
  - -> 2D (Fritz, Hager, Minor, 2003, 2004; Viroulet, Sauret, Kimmoun, 2014)
  - -> 3D (Mohammad and Fritz, 2012, 2015)
- Underwater granular slides (sand, glass beads) on a plane slope:
  - -> 2D (Assier Rzadkiewicz, Mariotti, Heinrich, 1997; Kimmoun, 2015)
- Underwater mud slides on a plane slope:
  - -> 3D (Sawyer, Flemings, Buttles, Mohrig, 2012)

Review of laboratory experiments

- Underwater rigid block slides (non-streamlined) on a plane slope:
  -> 2D (Watts, 1998)

WAVEMAKER CURVES FOR TSUNAMIS GENERATED BY UNDERWATER LANDSLIDES

By P. Watts[1]

ABSTRACT: A nondimensional wavemaker curve of a characteristic water wave amplitude is constructed from the landslide length, the initial landslide submergence, the incline angle measured from the horizontal, the characteristic distance of landslide motion, and the characteristic duration of landslide motion. This wavemaker curve applies broadly to water waves generated by unsteady motion of a submerged object, provided the motion is governed by only one characteristic distance scale and one characteristic time scale. An analytical solution of solid block motion provides the characteristic distance scale and time scale. Two-dimensional experimental results on a 45° incline confirm that a wavemaker curve for solid block landslides exists as a function of the nondimensional initial submergence and what is called the Hammack number. Water wave amplitudes generated by solid block landslides can be predicted from the wavemaker curve if the solid block motion is known. Criteria for the generation of linear water waves are given.

Review of laboratory experiments

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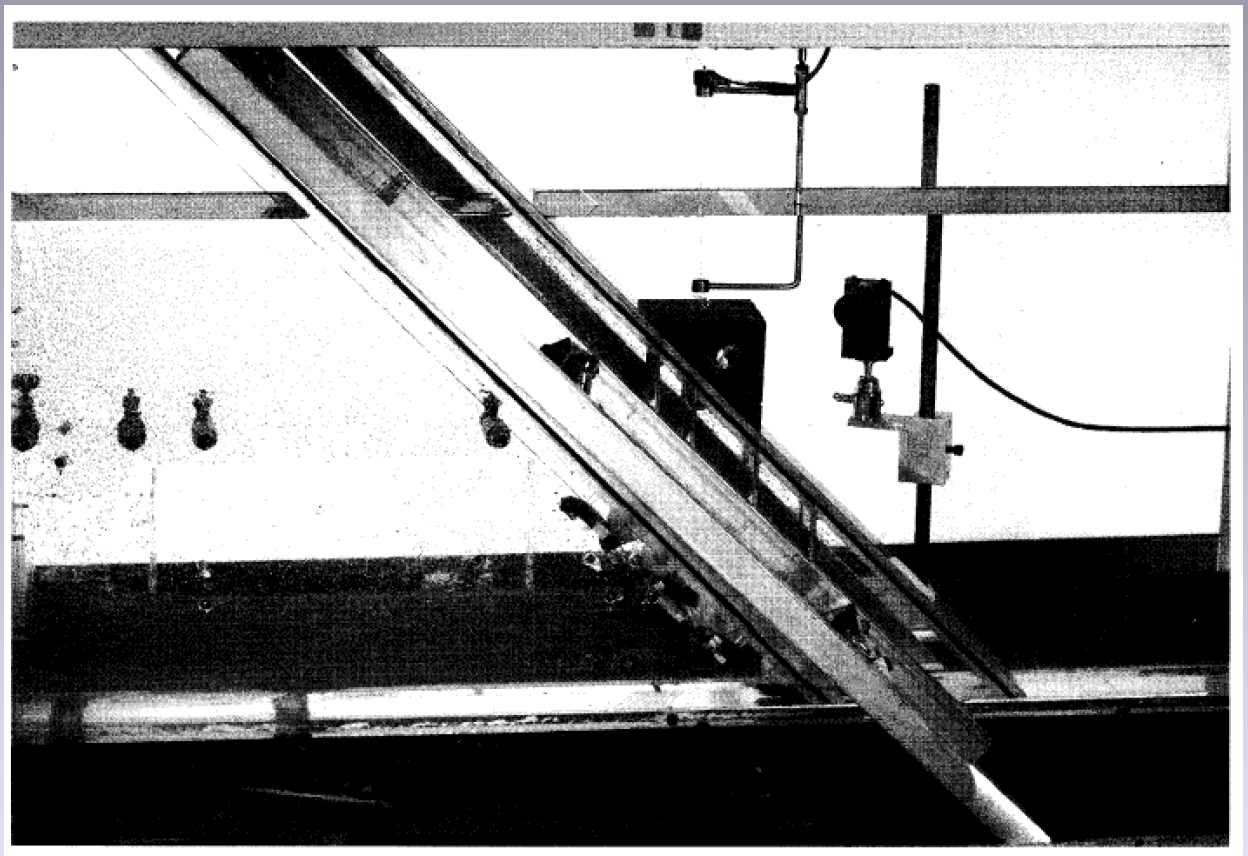
  -> 2D (Watts, 1998)



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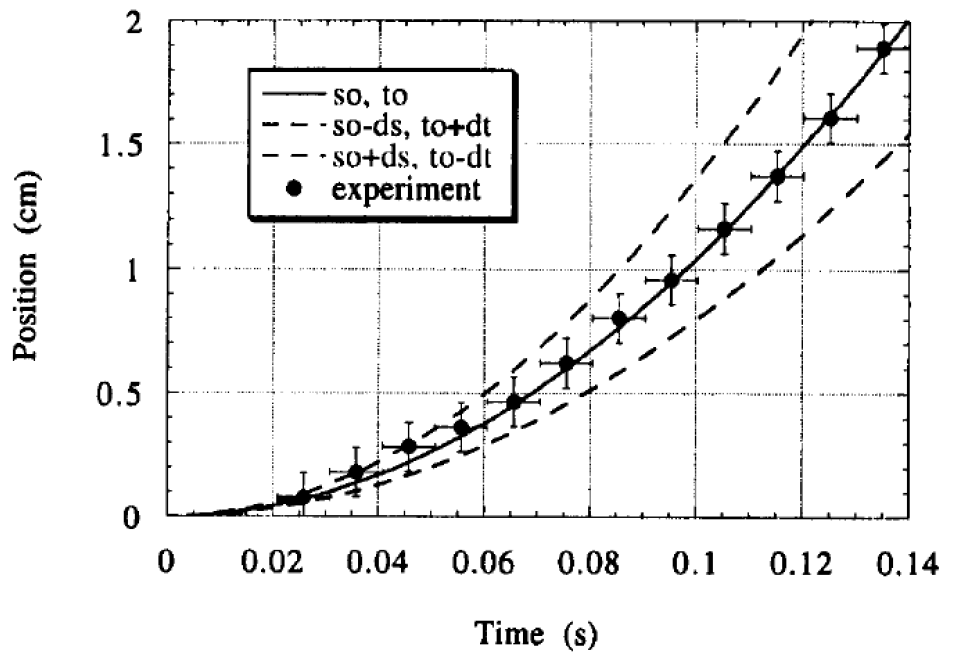

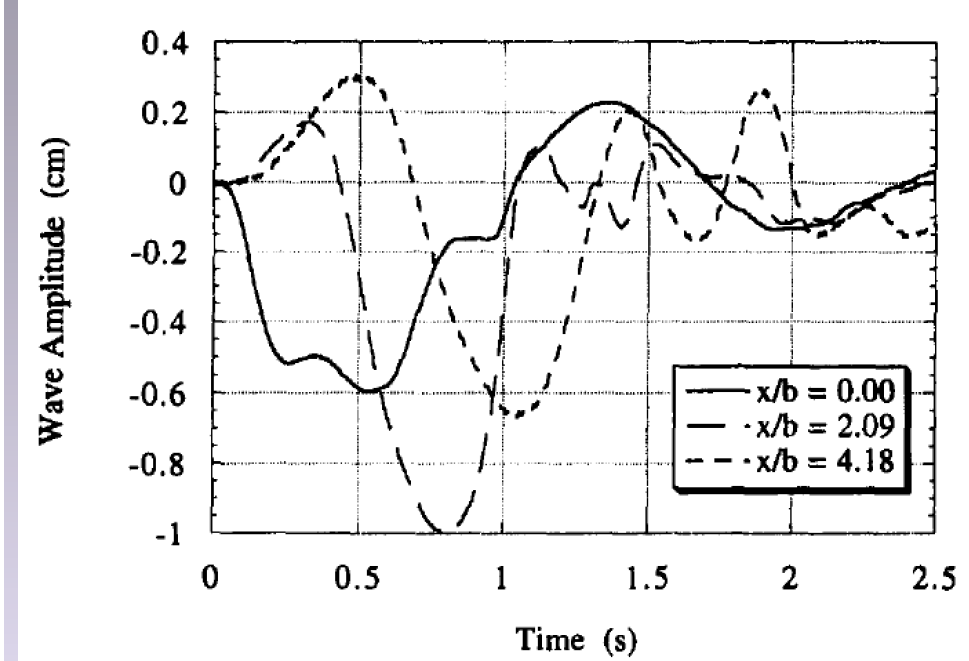

Review of laboratory experiments

- Underwater rigid block slides (non- and streamlined) on a plane slope:
  -> 2D (Watts, Grilli, Imamura, 2000; Grilli and Watts, 2005)

Tsunami Generation by Submarine Mass Failure. I: Modeling, Experimental Validation, and Sensitivity Analyses

Stéphan T. Grilli, M.ASCE,[1] and Philip Watts[2]

Abstract: Numerical simulations are performed with a two-dimensional (2D) fully nonlinear potential flow (FNPF) model for tsunami generation by two idealized types of submarine mass failure (SMF): underwater slides and slumps. These simulations feature rigid or deforming SMFs with a Gaussian cross section, translating down a plane slope. In each case, the SMF center of mass motion is expressed as a function of geometric, hydrodynamic, and material parameters, following a simple wavemaker formalism, and prescribed as a boundary condition in the FNPF model. Tsunami amplitudes and runup are obtained from computed free surface elevations. Model results are experimentally validated for a rigid 2D slide. Sensitivity studies are performed to estimate the effects of SMF–shape, type, and initial submergence depth—on the generated tsunamis. A strong SMF deformation during motion is shown to significantly enhance tsunami generation, particularly in the far-field. Typical slumps are shown to generate smaller tsunamis than corresponding slides. Both tsunami amplitude and runup are shown to depend strongly on initial SMF submergence depth. For the selected SMF idealized geometry, this dependence is simply expressed by power laws. Other sensitivity analyses are presented in a companion paper, and results from numerical simulations are converted into empirical curve fits predicting characteristic tsunami amplitudes as functions of nondimensional governing parameters. It should be stressed that these empirical formulas are only valid in the vicinity of the tsunami sources and, because of the complexity of the problem, many simplifications were necessary. It is further shown in the companion paper how 2D results can be modified to account for three-dimensional tsunami generation and used for quickly estimating tsunami hazard or for performing simple case studies.

DOI: 10.1061/(ASCE)0733-950X(2005)131:6(283)

CE Database subject headings: Tsunamis; Landslides; Experimentation; Boundary element method; Simulation; Sensitivity analysis.

Review of laboratory experiments

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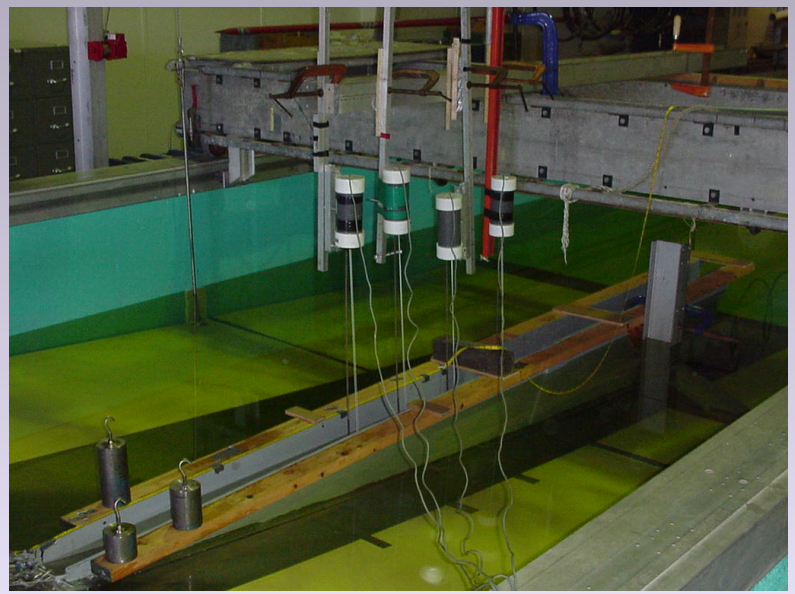

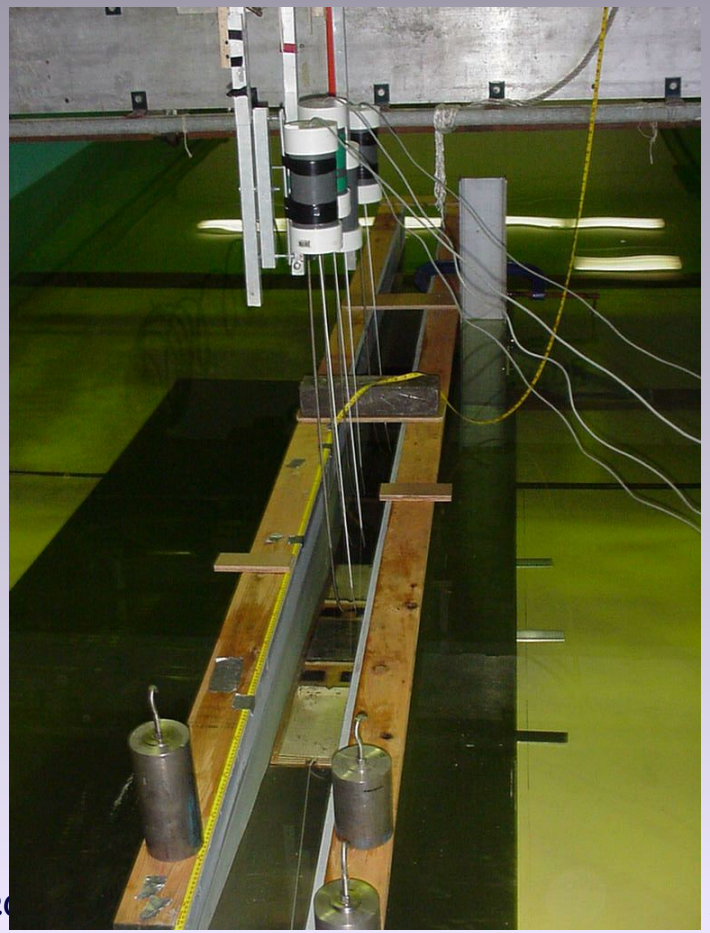

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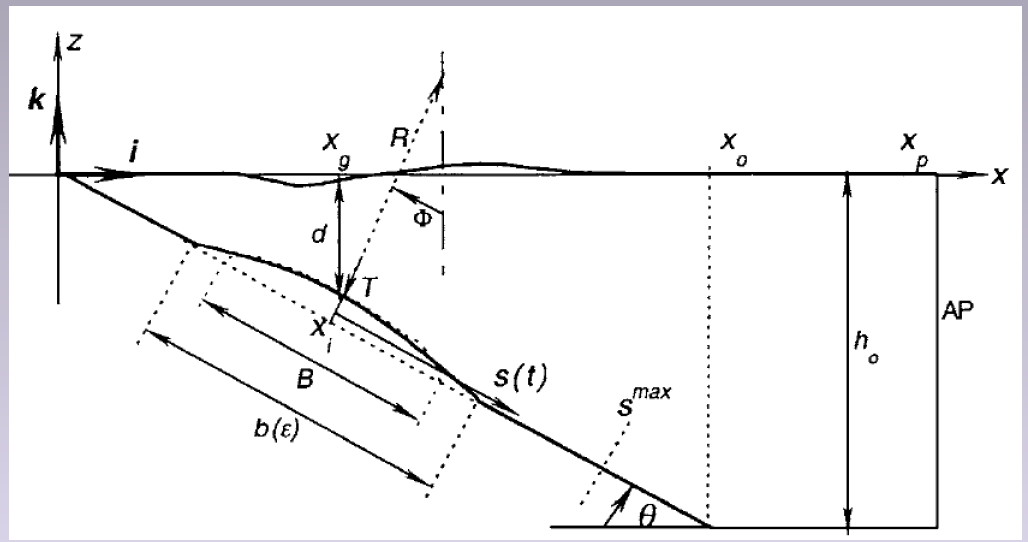

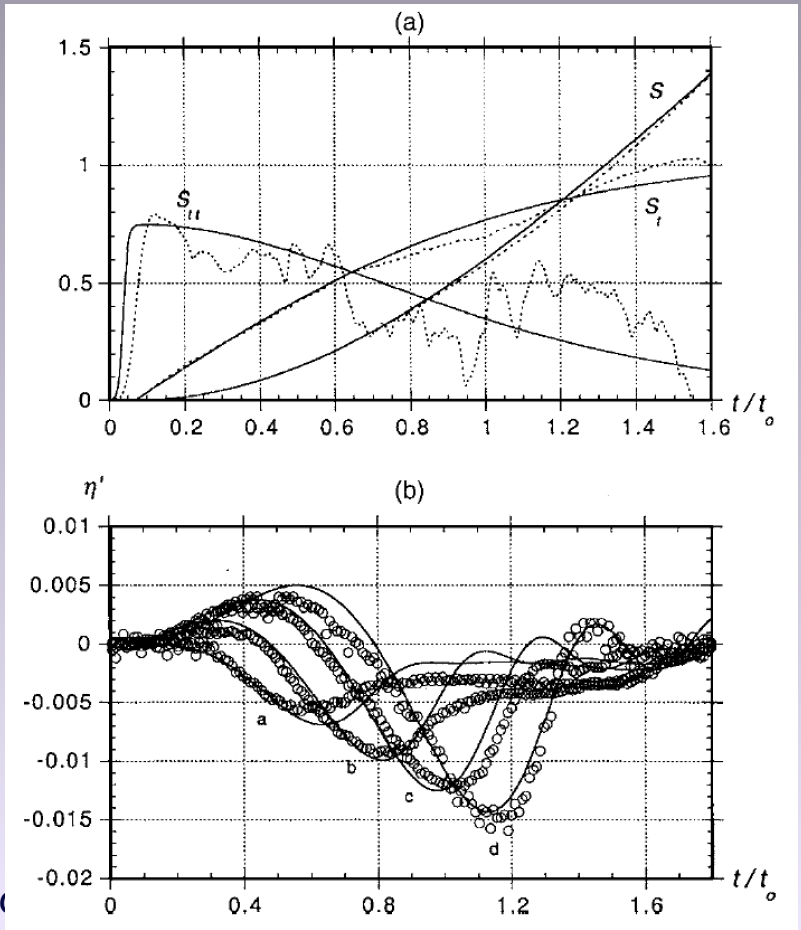

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Review of laboratory experiments

- Underwater rigid block slides (non- and streamlined) on a plane slope:
  -> 3D (Enet and Grilli, 2003, 2005, 2007)

Experimental Study of Tsunami Generation by Three-Dimensional Rigid Underwater Landslides

François Enet[1] and Stéphan T. Grilli, M.ASCE[2]

Abstract: Large scale, three-dimensional, laboratory experiments are performed to study tsunami generation by rigid underwater landslides. The main purpose of these experiments is to both gain insight into landslide tsunami generation processes and provide data for subsequent validation of a three-dimensional numerical model. In each experiment a smooth and streamlined rigid body slides down a plane slope, starting from different initial submergence depths, and generates surface waves. Different conditions of wave nonlinearity and dispersion are generated by varying the model slide initial submergence depth. Surface elevations are measured with capacitance gauges. Runup is measured at the tank axis using a video camera. Landslide acceleration is measured with a microaccelerometer embedded within the model slide, and its time of passage is further recorded at three locations down the slope. The repeatability of experiments is very good. Landslide kinematics is inferred from these measurements and an analytic law of motion is derived, based on which the slide added mass and drag coefficients are computed. Characteristic distance and time of slide motion, as well as a characteristic tsunami wavelength, are parameters derived from these analyses. Measured wave elevations yield characteristic tsunami amplitudes, which are found to be well predicted by empirical equations derived in earlier work, based on two-dimensional numerical computations. The strongly dispersive nature and directionality of tsunamis generated by underwater landslides is confirmed by wave measurements at gauges. Measured coastal runup is analyzed and found to correlate well with initial slide submergence depth or characteristic tsunami amplitude.

DOI: 10.1061/(ASCE)0733-950X(2007)133:6(442)

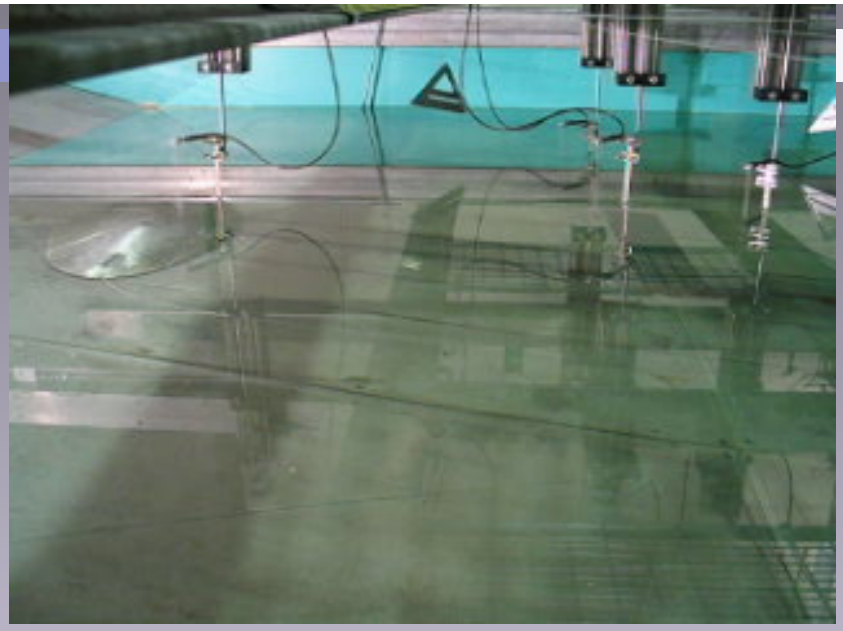
CE Database subject headings: Tsunamis; Landslides; Laboratory tests; Wave runup; Surface waves; Experimentation.

Experiments for Rigid 3D streamlined slide

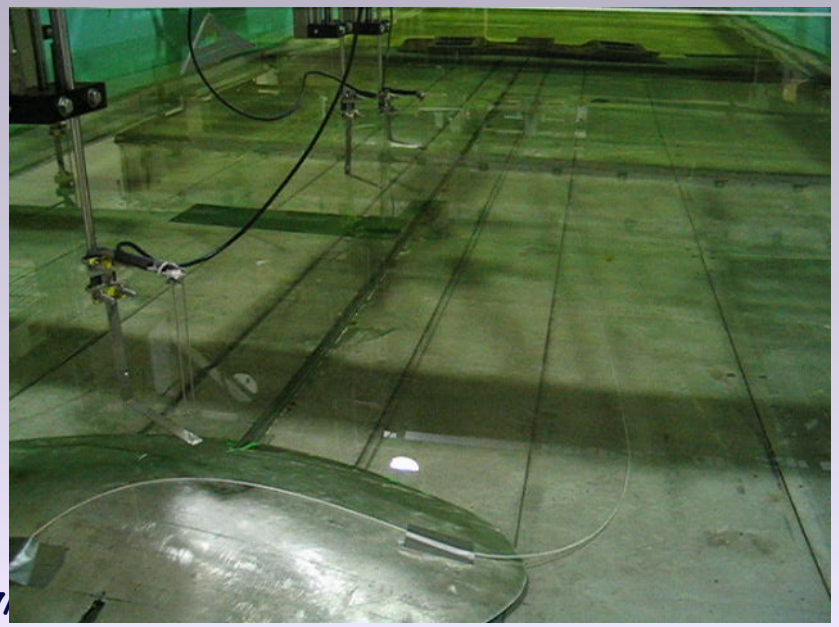
[Enet and Grilli, 2003, 2005, 2007]

- Gaussian shape rigid slide:

$$\zeta(\xi,\nu)=\frac{T}{1-\varepsilon}\left\{\operatorname{sech}\left(\frac{2C\xi}{b}\right)\operatorname{sech}\left(\frac{2C\nu}{w}\right)-\varepsilon\right\}$$



- 3D-experiments => various initial submergence depths and gages
- Fully nonlinear inviscid (BEM) computations => good agreement
- Waves are directional in slide direction of motion => significant coupling and energy focusing



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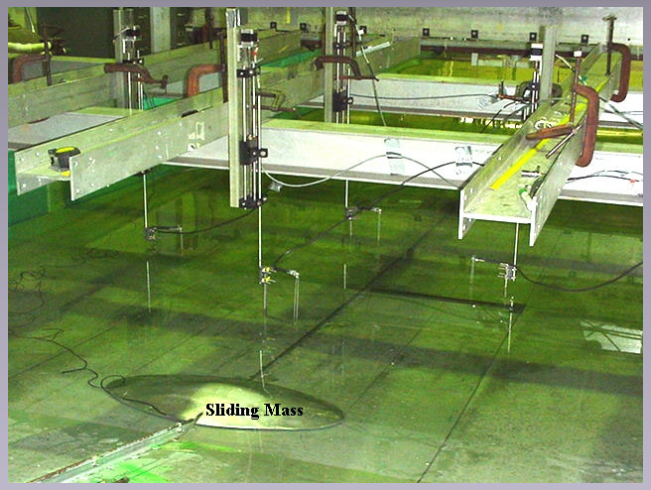
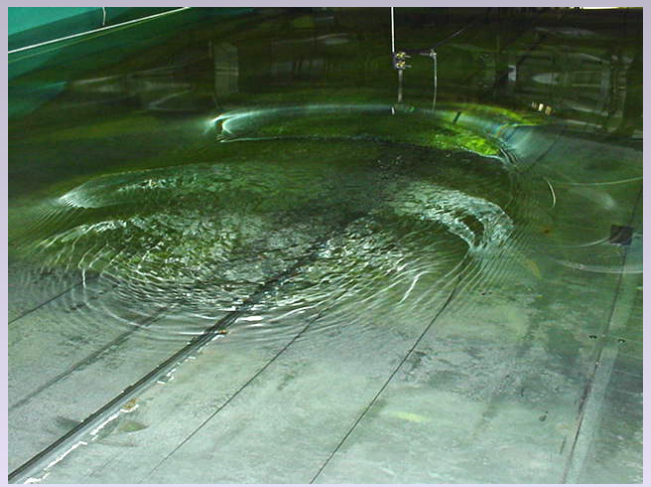
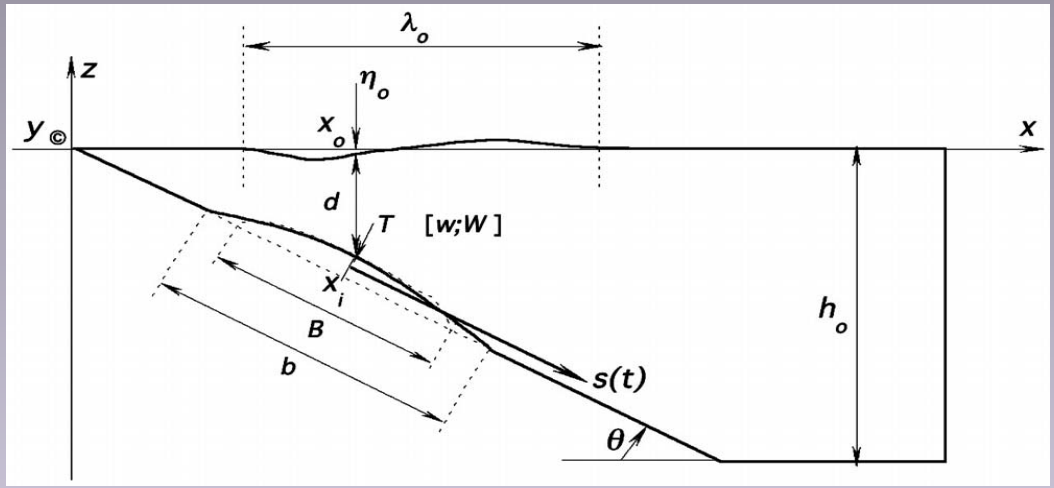
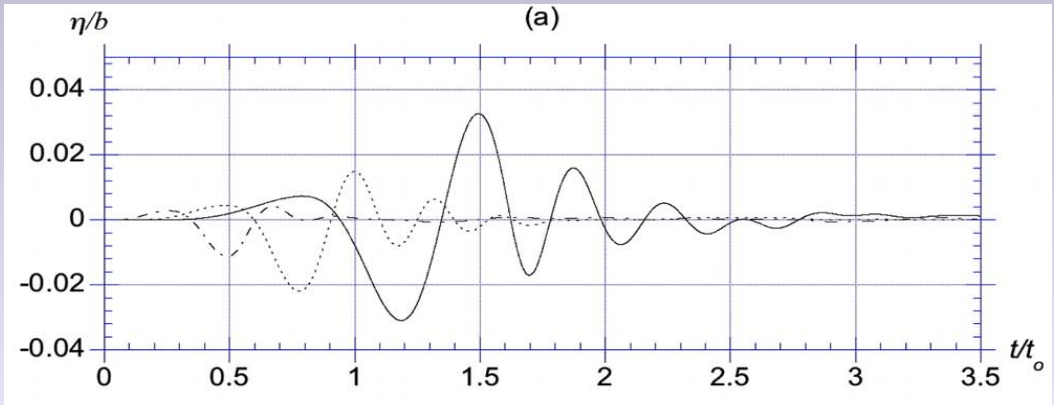
Experiments for Rigid streamlined slide





[Enet and Grilli, 2003, 2005, 2007]





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Review of laboratory experiments

- Subaerial rigid block slides (non-streamlined) on a plane slope:
  -> 3D (Liu, Raichlen, Synolakis, Borrero, 2005)

J. Fluid Mech. (2005), *vol.* 536, *pp.* 107–144. © 2005 Cambridge University Press 107
doi:10.1017/S0022112005004799 Printed in the United Kingdom

Runup and rundown generated by three-dimensional sliding masses

By P. L.-F. LIU[1], T.-R. WU[1], F. RAICHLEN[2], C. E. SYNOLAKIS[3] AND J. C. BORRERO[3]

[1]School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

[2]Division of Engineering and Applied Sciences, California Institute of Technology, Pasadena, CA 91108, USA

[3]Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089, USA

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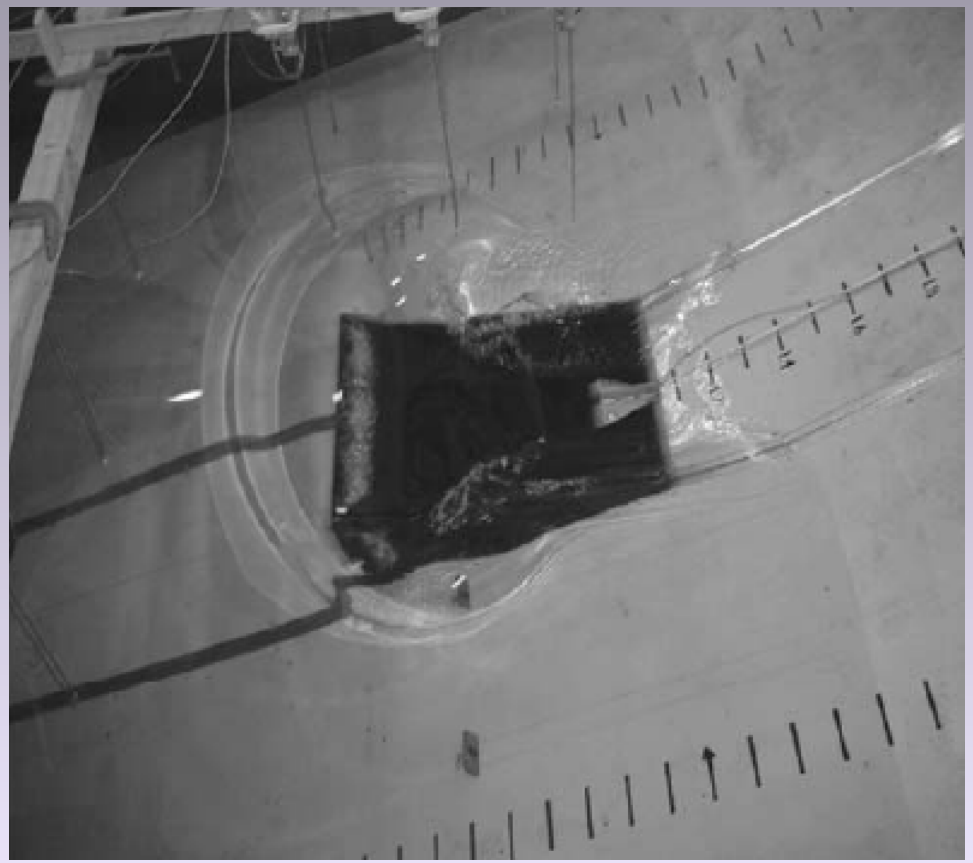

Review of laboratory experiments

- Subaerial granular slides (gravel, glass beads) on a plane slope:
  -> 2D (Fritz, Hager, Minor, 2003, 2004)

Near Field Characteristics of Landslide Generated Impulse Waves

H. M. Fritz[1]; W. H. Hager[2]; and H.-E. Minor[3]

Abstract: Landslide generated impulse waves were investigated in a two-dimensional physical laboratory model based on the generalized Froude similarity. The recorded wave profiles were extremely unsteady and nonlinear. Four wave types were determined: weakly nonlinear oscillatory wave, non-linear transition wave, solitary-like wave and dissipative transient bore. Most of the generated impulse waves were located in the intermediate water depth wave regime. Nevertheless the propagation velocity of the leading wave crest closely followed the theoretical approximations for a solitary wave. Between 4 and 50% of the kinetic slide impact energy propagated outward in the impulse wave train. The applicability ranges of the classical nonlinear wave theories to landslide generated impulse waves were determined. The main wave characteristics were related to the landslide parameters driving the entire wave generation process. The slide Froude number was identified as the dominant parameter. The physical model results were compared to the giant rockslide generated impulse wave which struck the shores of the Lituya Bay, Alaska, in 1958.

DOI: 10.1061/(ASCE)0733-950X(2004)130:6(287)

CE Database subject headings: Landslides; Tsunamis; Two-dimensional models; Wave generation; Alaska.

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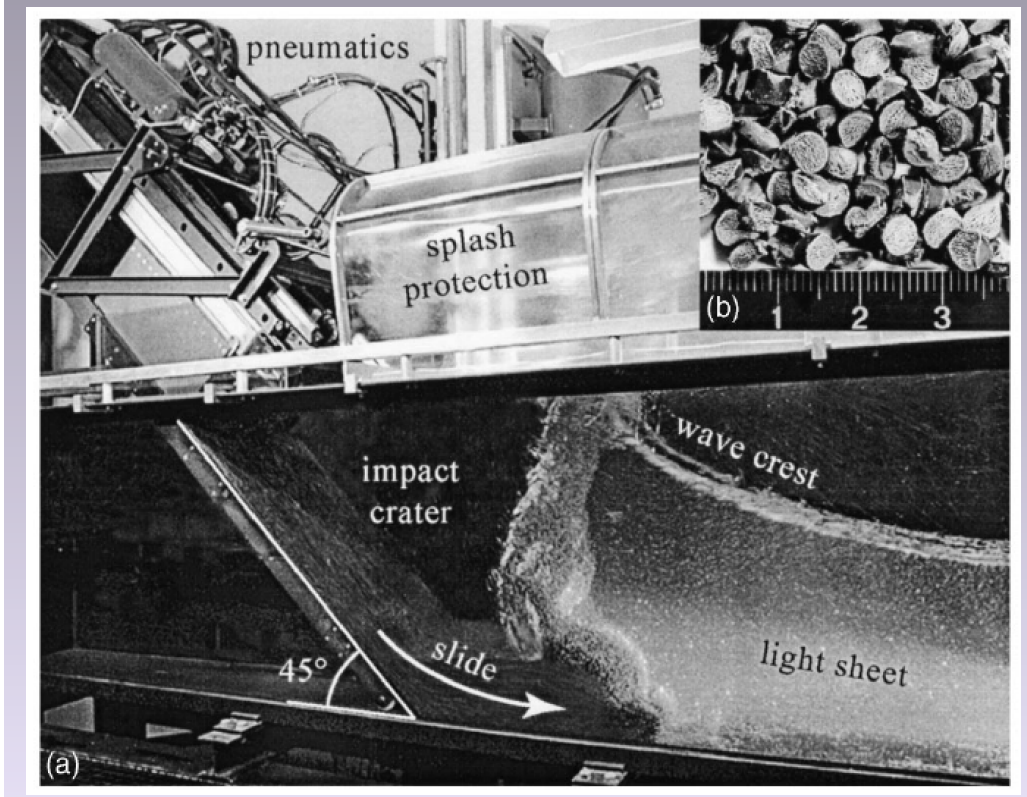

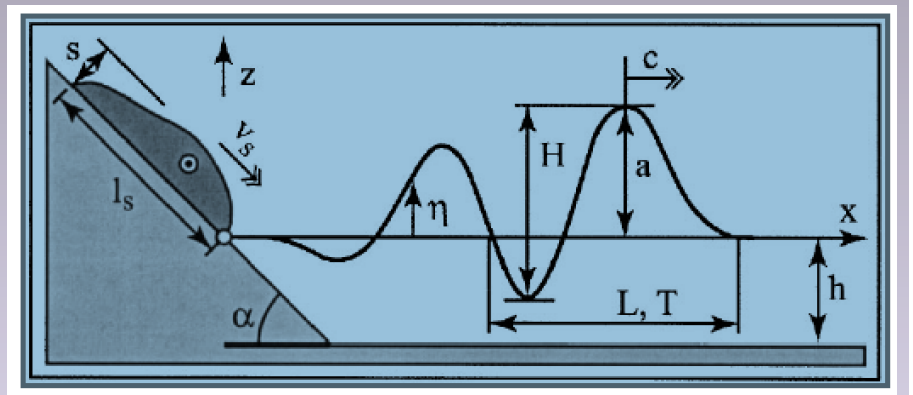

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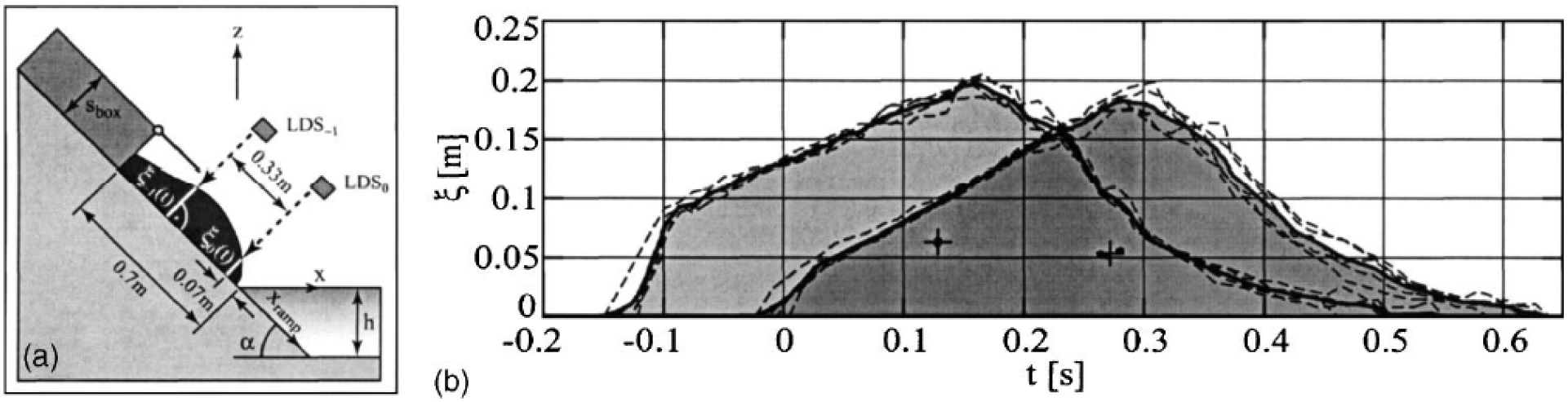

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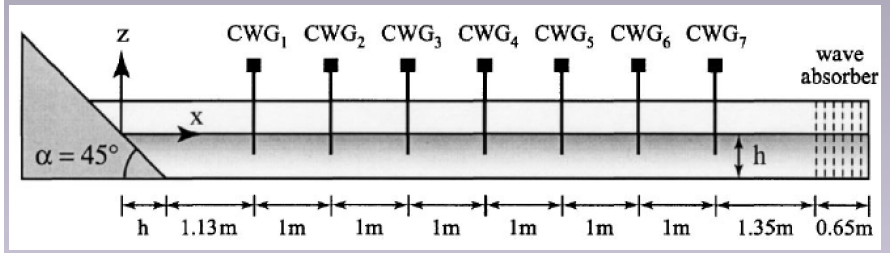

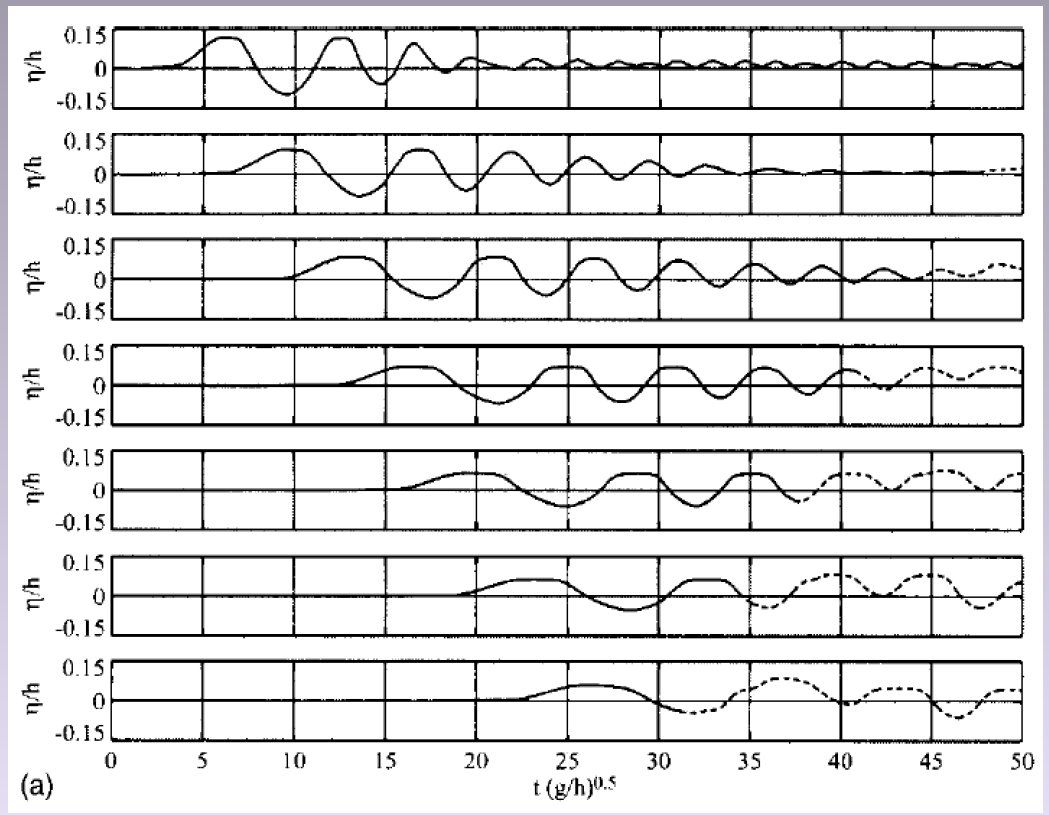

Review of laboratory experiments

- Subaerial granular slides (glass beads) on a plane slope:
  -> 2D (Viroulet, Sauret, Kimmoun, 2014)

epl draft

Tsunami generated by a granular collapse down a rough inclined plane

S. Viroulet[1], A. Sauret[2] and O. Kimmoun[1]

[1] *IRPHE, CNRS UMR 7342 - Aix-Marseille University - AMU - Ecole Centrale Marseille, France*
[2] *Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey 08544, USA*

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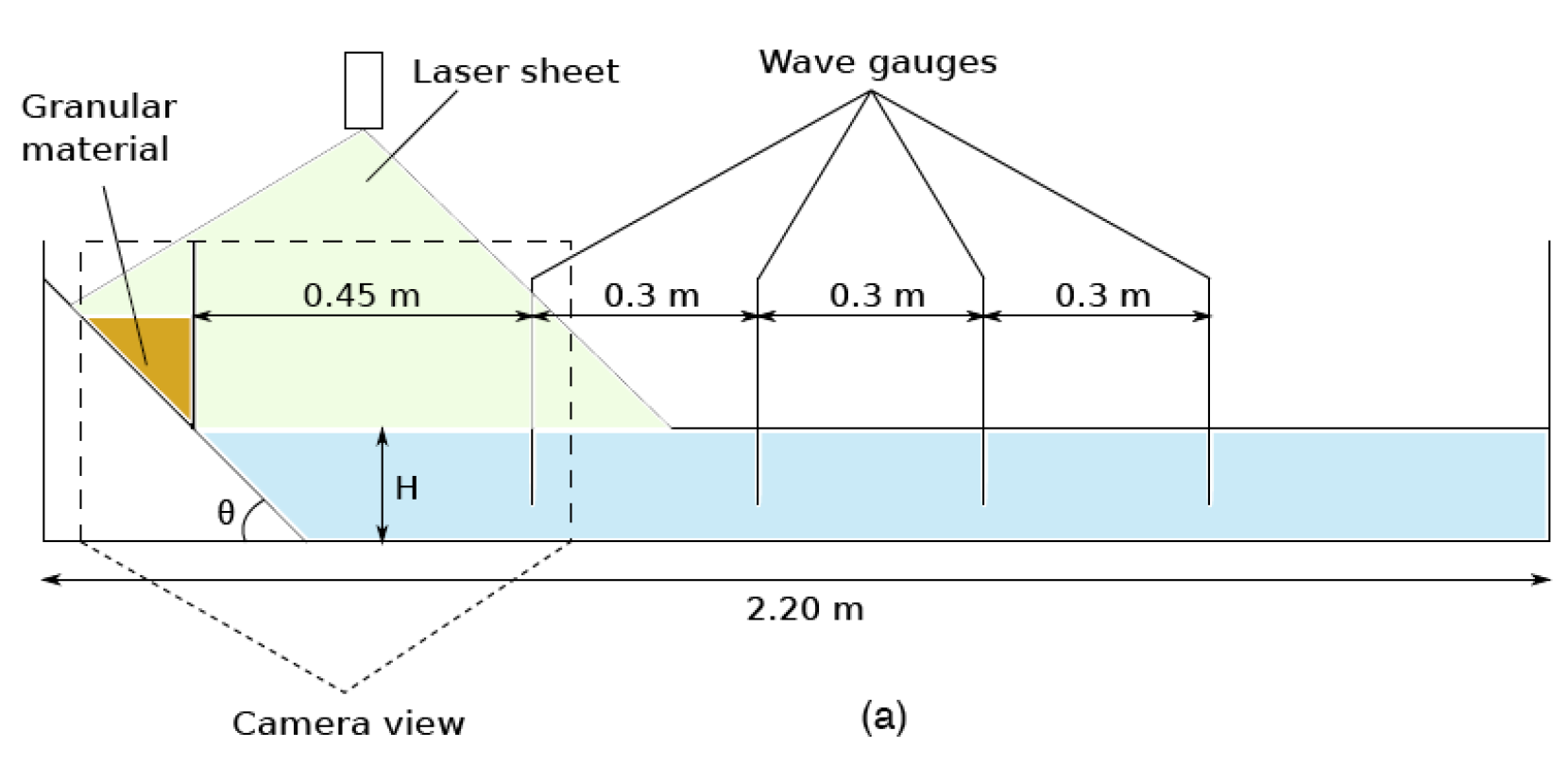

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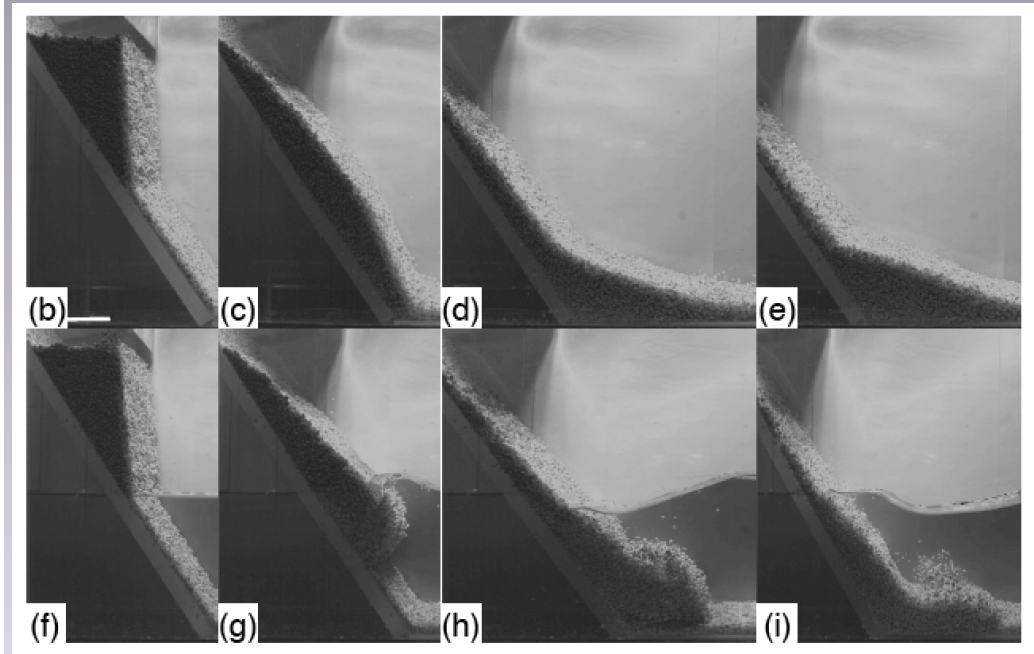

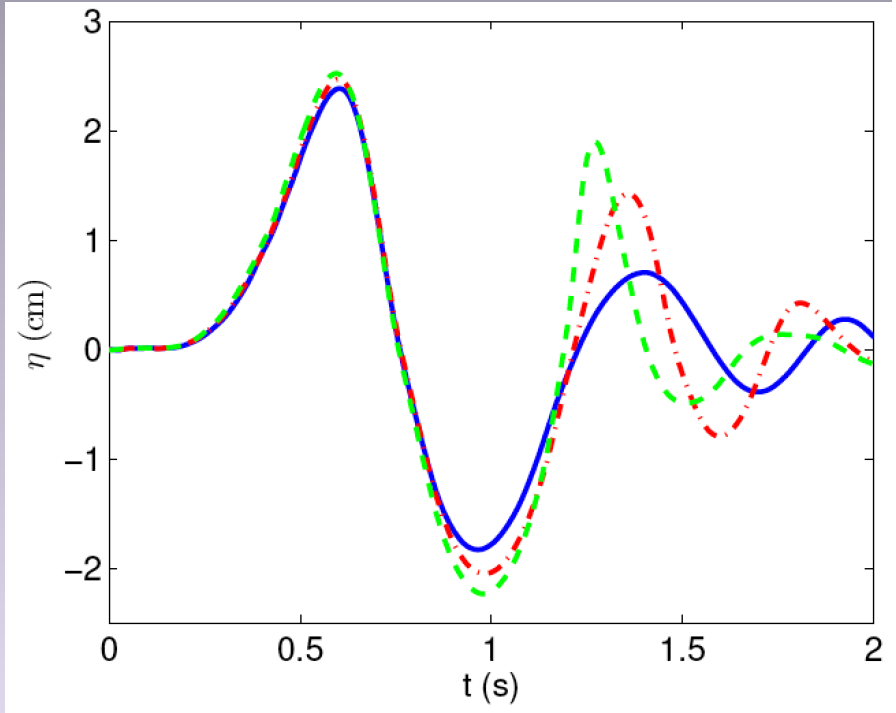

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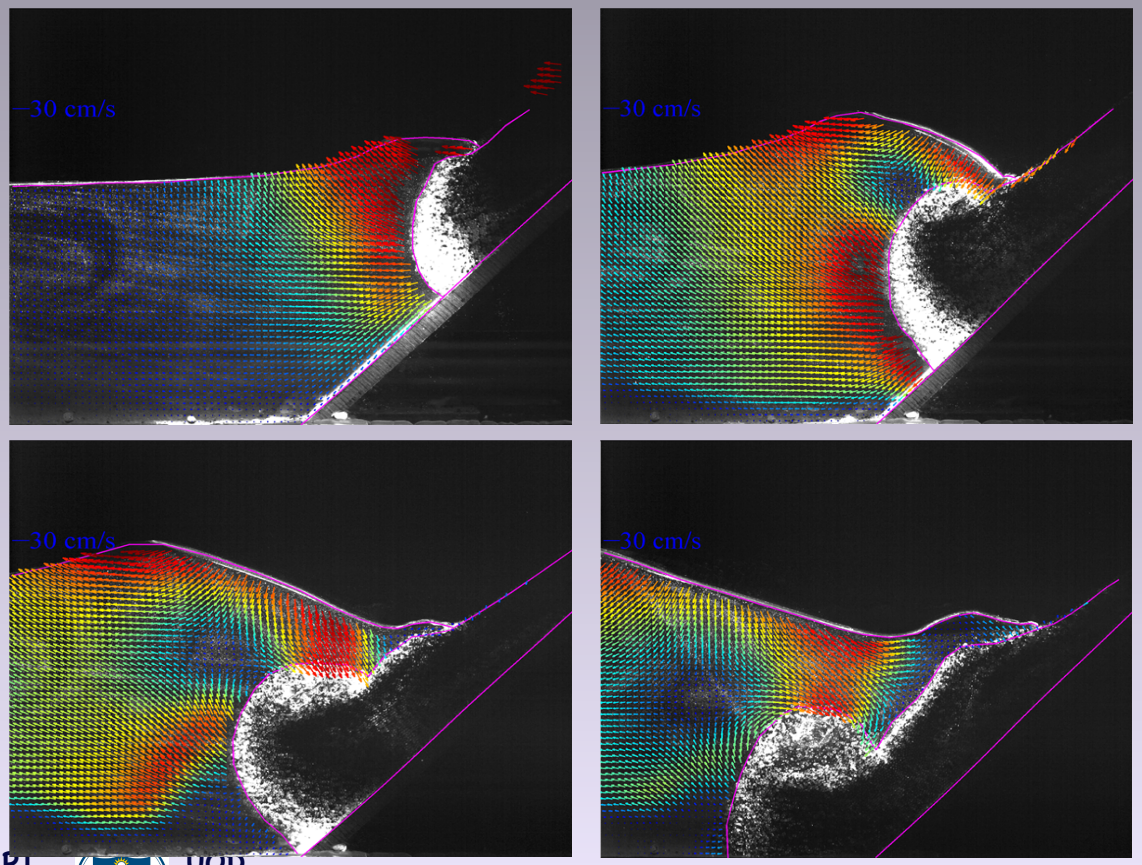

Review of laboratory experiments

- Subaerial granular slides (gravel, glass beads) on a plane slope:
  -> 3D (Mohhamad and Fritz, 2012, 2015)

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, C11015, doi:10.1029/2011JC007850, 2012

Physical modeling of tsunamis generated by three-dimensional deformable granular landslides

Fahad Mohammed[1,2] and Hermann M. Fritz[2]

Review of laboratory experiments

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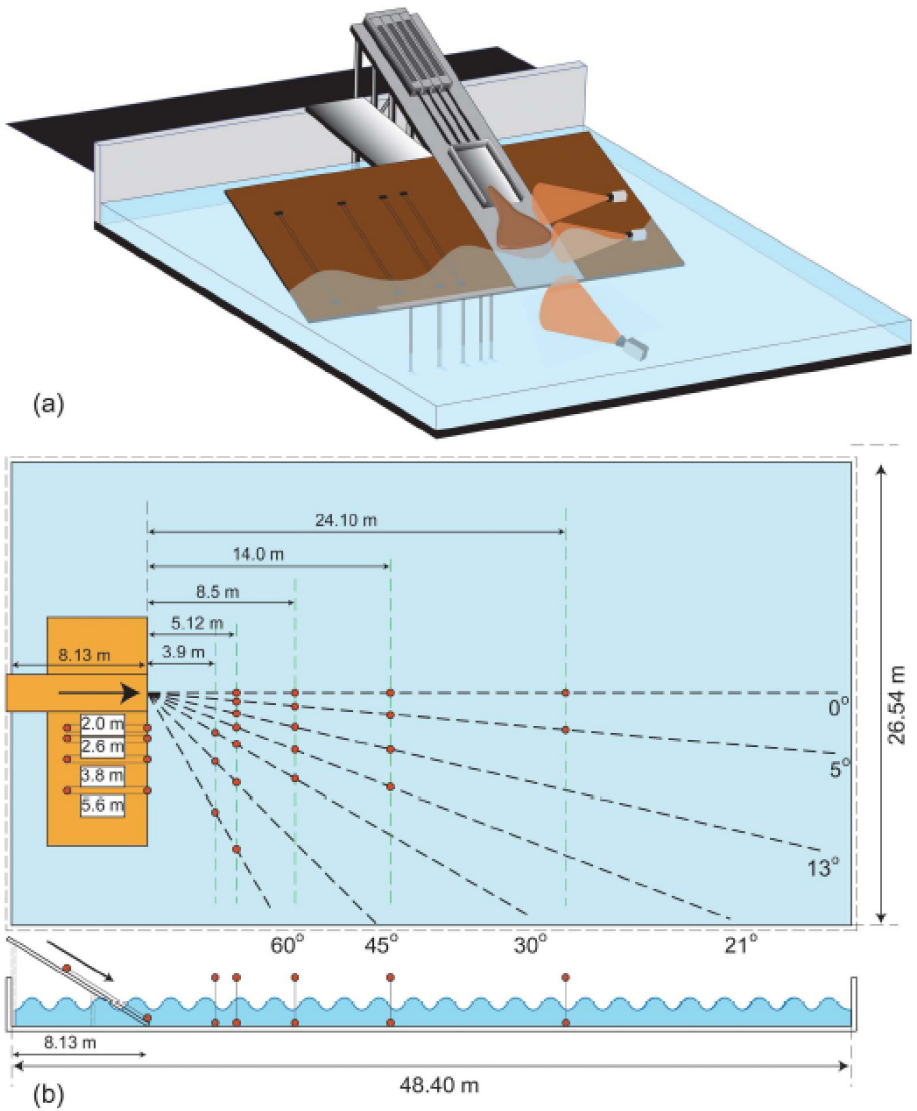
  -> 3D (Mohammad and Fritz, 2012, 2015)



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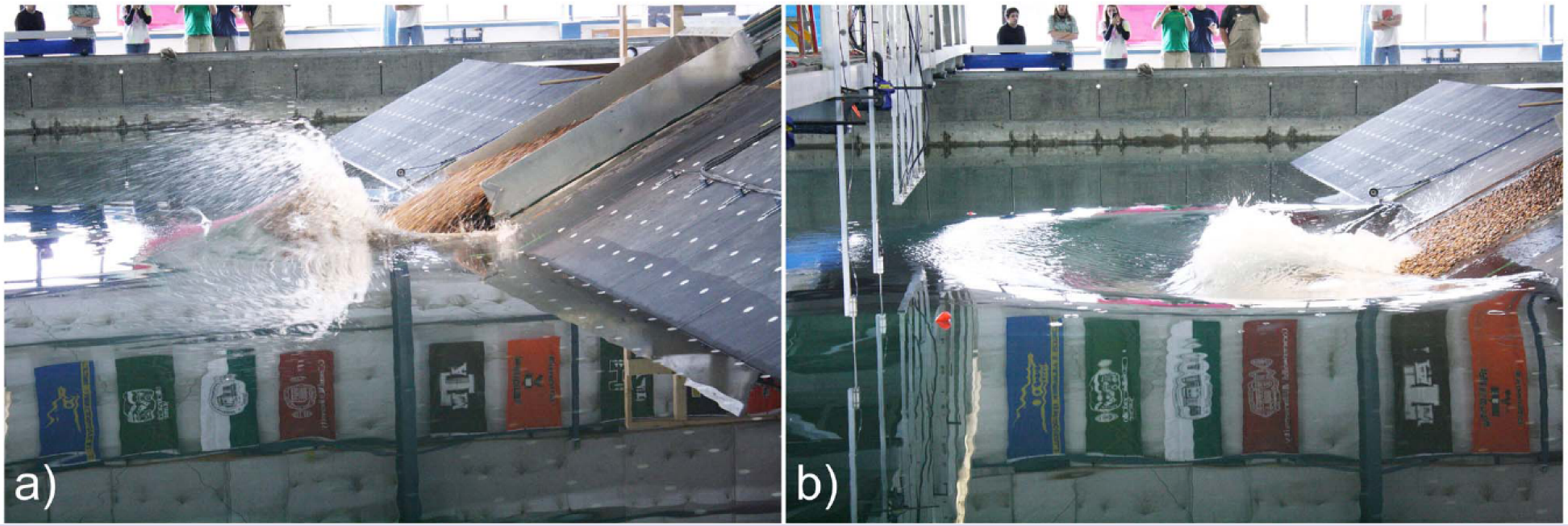

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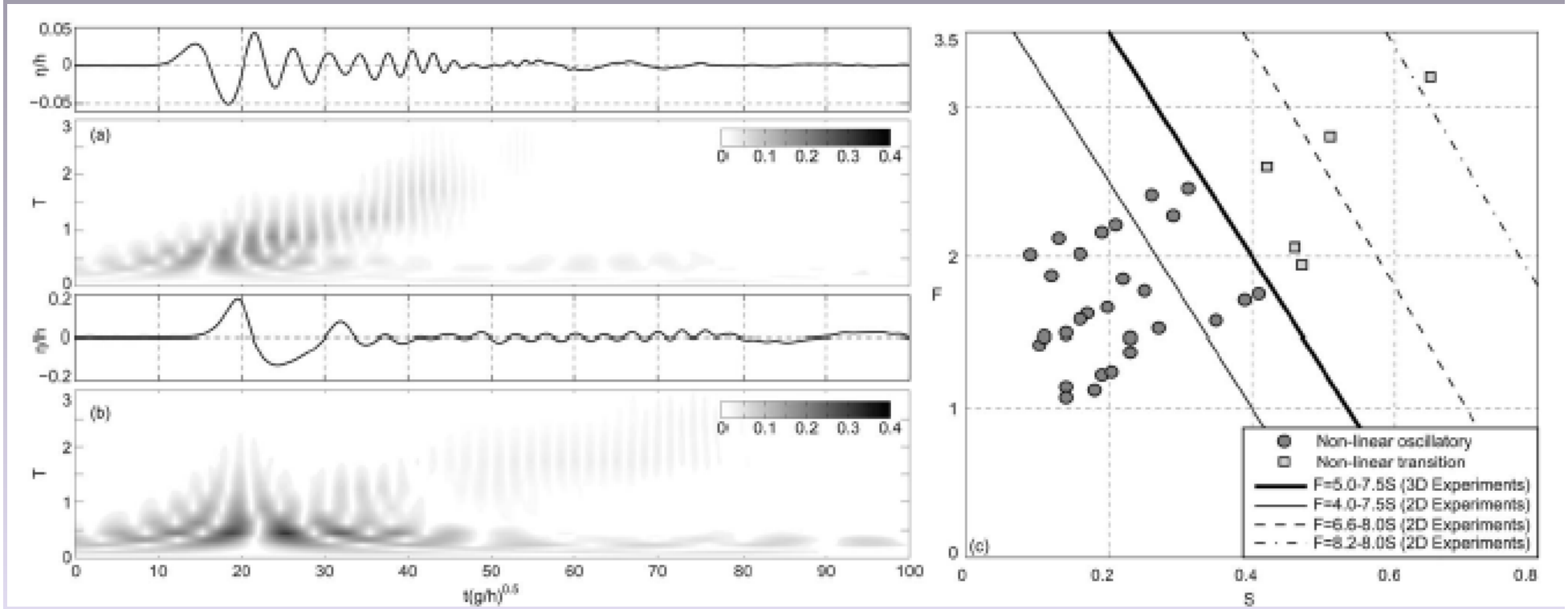


Review of laboratory experiments

- Underwater granular slides (sand) on a plane slope:
  -> 2D (Assier Rzadkiewicz, Mariotti, Heinrich, 1997)

Numerical Simulation of Submarine Landslides and Their Hydraulic Effects

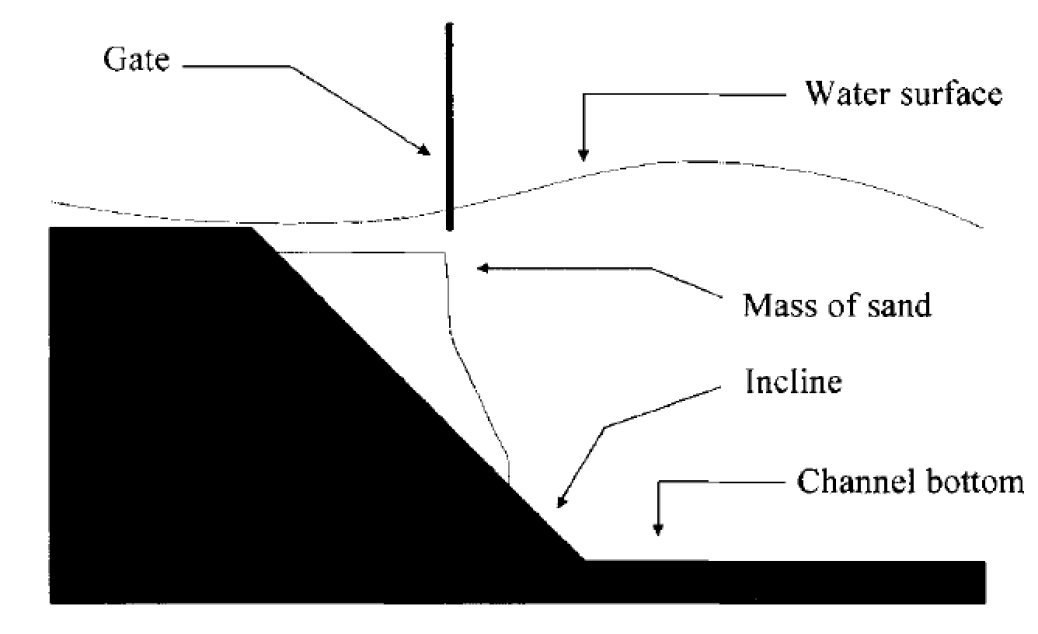
By S. Assier Rzadkiewicz,[1] C. Mariotti,[2] and P. Heinrich[3]

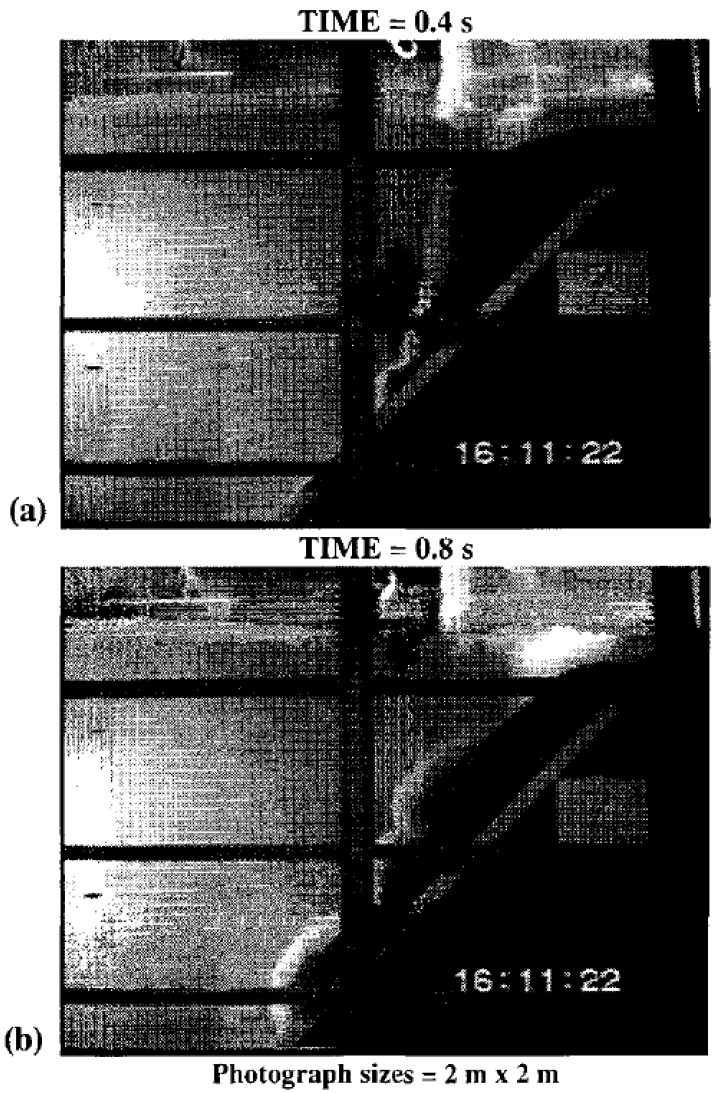
Abstract: The submarine flow slides and their hydraulic effects are studied by numerical means. These types of landslides are assumed to separate into a dense flow close to the bed and a turbulent dispersion above it. A two-dimensional fluid mechanics mixture model based on Navier-Stokes' equations has been developed to study water waves generated by these landslides. The dense part is considered as a viscoplastic fluid, whereas the dispersed part is modeled by an ideal fluid. The rheological parameters of the model comprise a diffusion coefficient, a Bingham yield stress, a viscosity coefficient, and friction on the slope. First, the numerical model is validated with an analytical solution for a viscous and a Bingham flow. Then, it has been tested for a rigid box sliding into water along an inclined plane. The results of this simulation have been compared with experiments conducted in a channel. Finally, laboratory experiments consisting in the slide of a gravel mass have been carried out. The results of these experiments have shown the importance of the sediment rheology and the diffusion. The model parameters are adjusted by trial and error to match the observed ''landslide'' flow.

Review of laboratory experiments

- Underwater granular slides (sand) on a plane slope:

  -> 2D (Assier Rzadkiewicz, Mariotti, Heinrich, 1997)





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Review of laboratory experiments

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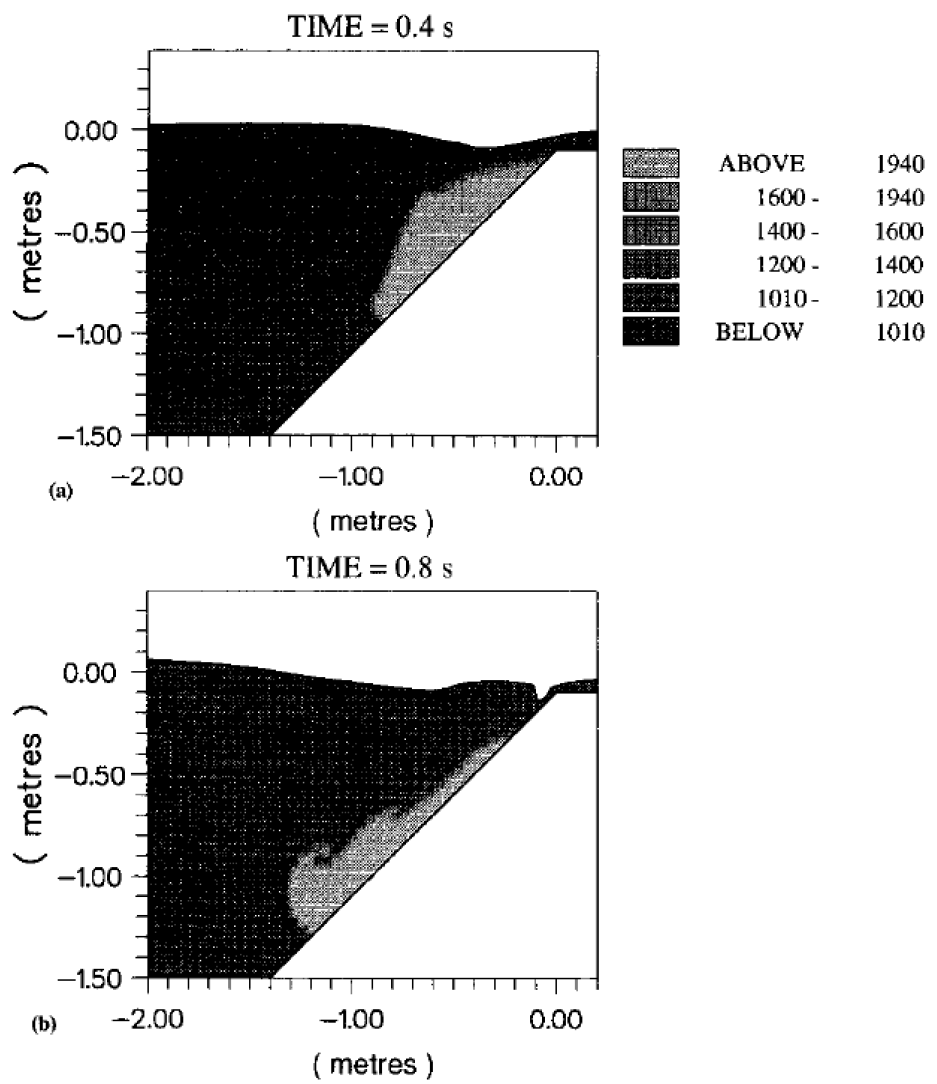
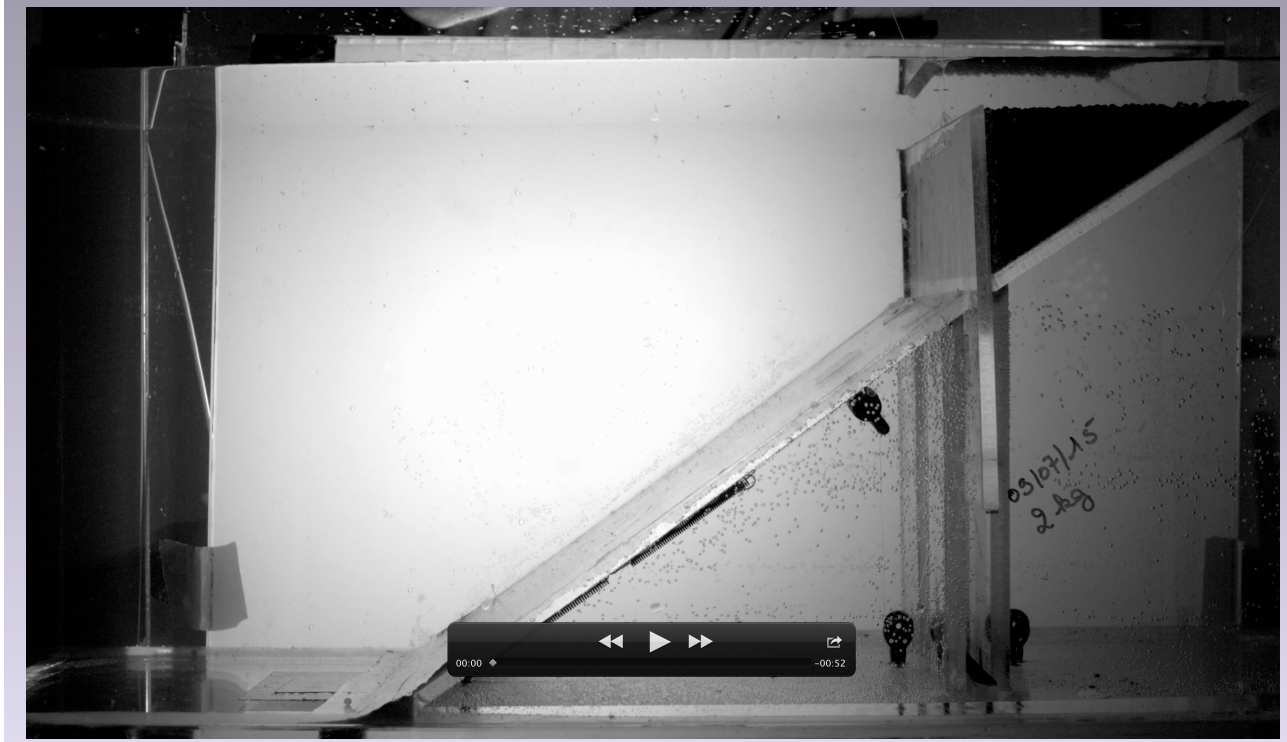
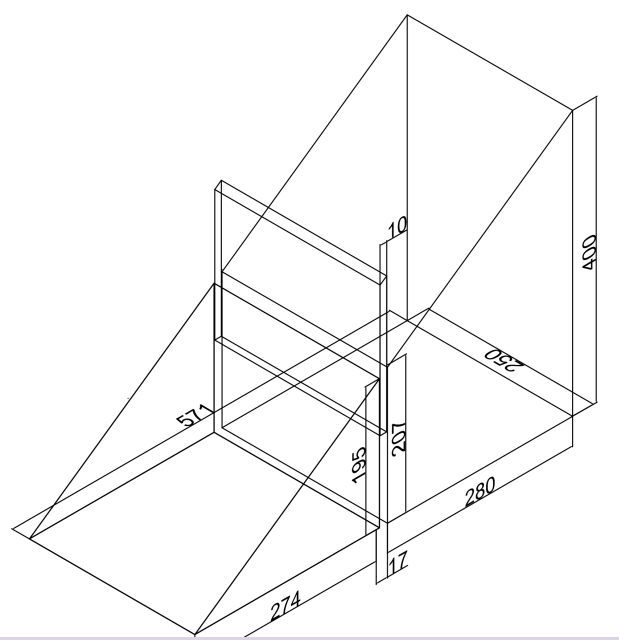


Review of slide laboratory experiments

- Underwater granular slides (glass beads) on a plane slope:
  -> 2D (Kimmoun et al., 2015)





Review of slide laboratory experiments

- Underwater granular slides (glass beads) on a plane slope:
  -> 2D (Kimmoun et al., 2015)

Review of slide laboratory experiments

- Underwater granular slides (glass beads) on a plane slope:

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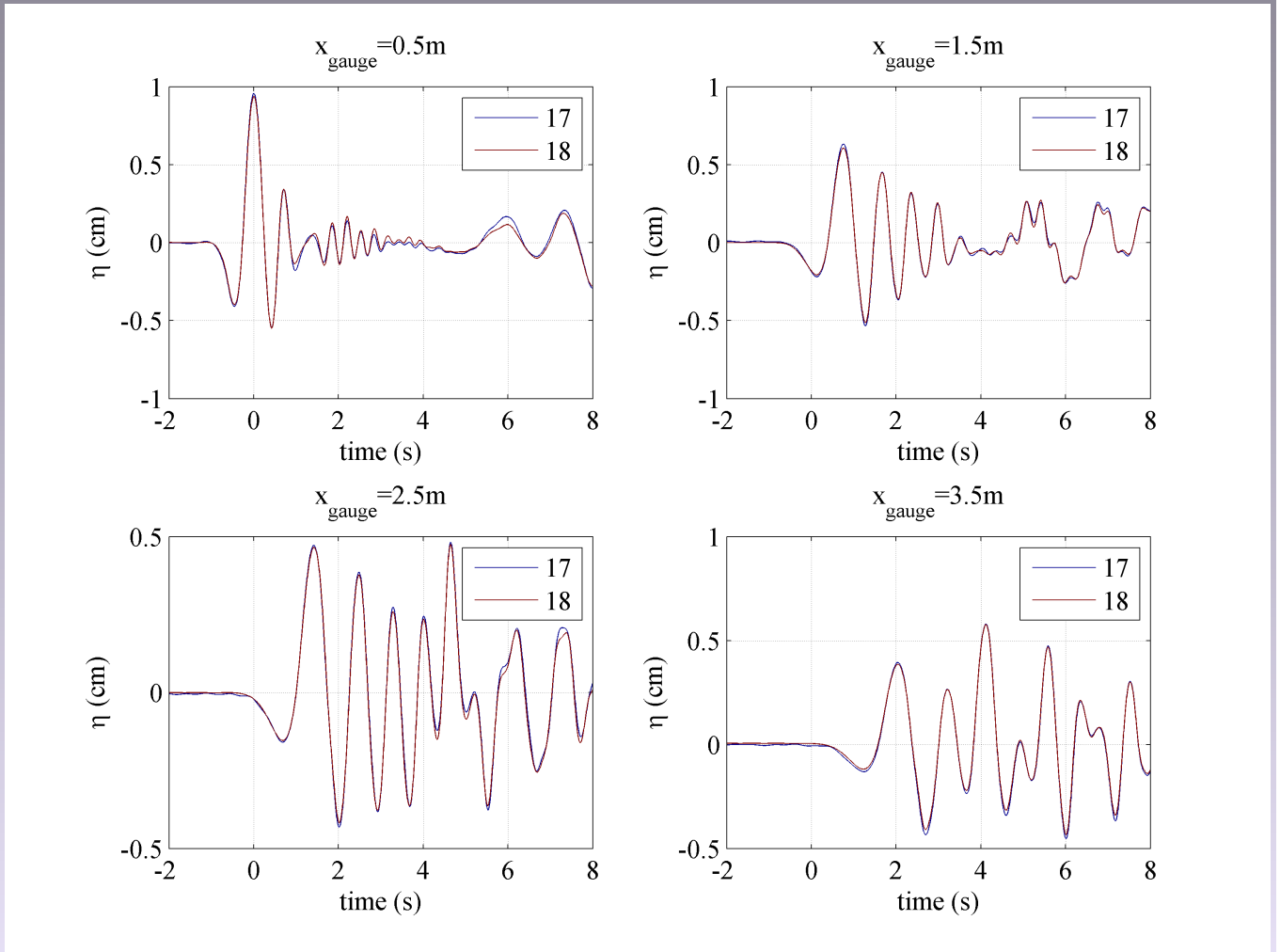

Review of slide laboratory experiments

- Underwater mud slides on a plane slope:
  -> 3D (Sawyer, Flemings, Buttles, Mohrig, 2012)

Marine Geology 307–310 (2012) 28–39

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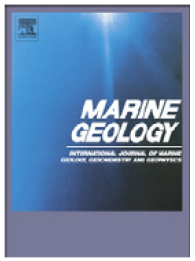


Mudflow transport behavior and deposit morphology: Role of shear stress to yield strength ratio in subaqueous experiments

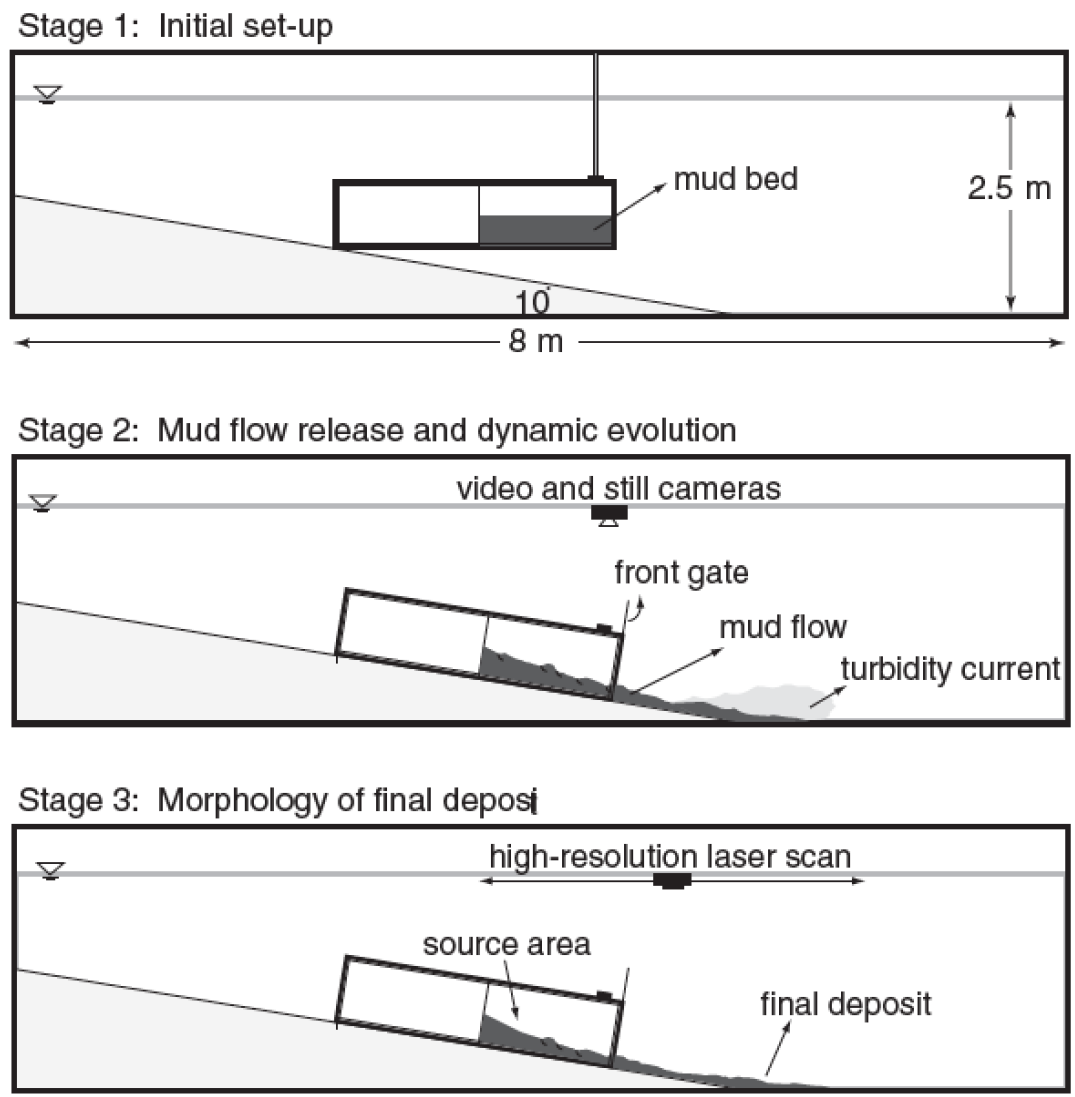
Derek E. Sawyer [a,*], Peter B. Flemings [a], James Buttles [b], David Mohrig [a]

[a] Jackson School of Geosciences, The University of Texas at Austin, University Station, Box X, Austin, TX, 78713, United States
[b] Bureau of Economic Geology, The University of Texas at Austin, University Station, Box X, Austin, TX, 78713, United States

Review of slide laboratory experiments

- Underwater mud slides on a plane slope:

  -> 3D (Sawyer, Flemings, Buttles, Mohrig, 2012)



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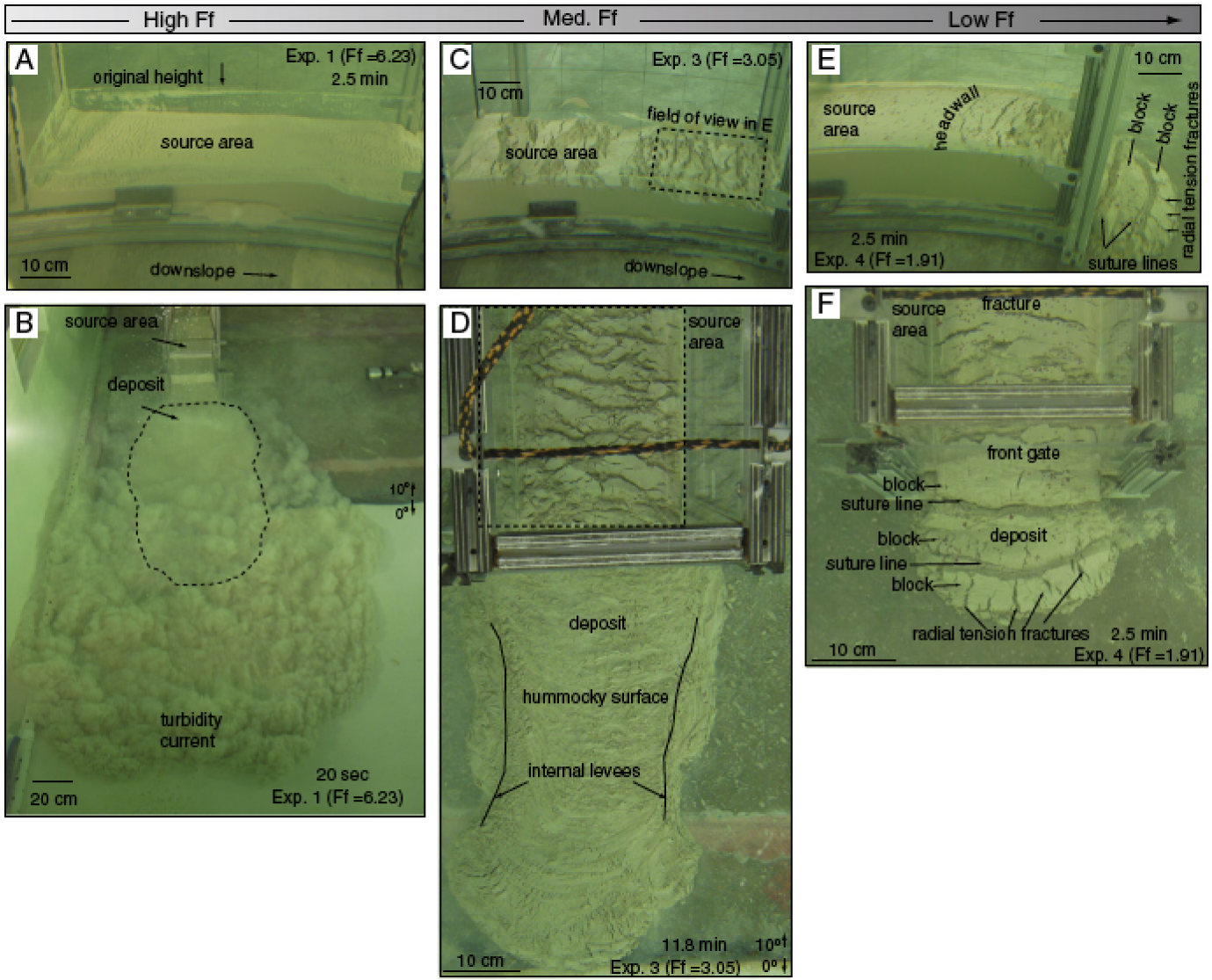
Review of slide laboratory experiments

- Underwater mud slides on a plane slope:

  -> 3D (Sawyer, Flemings, Buttles, Mohrig, 2012)



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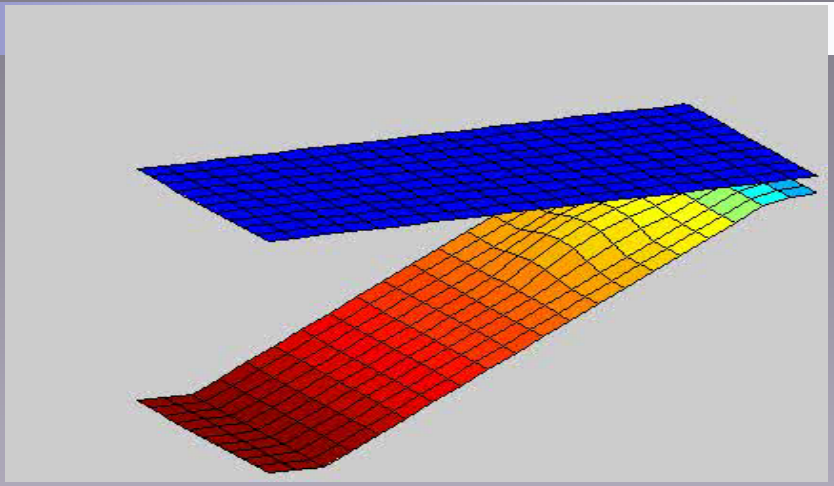
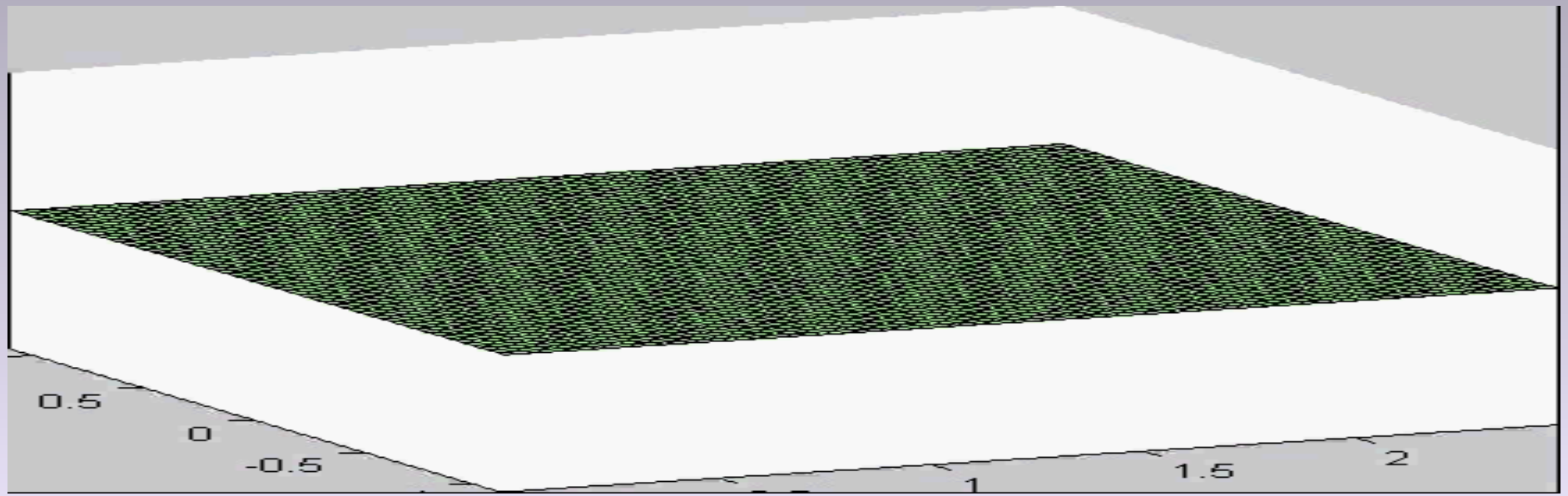
Review of models/modeling approaches

- Potential flow/Euler eqs. modeling of rigid block (streamlined) SMFs on a plane slope:
  - => Semi-empirical laws of motion (based on a balance of forces) and initial surface elevation (Watts et al., 2005)
  - => Specified SMF motion
    - -> 2D (e.g., Grilli and Watts, 1999, 2005)
    - -> 3D (e.g., Grilli et al., 2002-2010)
    - -> Long wave (Boussinesq) models (e.g., Lynett and Liu, 2002-2005; Fuhrman et al., 2009)
    - -> Non-hydrostatic sigma-layer model (NHWAVE; Ma et al., 2012)
  - => Many case studies (PNG 2008, Unimak 1946, Kalapana 1975, Tohoku 2011, Goleta, Currituck,...) (Fryer and Watts, 2004; Day et al., 1975; Tappin et al., 2008, 2014; Greene et al., 2006; Geist et al., 2009; Grilli et al., 2015;...)

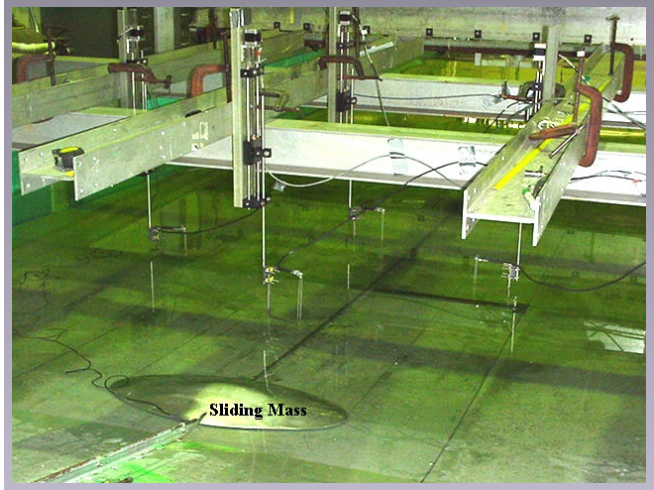
Rigid slide/inviscid 3D-BEM-FNPF model

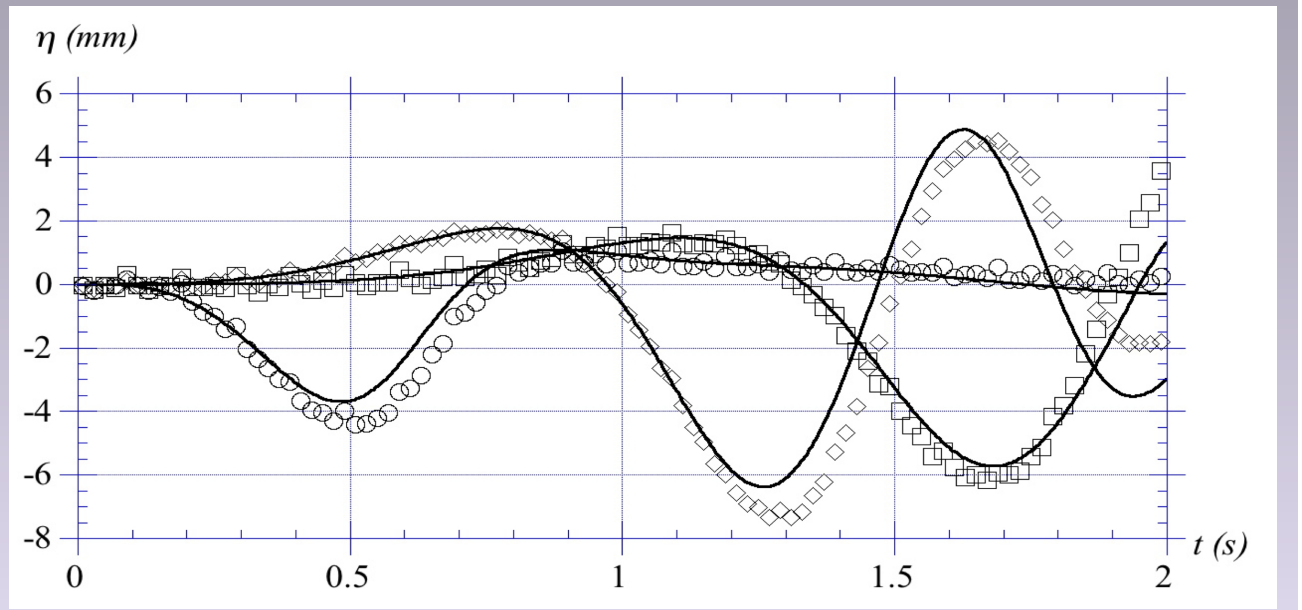


- 2D then 3D-BEM Fully Nonlinear Potential Flow model (Grilli et al., 1999, 2001-2010):
  - -> Specified slide shape and motion
  - -> Free surface time deformation



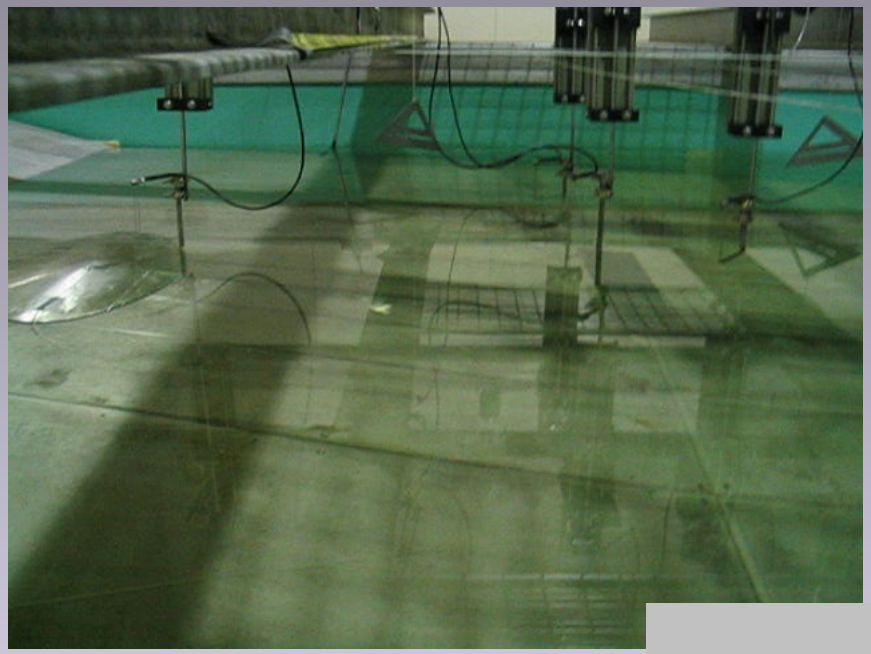
BEM-FNPF Computations vs. gage measurements





[Enet and Grilli, 2005, 2007; Grilli et al., 2010; symbols are experiments]

NHWAVE simulation of Enet and Grilli's slide exper.



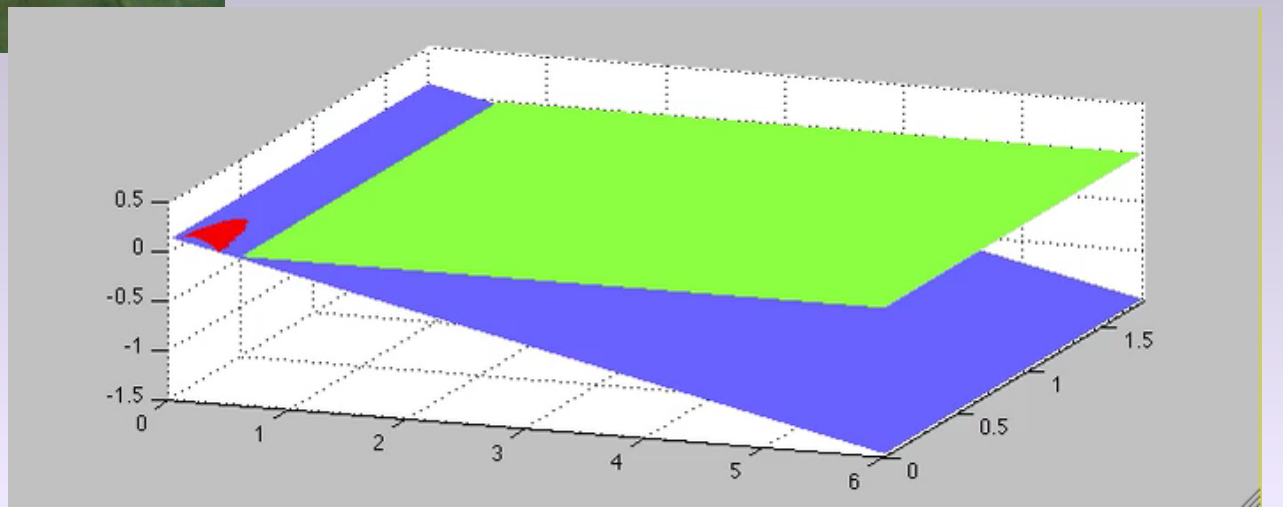
NHWAVE (Ma et al., 2012):

-> Non-hydrostatic 3D (σ–layer in the vertical) model solving Euler or Navier-Stokes equations

-> Enet and Grill's exp., 7 layers

-> Grilli et al. (2015) Currituck modeling and US East Coast slides

-> Tappin et al. (2014) Tohoku-SMF



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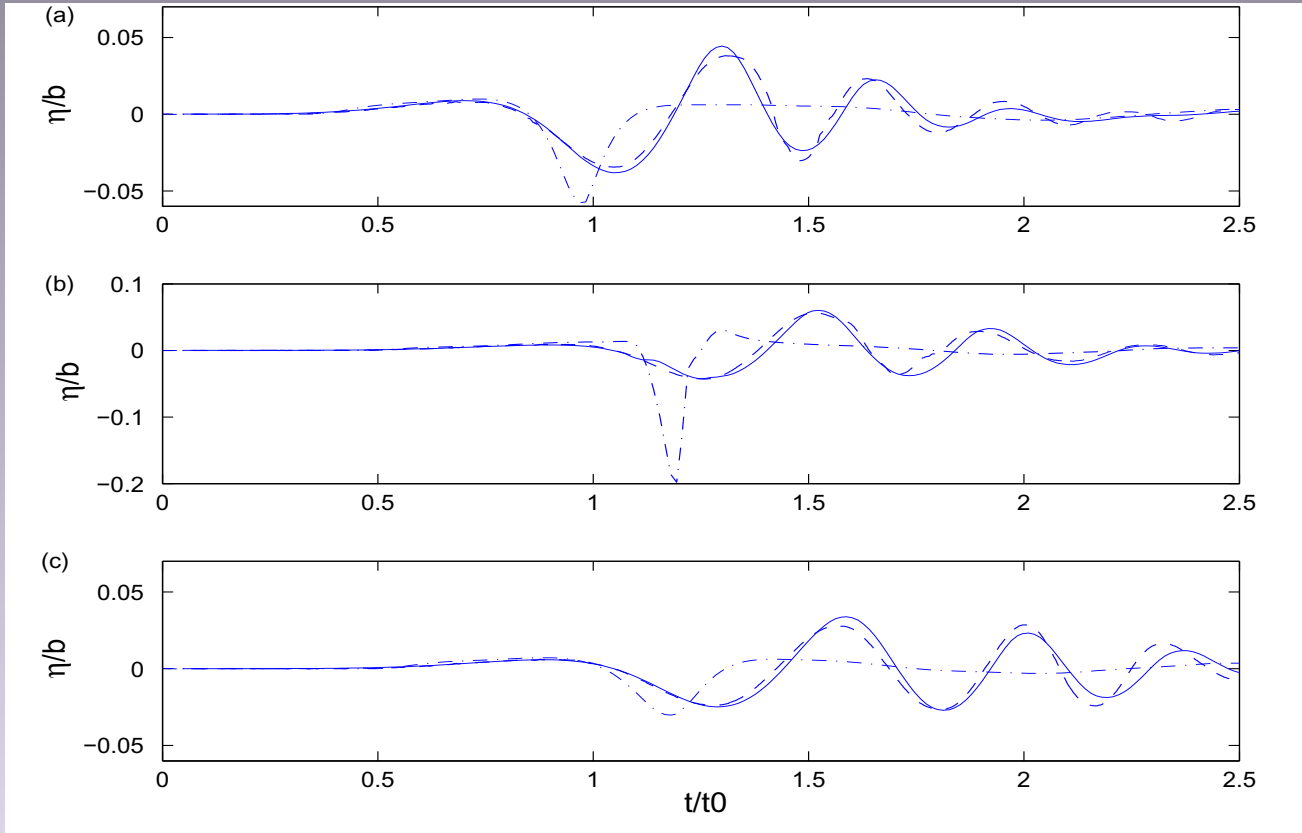
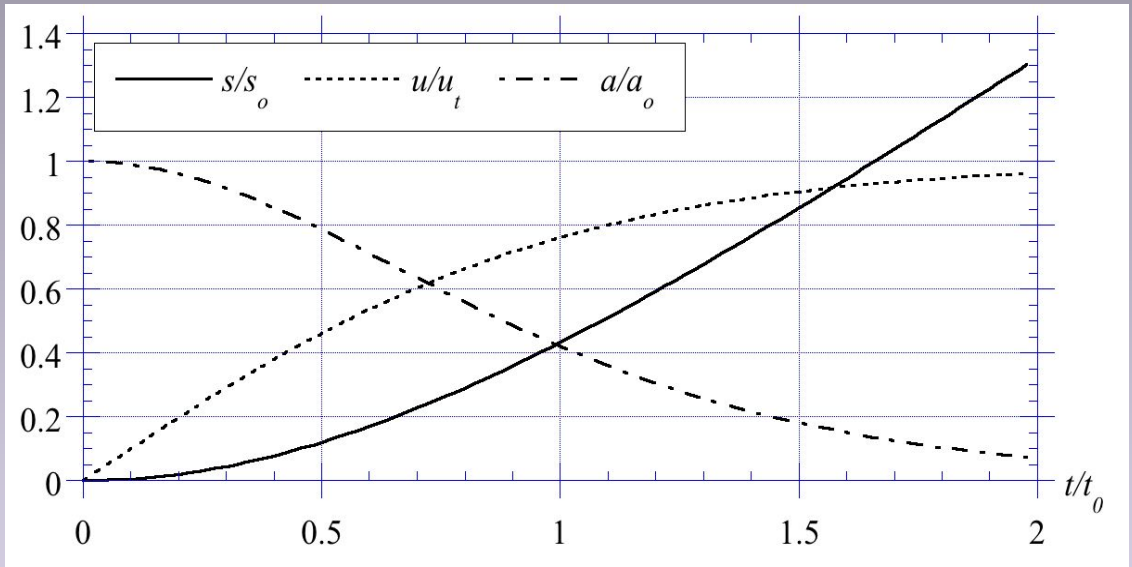
NHWAVE simulation of Enet and Grilli's slide exper.



Solid: observed; dash: fully-dispersive; dash-dot: non-dispersive

Rigid Slide law of motion and curve fit

[Grilli and Watts 1999-2005]



$$s(t) = s_o \ln\left(\cosh\left(\frac{t}{t_o}\right)\right) \quad \text{with} \quad s_o = \frac{u_t^2}{a_o} \quad \text{and} \quad t_o = \frac{u_t}{a_o}$$

$$a_o = g\sin\theta\left(\frac{\gamma-1}{\gamma+C_m}\right) \quad \text{and} \quad u_t = \left(gB\sin\theta\frac{\pi(\gamma-1)}{2C_d}\right)^{\frac{1}{2}}$$

with $\gamma = \rho_b/\rho_w$

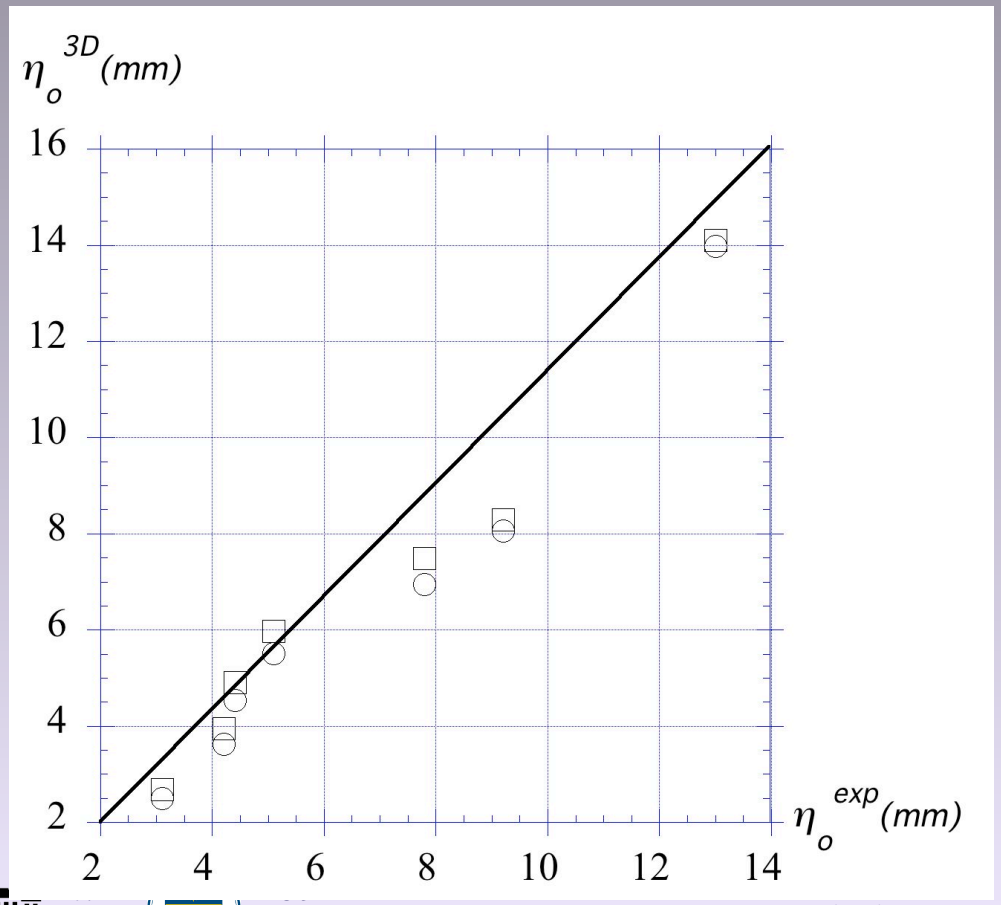
Curve fitting of numerical results -> η_o " maximum depression at initial location"

$$\eta_o = s_o(0.0592 - 0.0636\sin\theta + 0.0396\sin^2\theta)\left(\frac{T}{B}\right)\left(\frac{B\sin\theta}{d}\right)^{1.25}(1-e^{-2.2(\gamma-1)})$$

$$\eta_o^{3D} = \eta_o \frac{0.935}{\left(1+\frac{\lambda_o}{W}\right)^{0.872}} \quad \text{with} \quad \lambda_o = t_o\sqrt{gd}$$

Measurements vs. "curve fits" for rigid slide

[Grilli and Watts 2005; Enet and Grilli, 2007]



Curve fitting of numerical results agrees well with laboratory experiments

With R^2 = 0.961

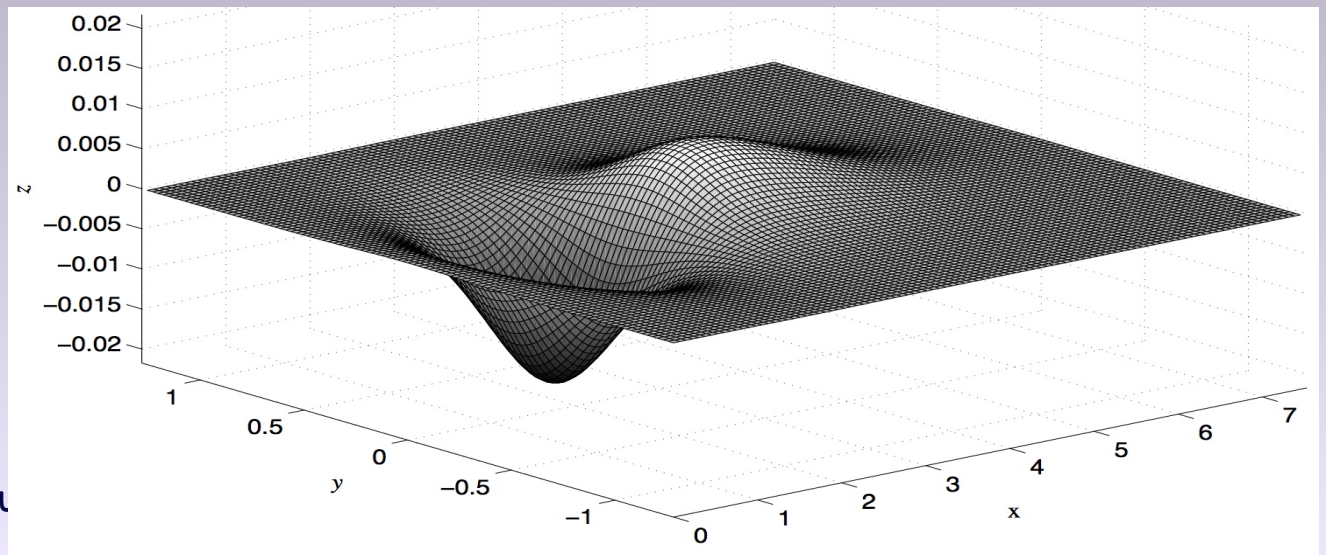
Rigid slide/inviscid 3D-BEM-FNPF model

[Grilli and Watts 2005; Watts et al, 2005]

- Definition of semi-empirical tsunami sources for rigid underwater slides or slumps, based on many FNPF simulations for a wide variety of governing parameters :

$$\eta_{3D}(x,y,t_o) = \eta_{\min} f(W)\,\mathrm{sech}^2\left(\kappa f(W)\frac{y}{W}\right)\left\{\alpha_1 g_1(x) - \alpha_2 \kappa' g_2(x)\right\}$$

$$g_1(x) = \mathrm{e}^{-\left(\frac{x-x_{\min}}{\kappa'\lambda_o}\right)^2} \;;\; g_2(x) = \mathrm{e}^{-\left(\frac{x-x_{\min}-\Delta x}{\lambda_o}\right)^2} \;;\; \alpha_1 = \frac{1+\kappa' g_2(x_{\min})}{1-g_1(x_{\max})g_2(x_{\min})} \;;\; \alpha_2 = \frac{1+(1/\kappa')g_1(x_{\max})}{1-g_1(x_{\max})g_2(x_{\min})}$$



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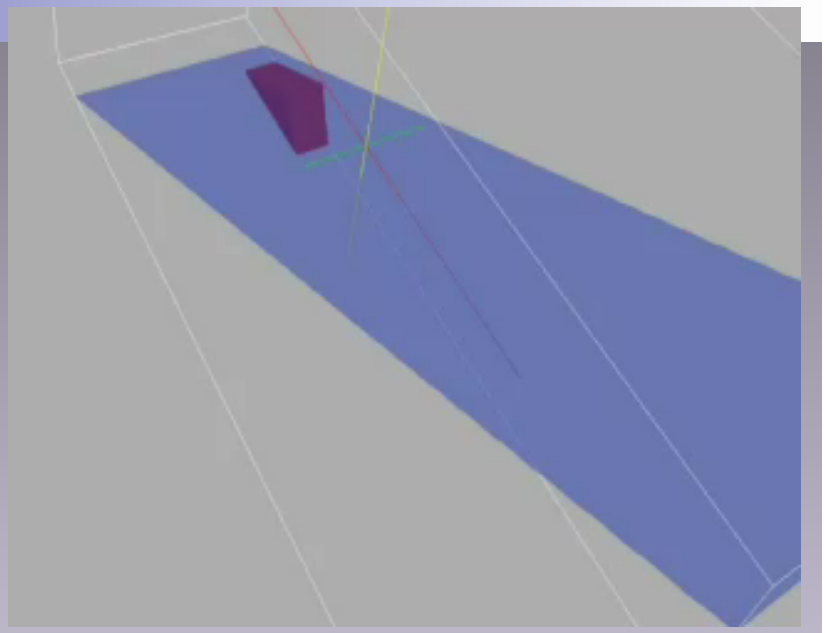
Review of models/modeling approaches

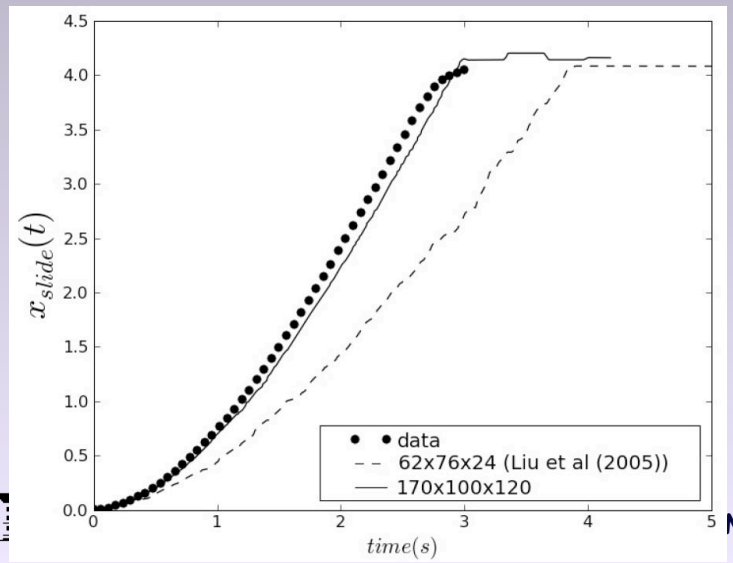
- Navier-Stokes modeling of rigid block (non-streamlined) subaerial slides on a plane slope:
  - -> 2D,3D (Abadie et al., 2008-2010 => implicit motion)
  - -> 3D (Liu, Raichlen, Synolakis, Borrero, 2005 => specified motion)
- Navier-Stokes modeling of deforming/granular subaerial slides on a plane/or arbitrary slope => implicit motion :
  - -> 2D Bingham fluid (Watts and Grilli, 2003)
  - -> 3D multi-material (air-water-slide as heavy Newtonian fluid (Heinrich, 1992; Assier-Rzadkiewicz et al., 1997; Gisler et al., 2006; Abadie et al., 2008-2012; Weiss et al., 2009; Horrillo et al., 2013; Viroulet et al., 2014)
  - -> 3D multi-layer (NHWAVE for sediment/density flow; Ma et al., 2013) => implicit motion
- NSW/NSW modeling of deforming/granular subaerial slides on a plane/or arbitrary slope: (Jiang and Leblond, 1992, 1993; Fine et al., 2005)

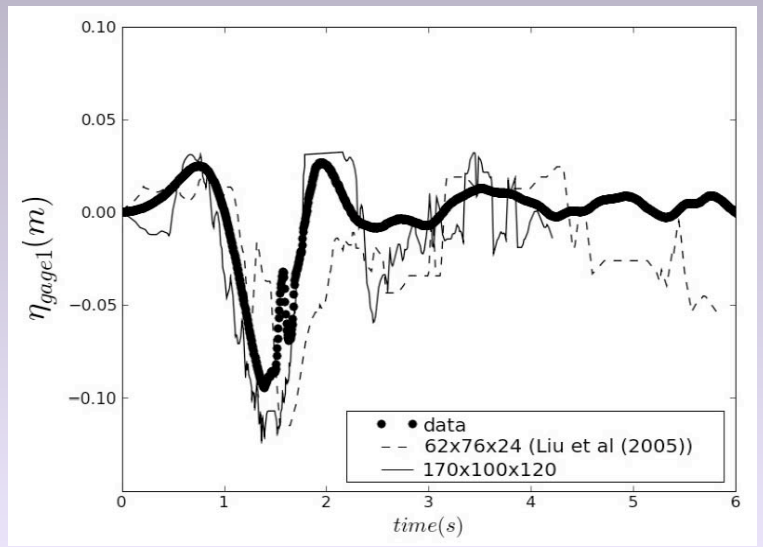
Modeling rigid, non-streamlined, slide as viscous fluid

- Multi-fluids 3D-Navier Stokes-VOF model (THETIS) (Abadie et al., 2010)
- Model of Liu et al.'s (2005) slide experiments as heavy fluid of very large viscosity

  => very good agreement with experiments for both slide motion and waves

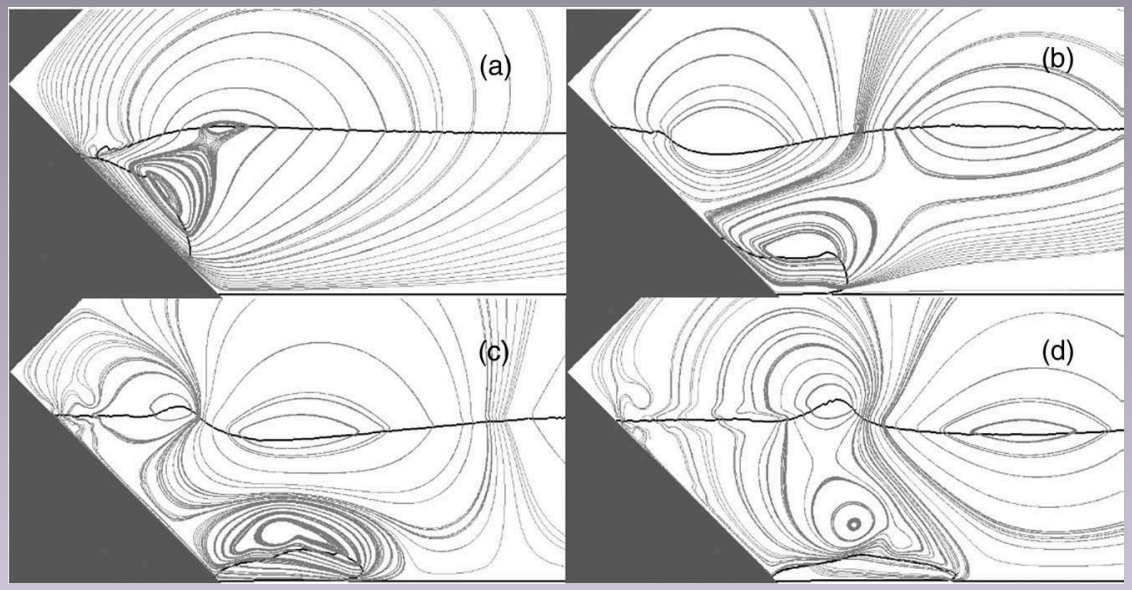


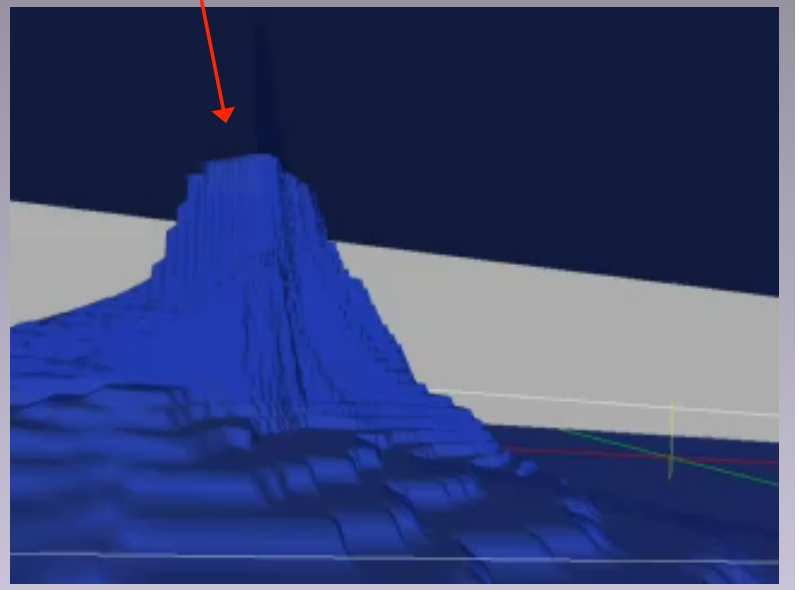


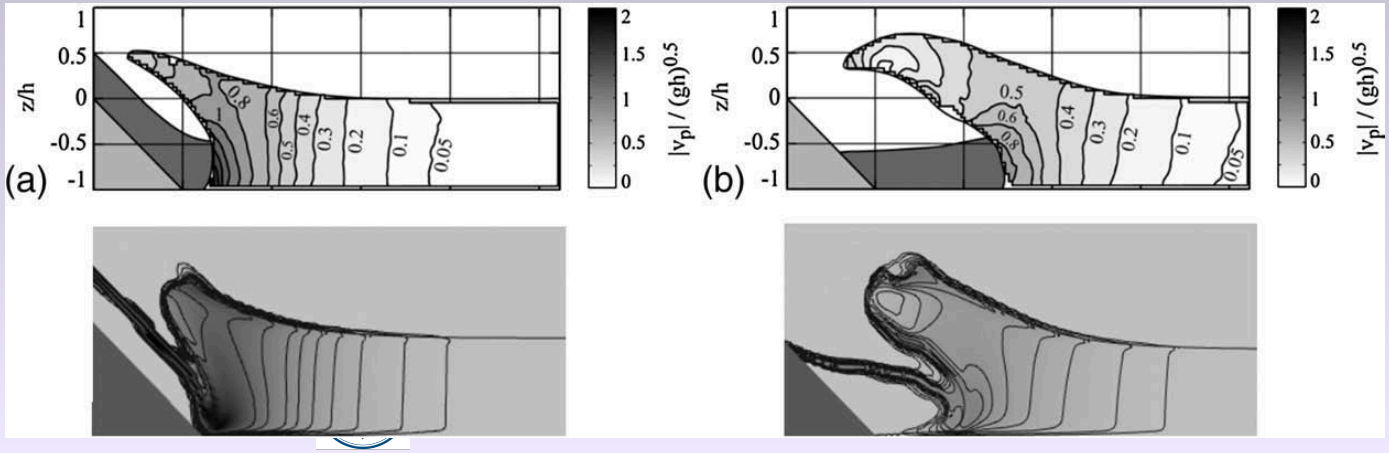


Deforming slide modeled as a viscous fluid

- Multi-fluids 3D-Navier Stokes-VOF model (THETIS) (Abadie et al., 2010)
- CVV flank collapse Abadie et al. (2012)



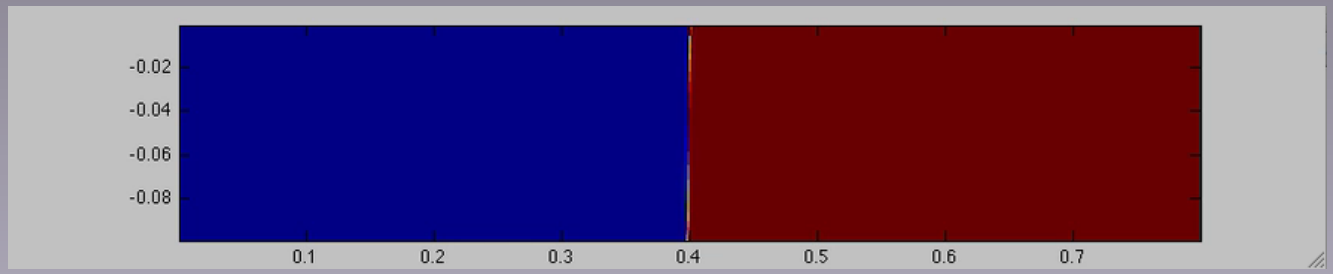


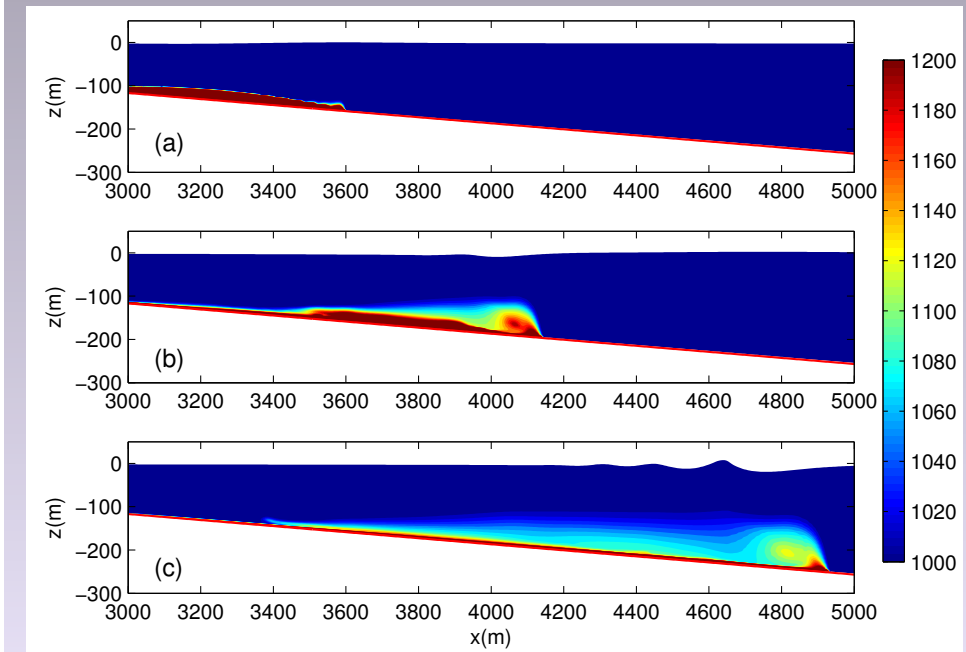


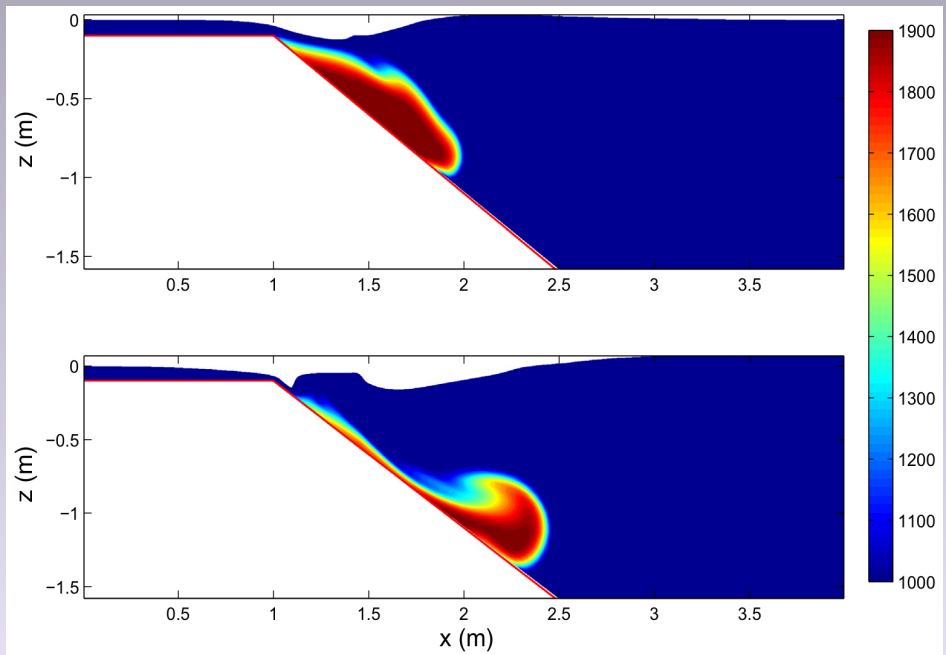
[Model of Fritz et al., 2004]

Extension of NHWAVE to multiple-fluids/debris flows

[Ma et al. (2013)]



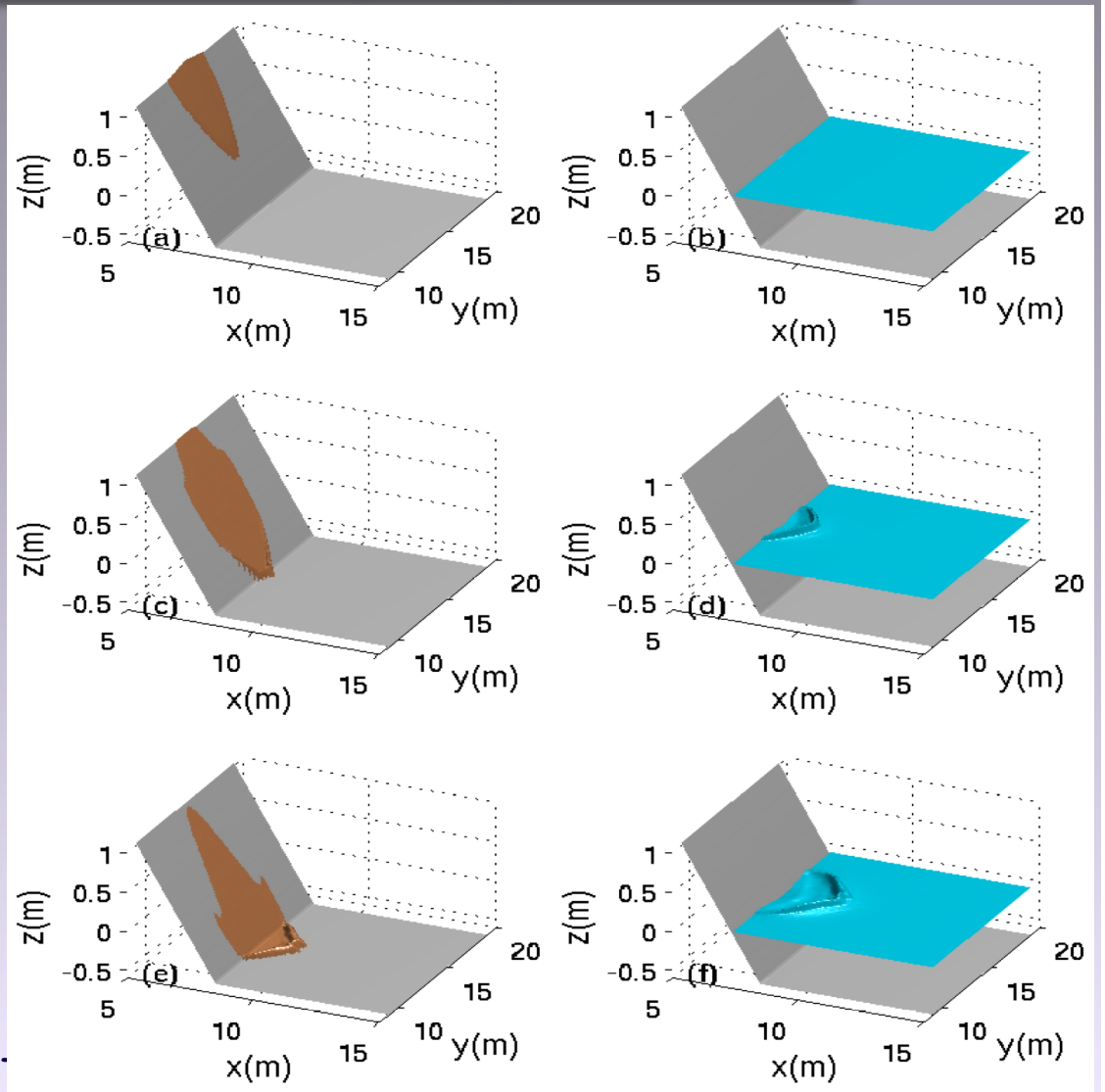




Review of models/modeling approaches

- Navier-Stokes modeling of deforming/granular subaerial/submarine slides on a plane/or arbitrary slope:

  -> 3D multi-layer (NHWAVE for granular flows; Ma et al., 2015)



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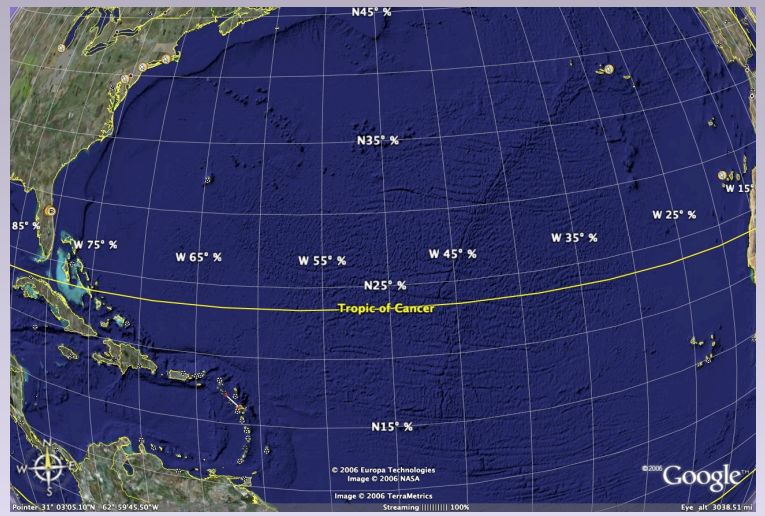
Case study: CVV flank collapse case study (Abadie et al. 2012)

[Ward and Day (2001); Grilli et al., (2005); Pérignon (2006); Lovholt et al., 2008; Abadie et al. (2008-2012), Theranirad et al. (2015)]

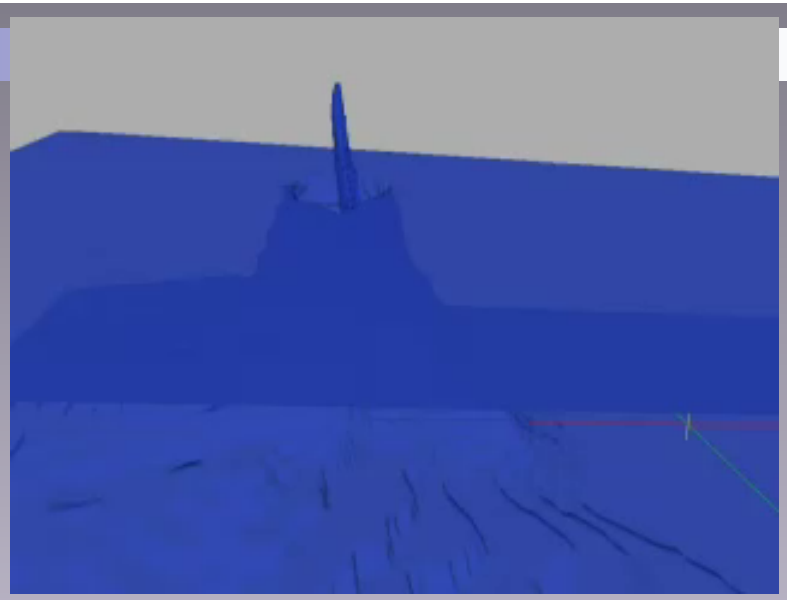


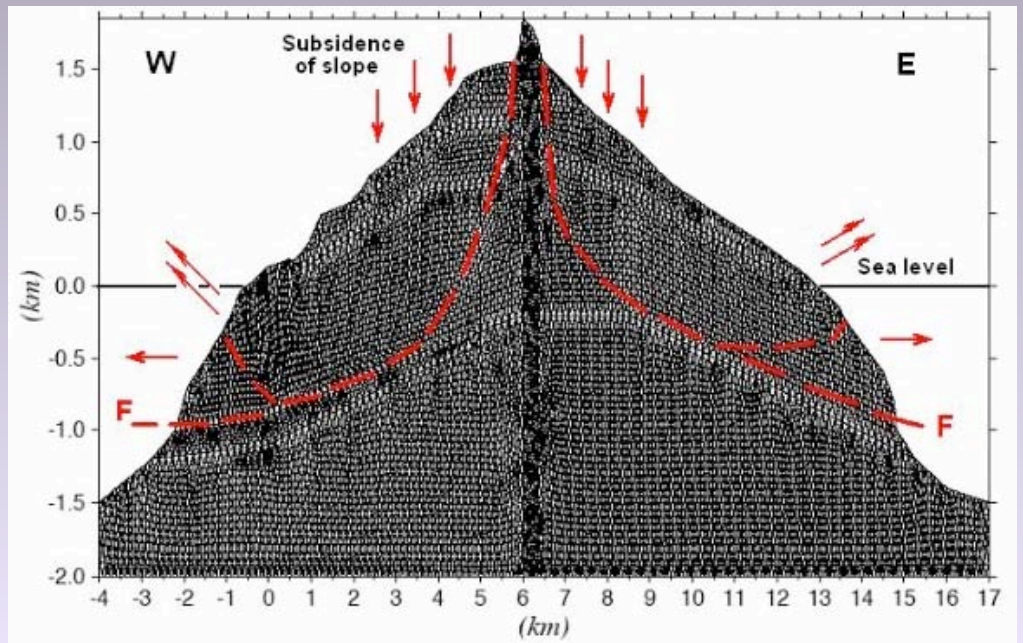
CVV Flank Collapse source

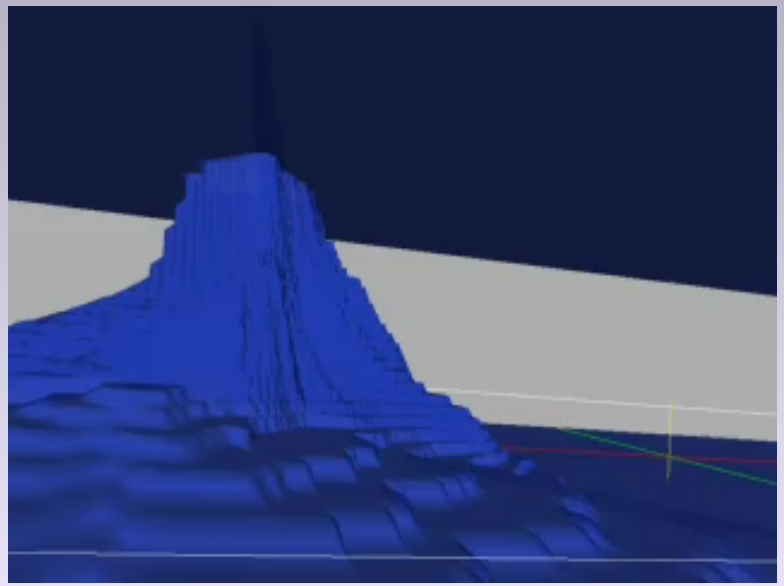
- Multi-fluids 3D-Navier Stokes-VOF model (THETIS) (Abadie et al.; 2006-11)
- Slope stability analysis (FLAC 2D; 2D-FEM)

-> Most likely scenario of 80 km^3

- Various scenario simulated with 20-450 km^3. Large 3D grids.





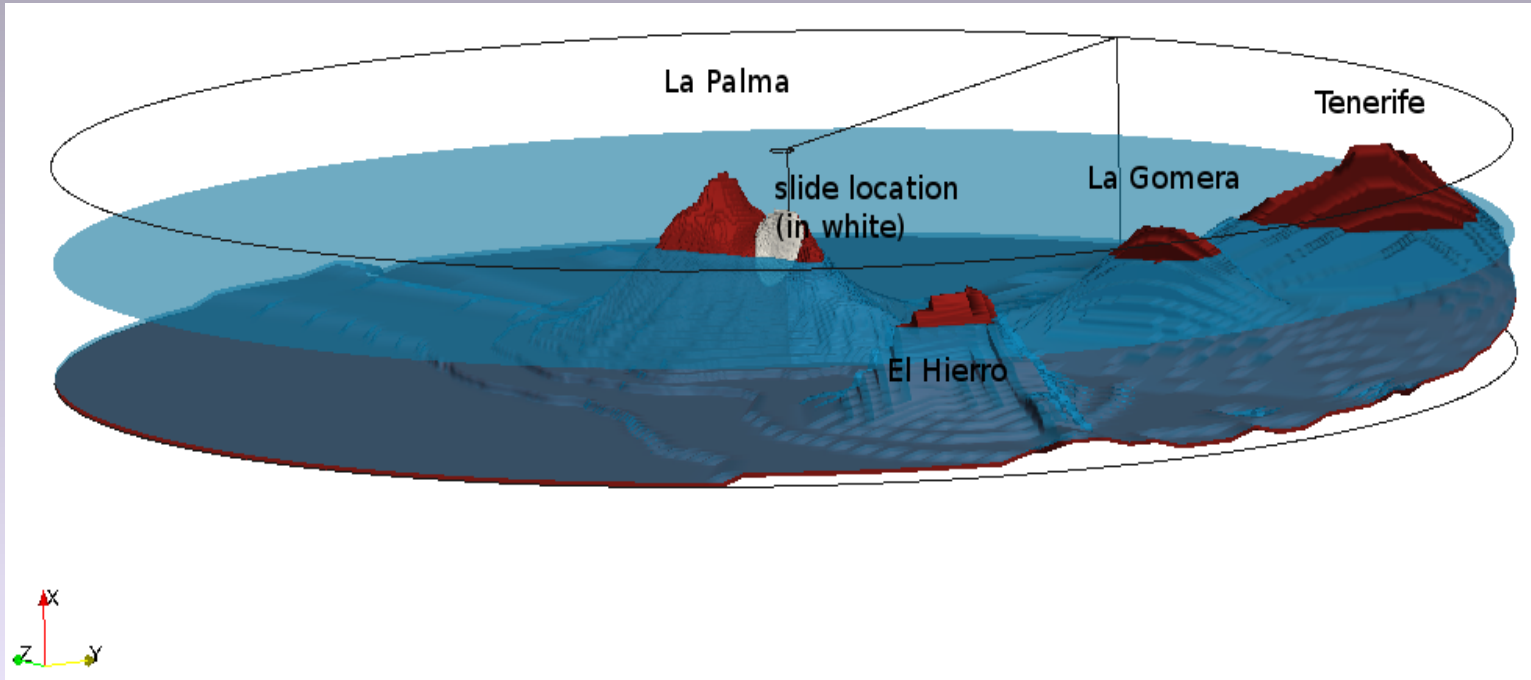


Flank Collapse : 3D THETIS grid

- Source + near-field propagation : Multi-fluids 3D-NS-VOF model (THETIS)

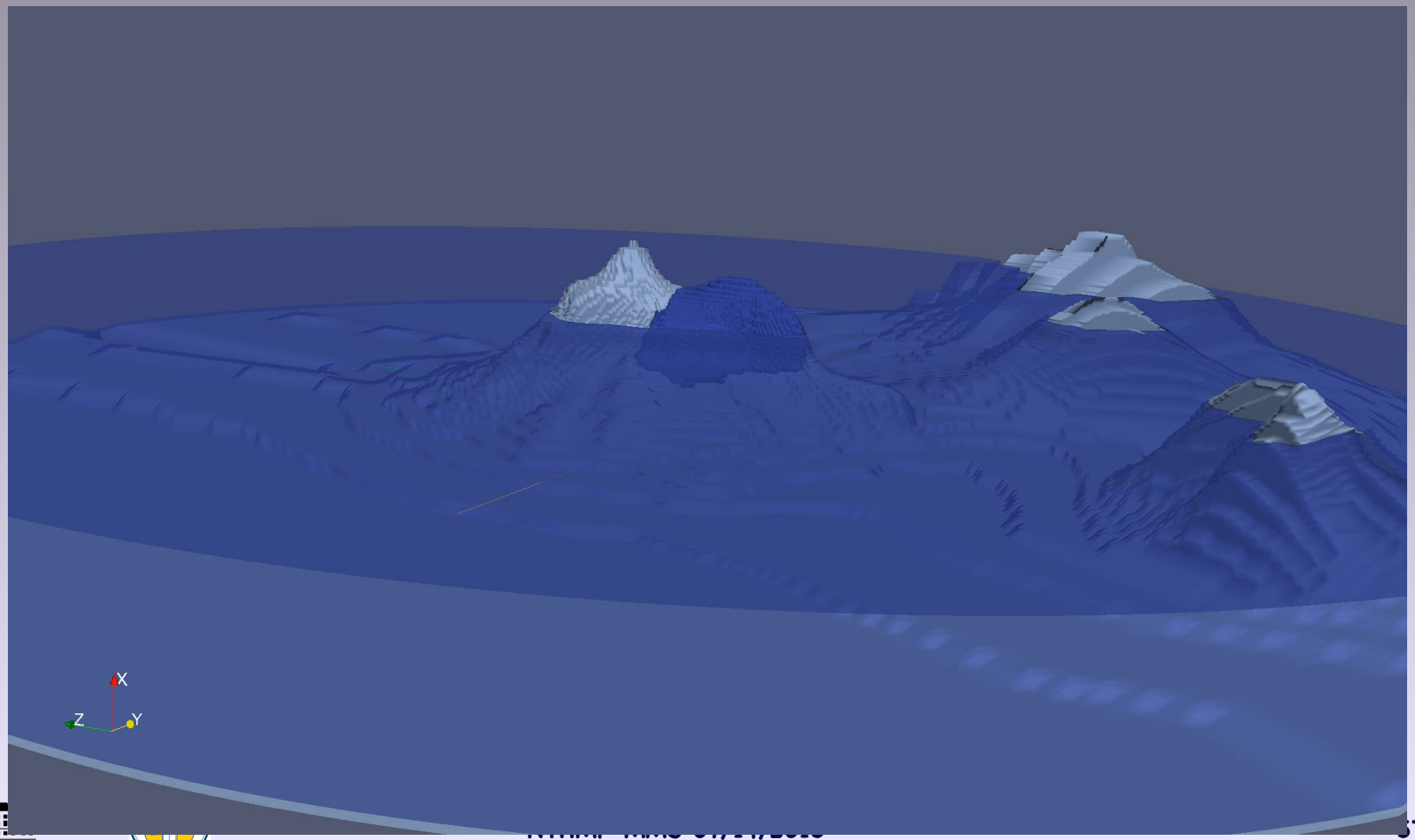
For lack of better information, slide is assumed to behave as an inviscid fluid with constant density (basalt, 2.9) => worst case scenario.

- If known, an arbitrary rheology can be used.



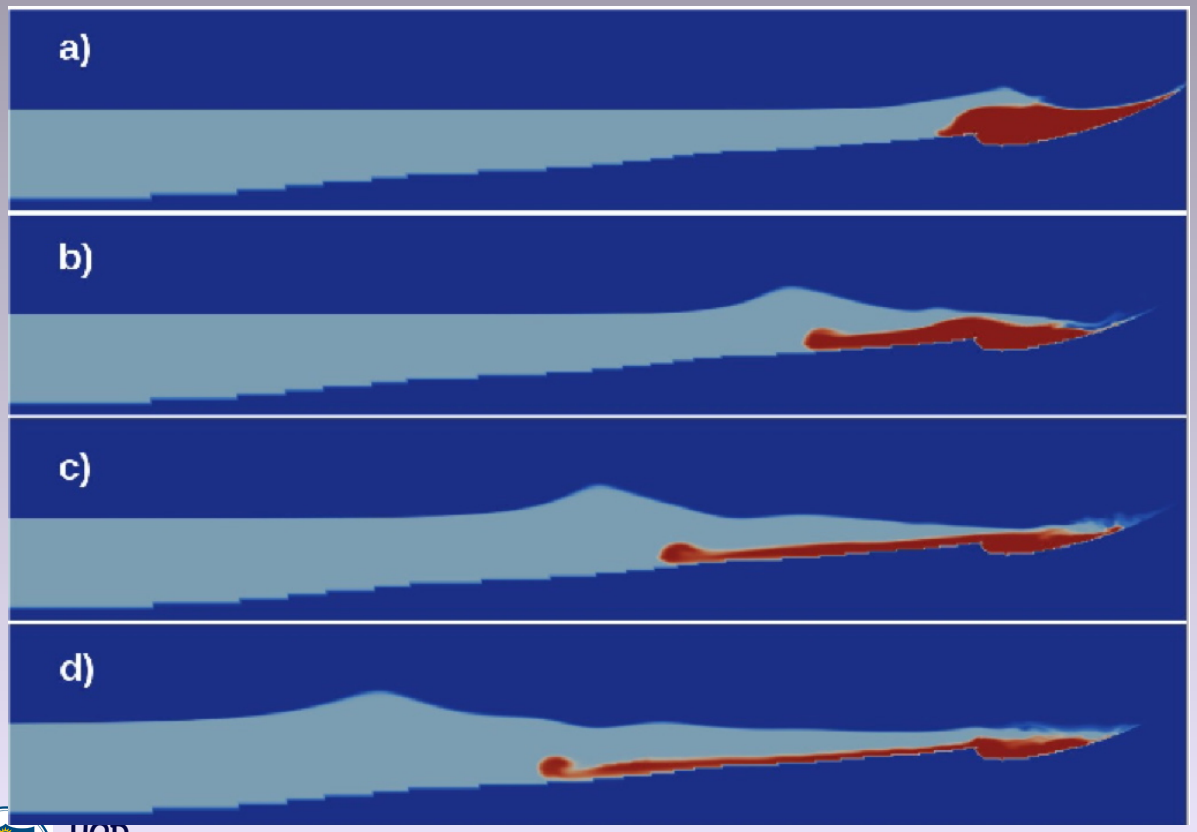
CVV Flank Collapse : extreme scenario

- Source + near-field propagation : THETIS 450 km^3 CVV source (as WD 01)



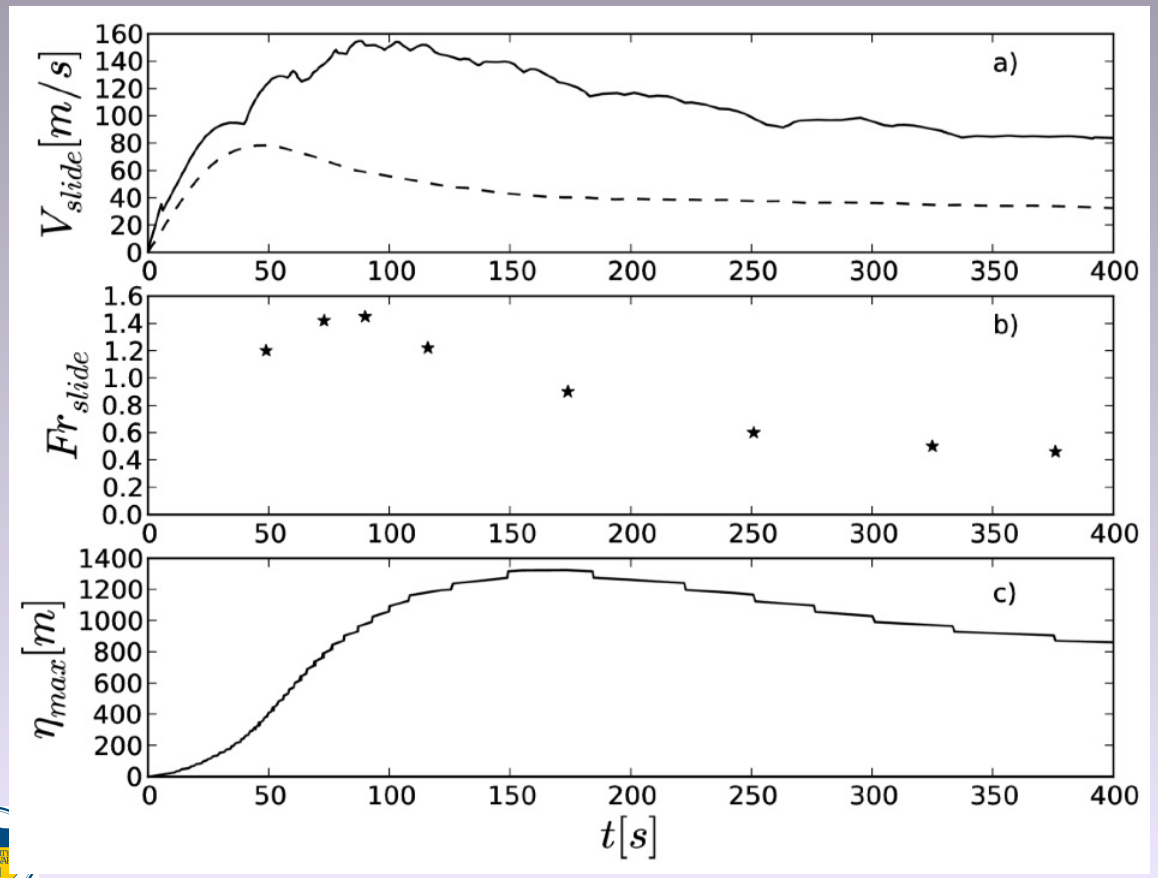
CVV Flank Collapse : 2D sensitivity analysis

- Source + near-field propagation : THETIS 80 km^3 CVV source :
High resolution (50-100 m grid) 2D simulations (t = 50, 100, 150, 200 s)



CVV Flank Collapse : 2D sensitivity analysis

- Source + near-field propagation : THETIS 80 km^3 CVV source :
  Slide max./mean velocity; Froude number; Max. leading wave elevation



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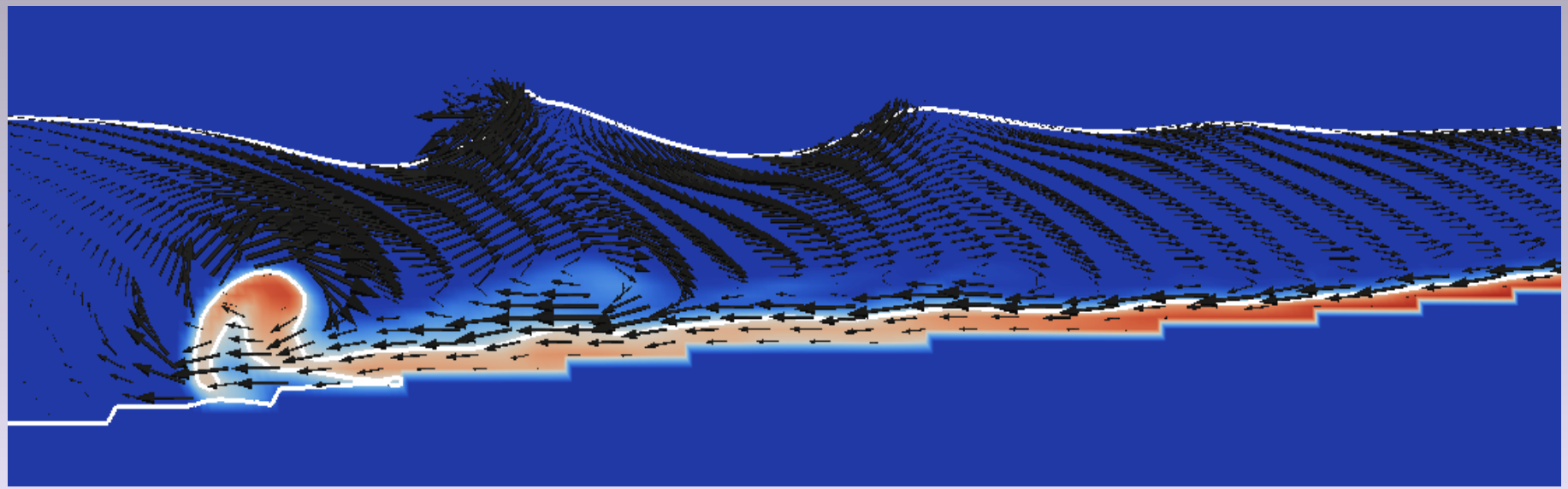
CVV Flank Collapse : 2D sensitivity analysis

- Source + near-field propagation : THETIS 80 km^3 CVV source :

Detailed velocity field around slide tip at t = 396 s, showing the strong current generated in the water by the slide motion and Kelvin-Helmholtz instabilities along the slide/water interface.

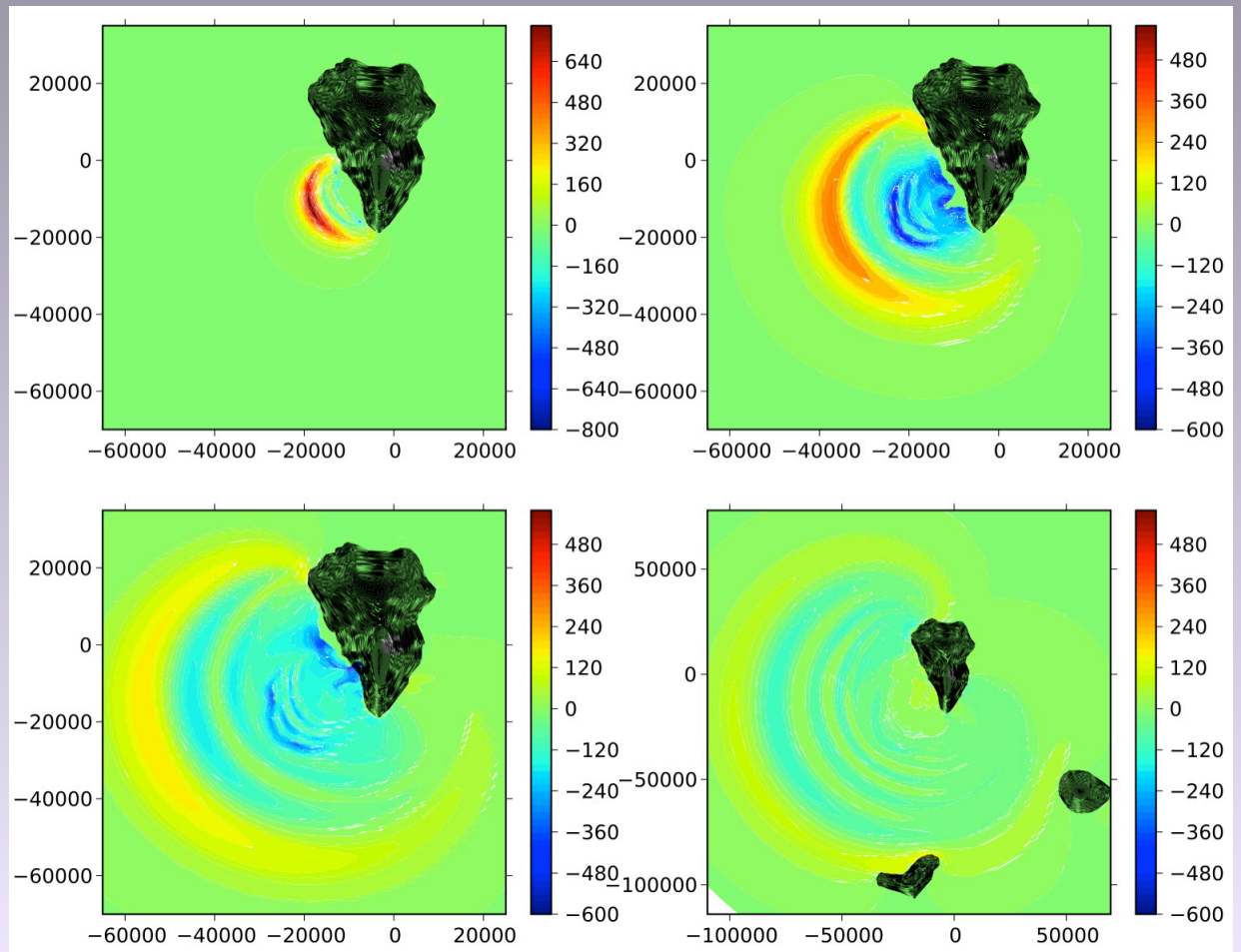


CVV Flank Collapse : 3D sensitivity analysis

- Source + near-field propagation : 3D-THETIS 80 km^3 CVV source

Surface elevation (m) at t =: a) 101 s, b) 232 s, c) 340 s, d) 558 s

=> Main direction of propagation 20 deg. off W



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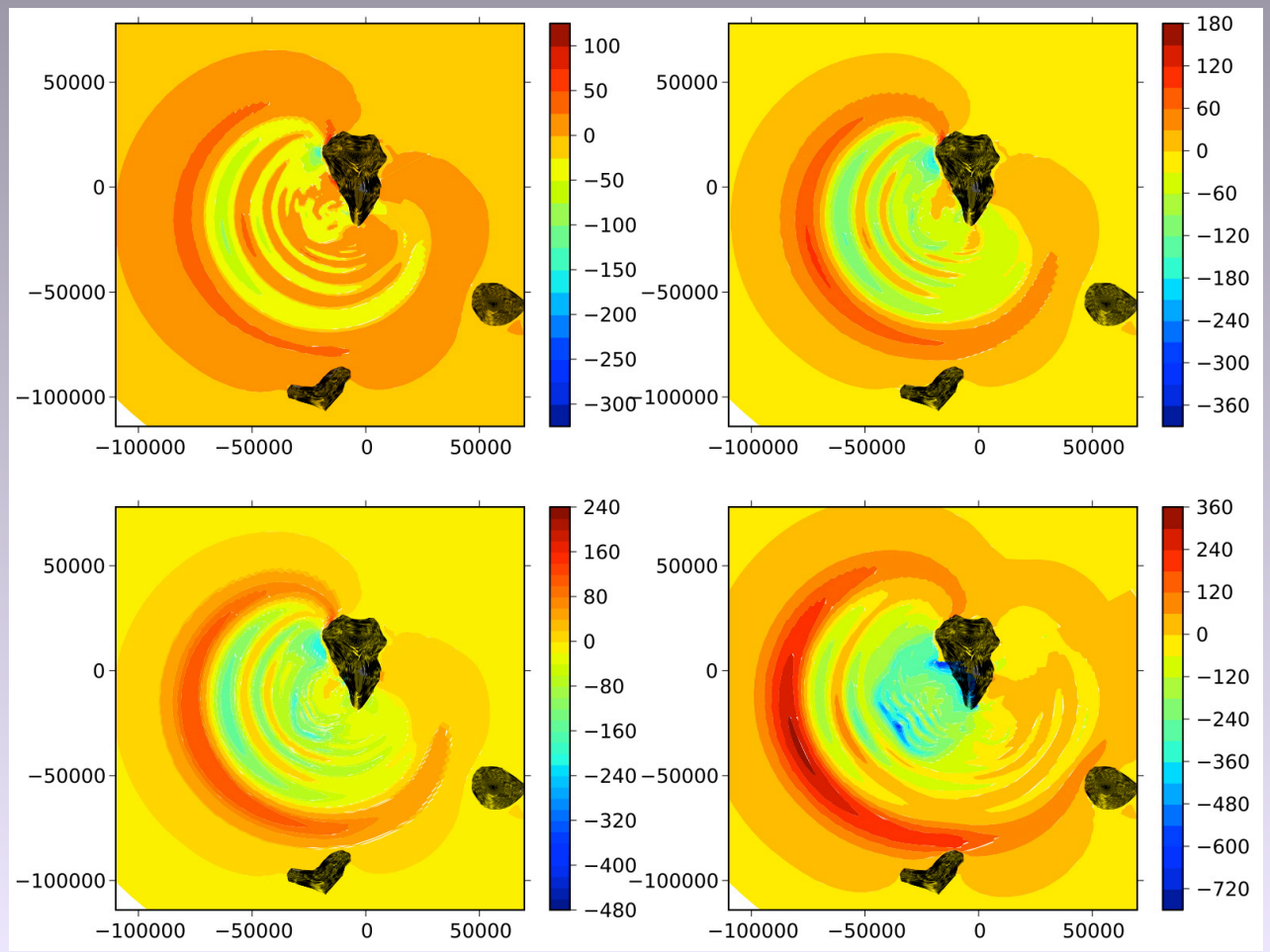
CVV Flank Collapse : 3D sensitivity analysis

- Source + near-field propagation : 3D-THETIS 20, 40, 80, 450 km^3 CVV sources

Surface elevation (m) at : t = 450 s



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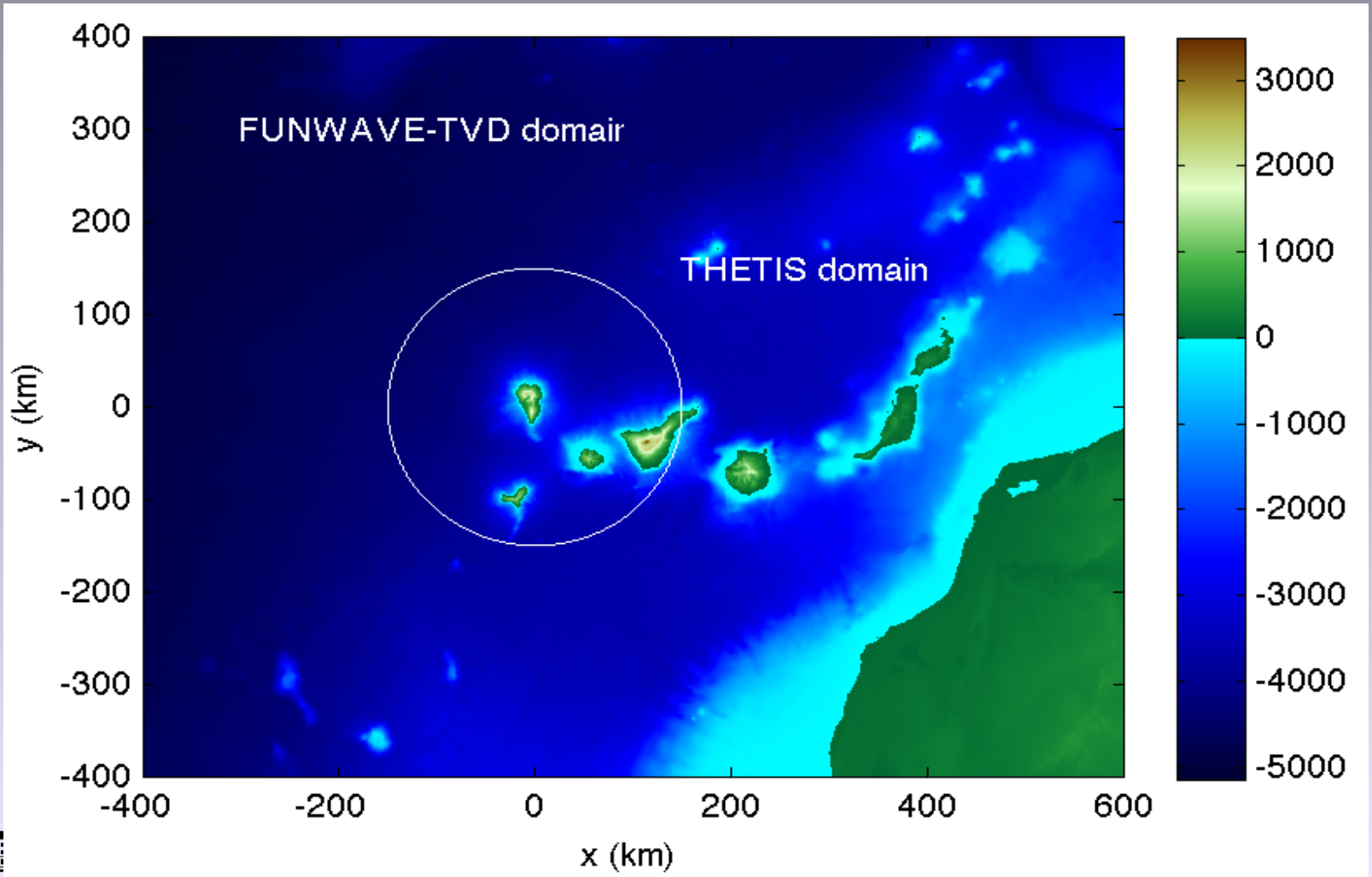
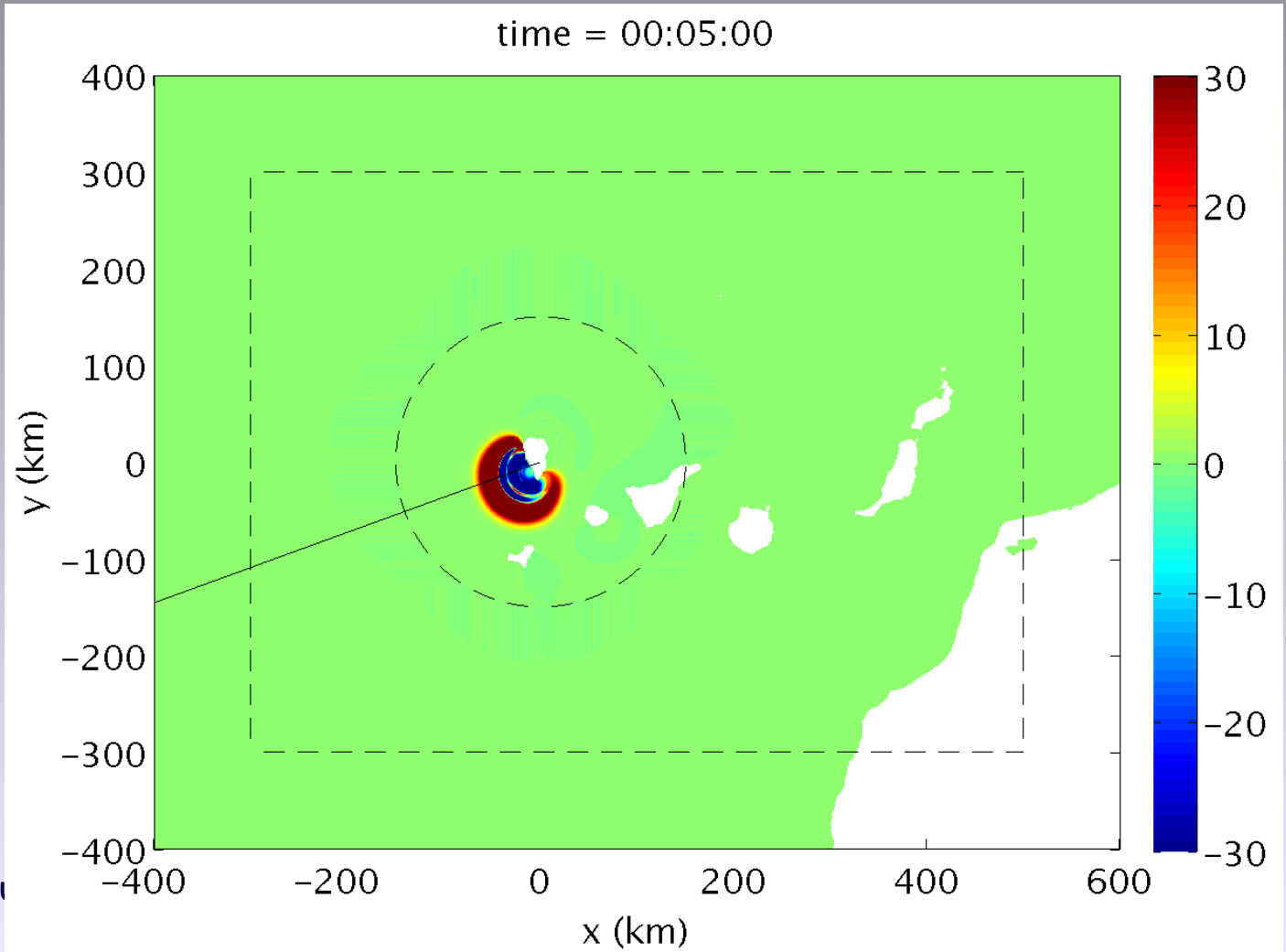
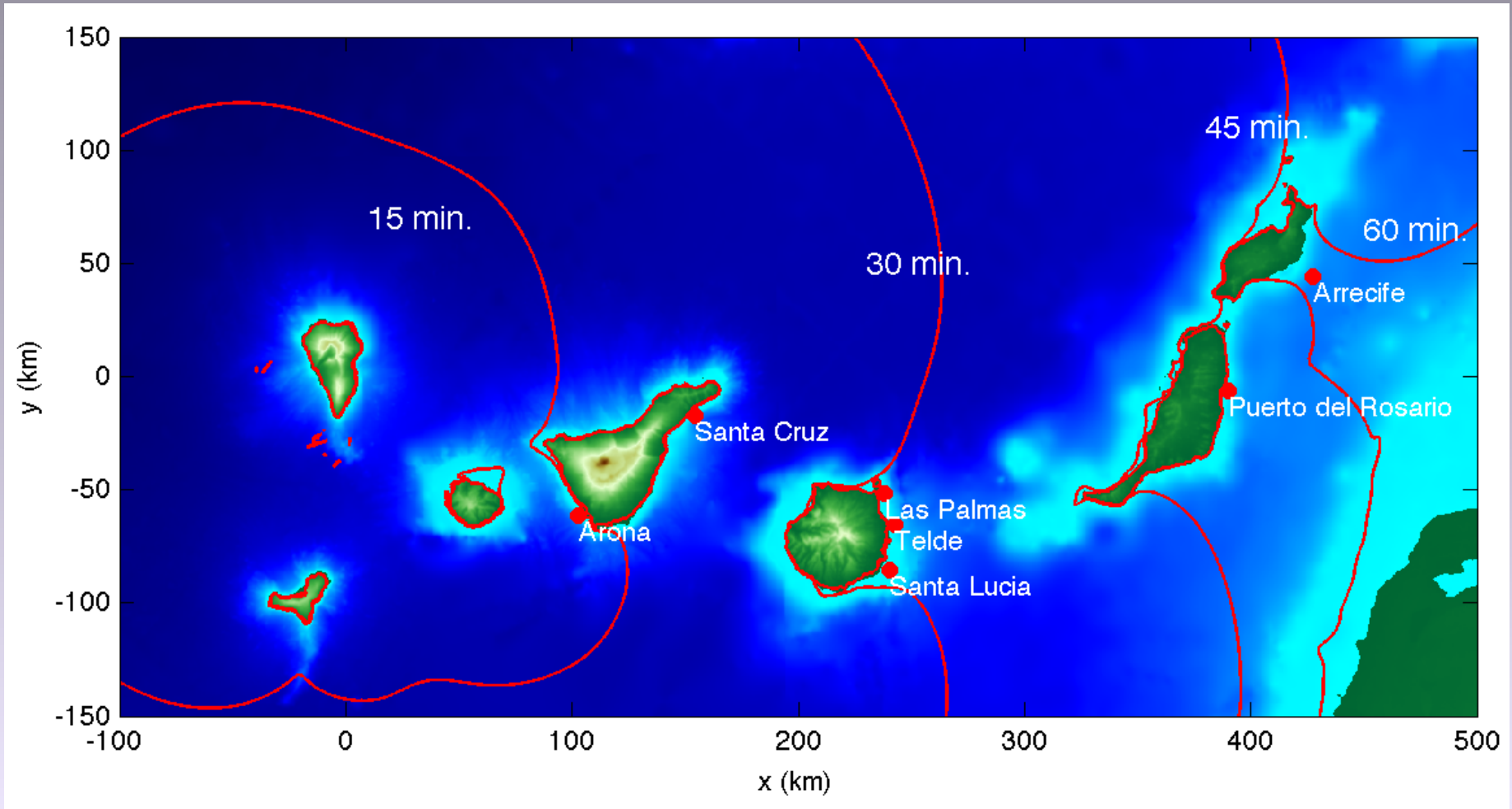
- Regional/Transoceanic/East coast propagation : 2D-horiz Fully Nonlinear Boussinesq model FUNWAVE in various nested grids



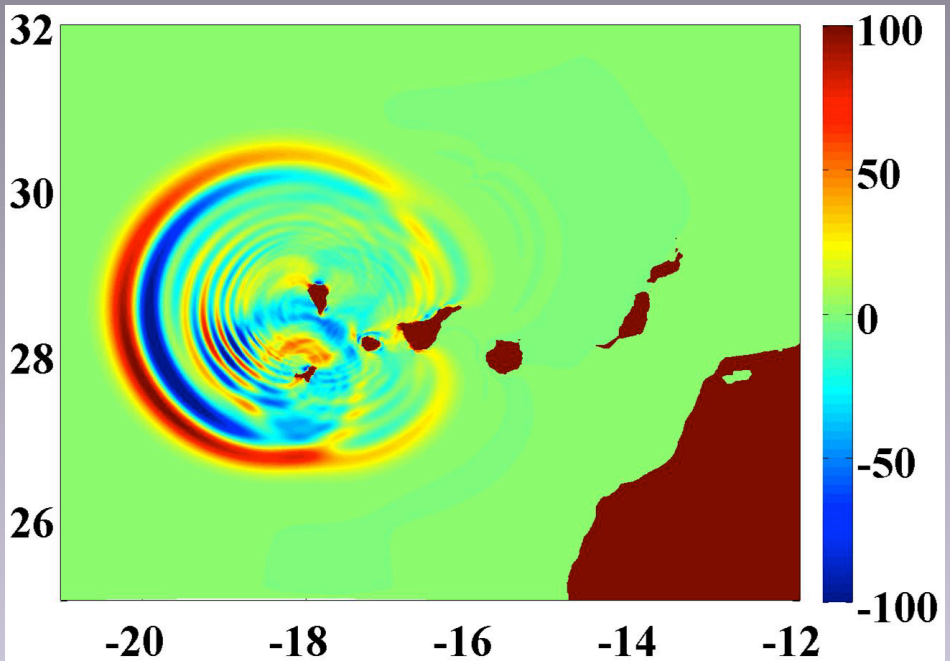
- Regional/Transoceanic/East coast propagation : 2D-horiz Fully Nonlinear Boussinesq model FUNWAVE in various nested grids (80 km^3 CVV source)

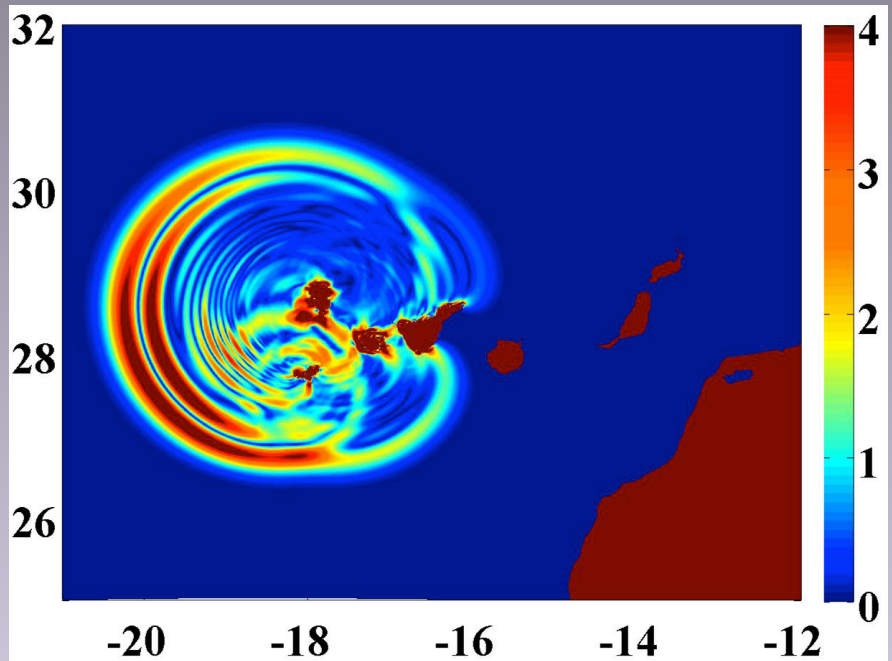


- Regional/Transoceanic/East coast propagation : 2D-horiz Fully Nonlinear Boussinesq model FUNWAVE in various nested grids (80 km^3 CVV source)



Far-field sources modeling : CVV collapse

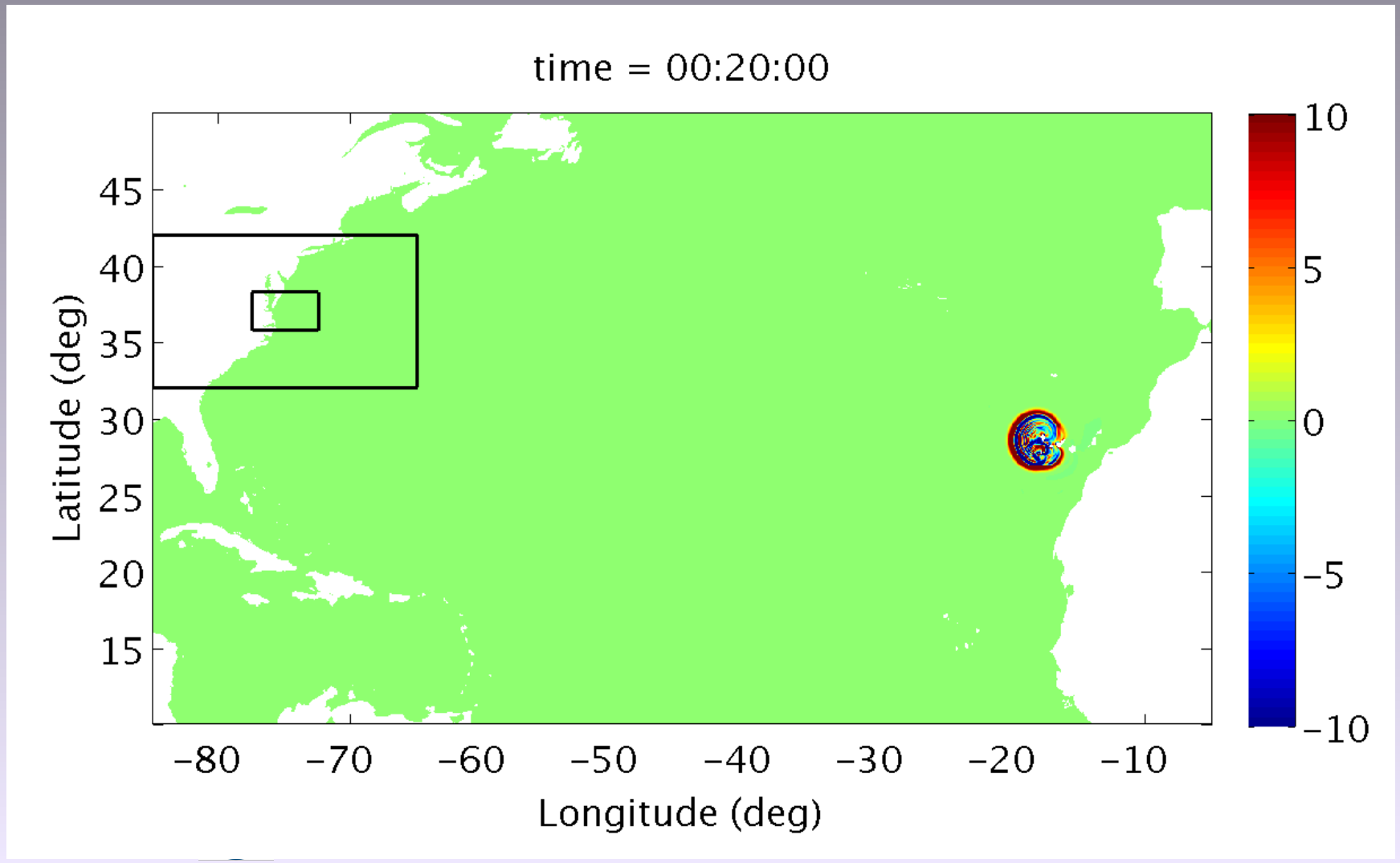




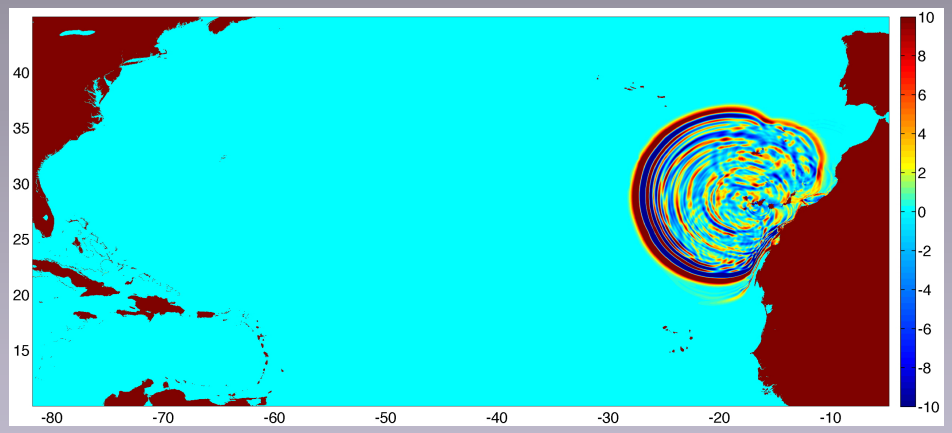
-> Initial surface elevation (m; left) specified in grid G1, from 3D THETIS/FUNWAVE-TVD simulations of the 450 km^3 CVV flank collapse scenario, 20 min. after the event.

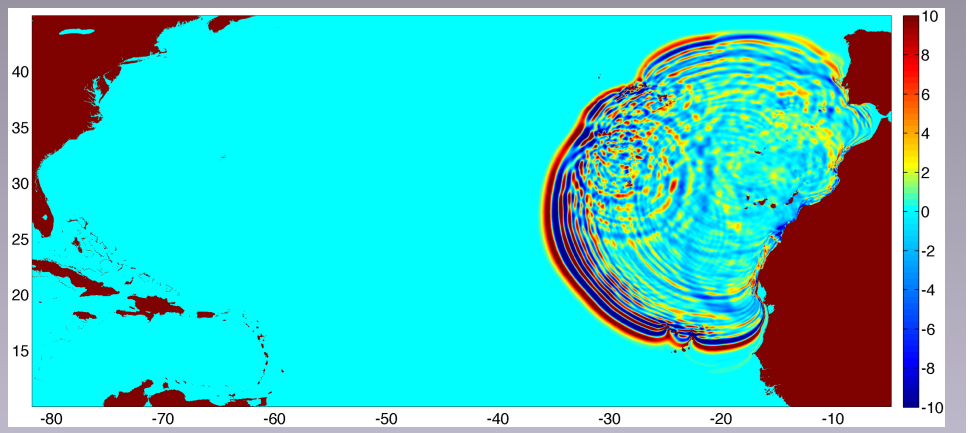
-> Initial horizontal velocity (m/s; right), 20 min. after the event

- Regional/Transoceanic/East coast propagation in FUNWAVE-TVD grid G1 of 450 km^3 CVV source: -> Instantaneous surface elevation (m)

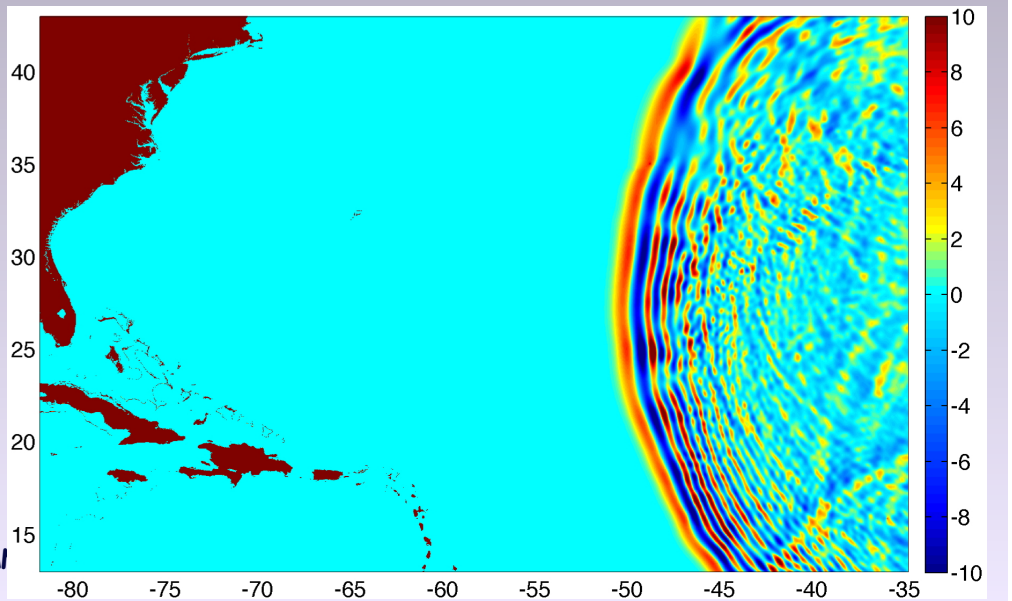


- Modeling of regional/Transoceanic propagation in FUNWAVE-TVD for 450 km^3 CVV source :





-> Surface elevation (m) in grid G1, after : 1h20', 2h20' and 4h20' of transoceanic propagation since the event.



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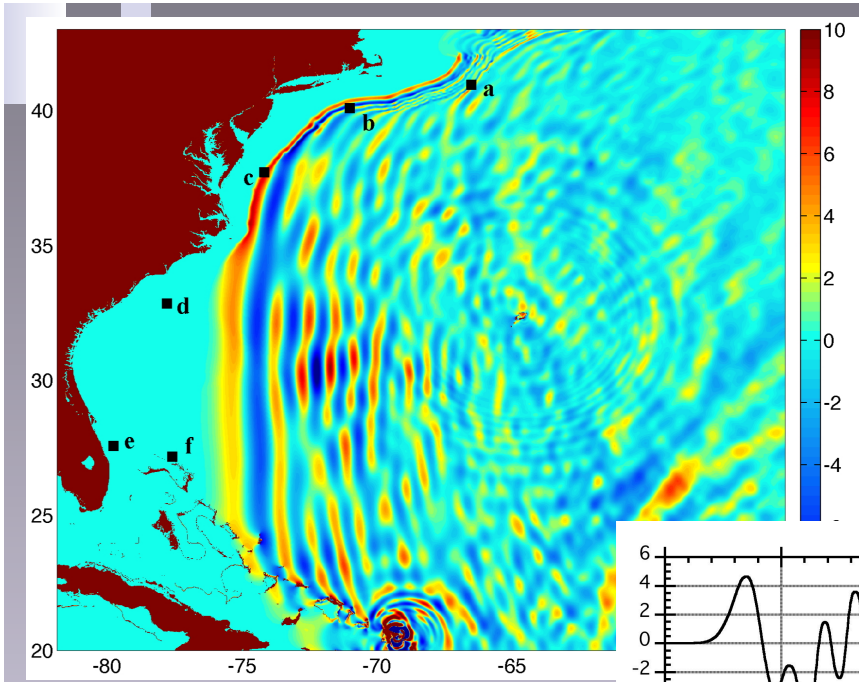
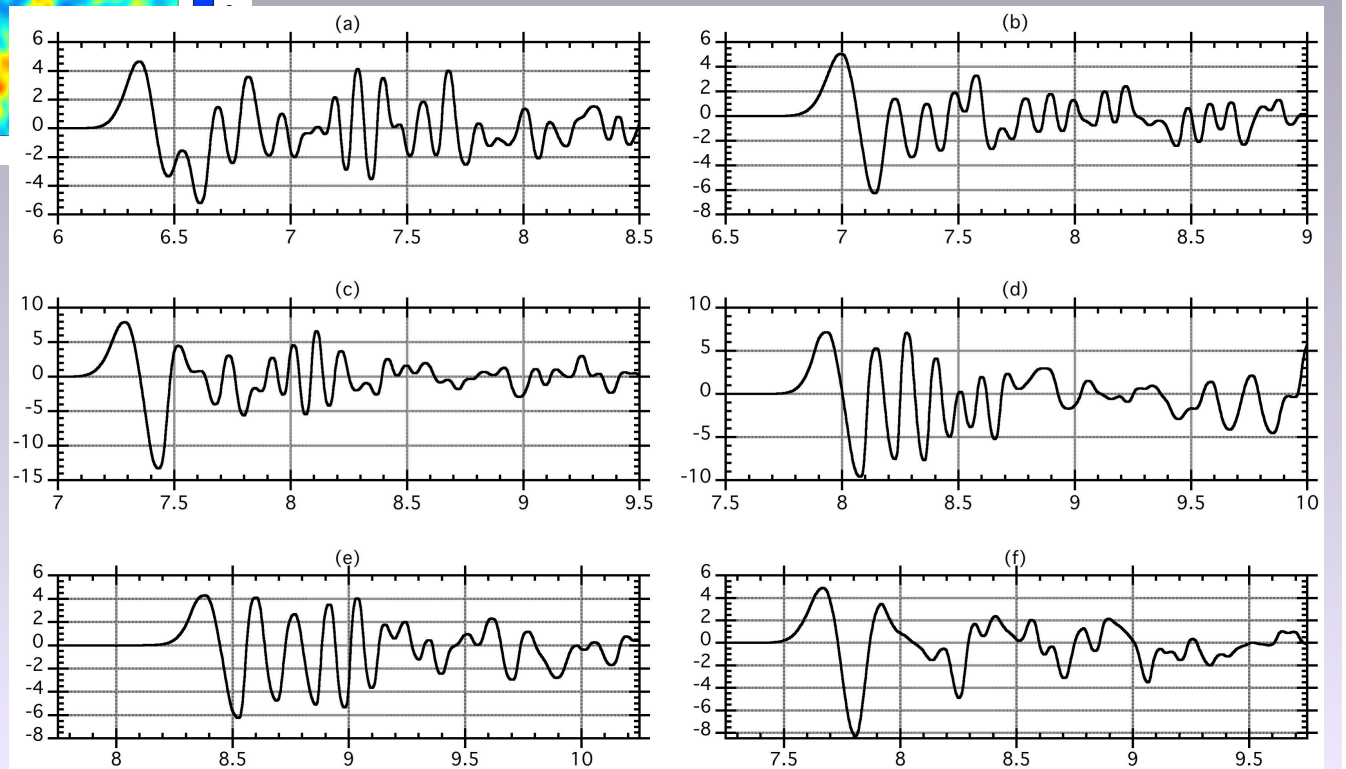


- Modeling of regional/Transoceanic propagation in FUNWAVE-TVD for 450 km^3 CVV source :

-> Surface elevation (m) in grid G1, after 7h20' of propagation and time series at 6 numerical gages



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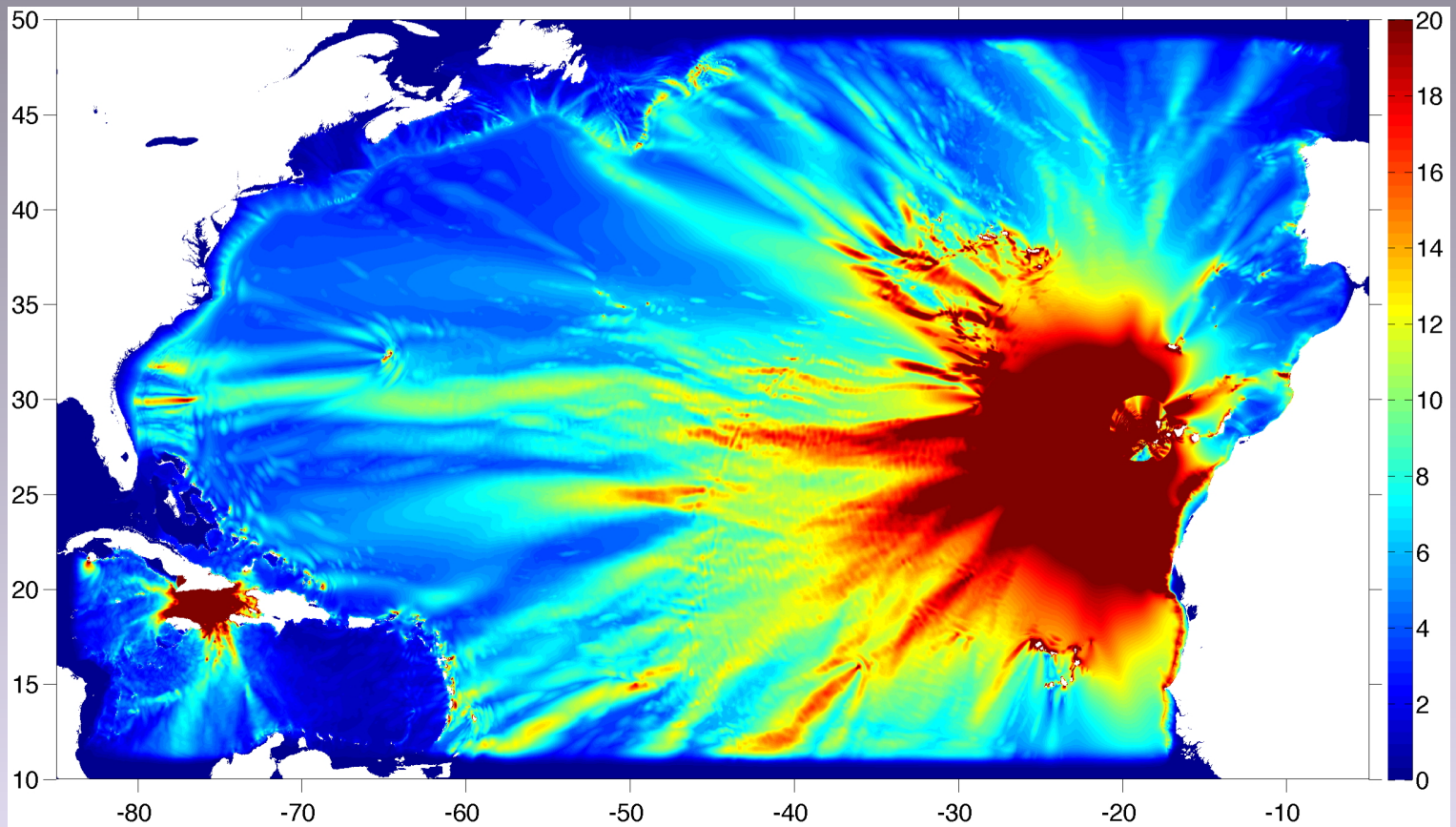
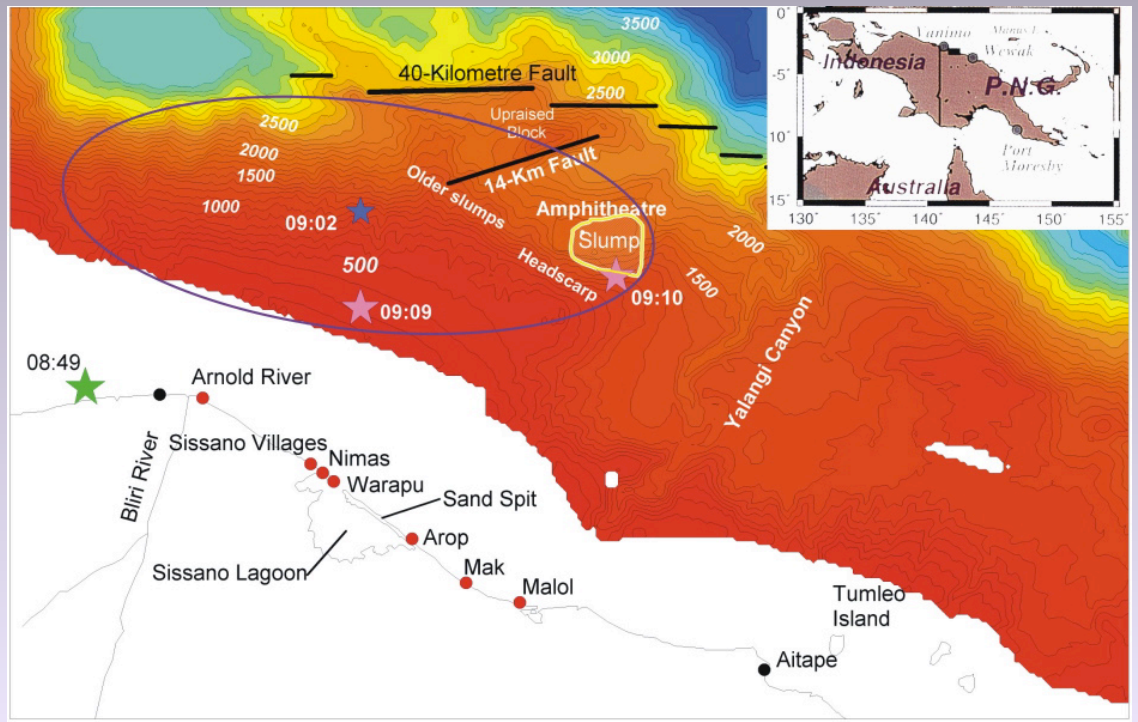
- Modeling of regional/Transoceanic propagation in FUNWAVE-TVD for 450 km^3 CVV source :



-> Envelope of maximum surface elevation after 8h of propagation

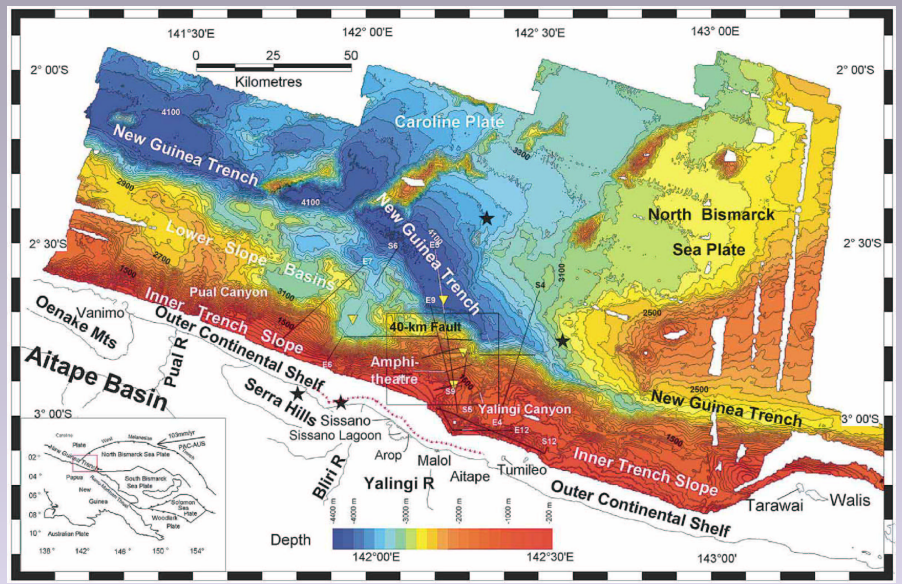
Case Study: PNG 1998 propagation simulation

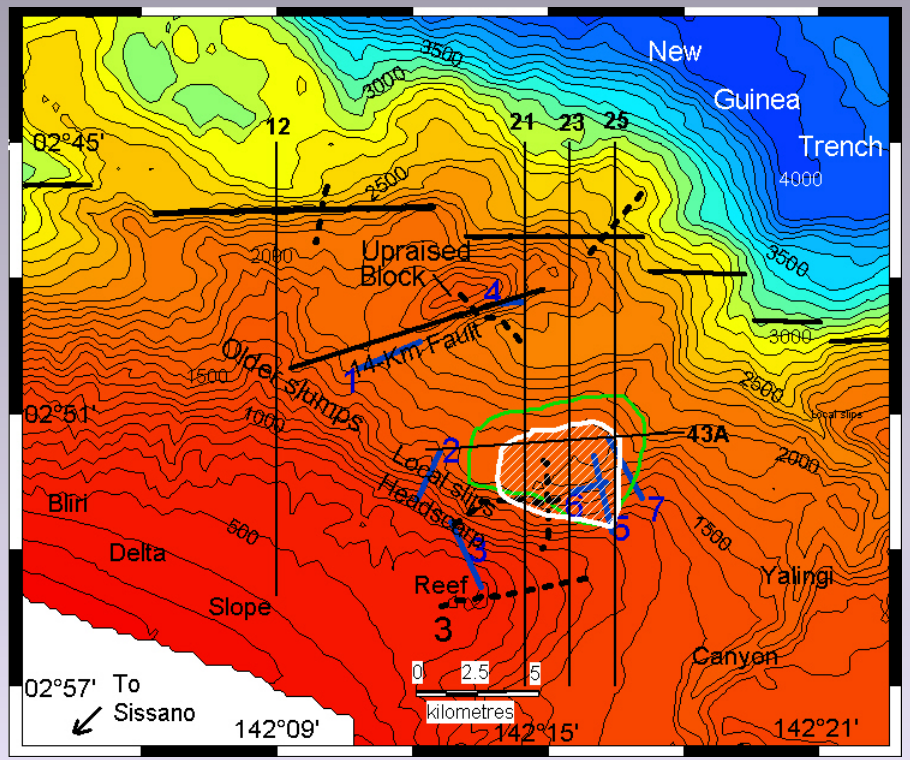
- July 17th, 1998: A modest earthquake (Mw = 7.1) off of Papua New Guinea (PNG) north shore triggers a tsunami that floods Sissano lagoon with over 16 m inundation/runup and kills 2000 people.



PNG 1998 Case Study: geological map (2003)

- PNG 1998: Very complex geology (Tappin, 2003)





-> 1500 m deep, 6 km^3 slump

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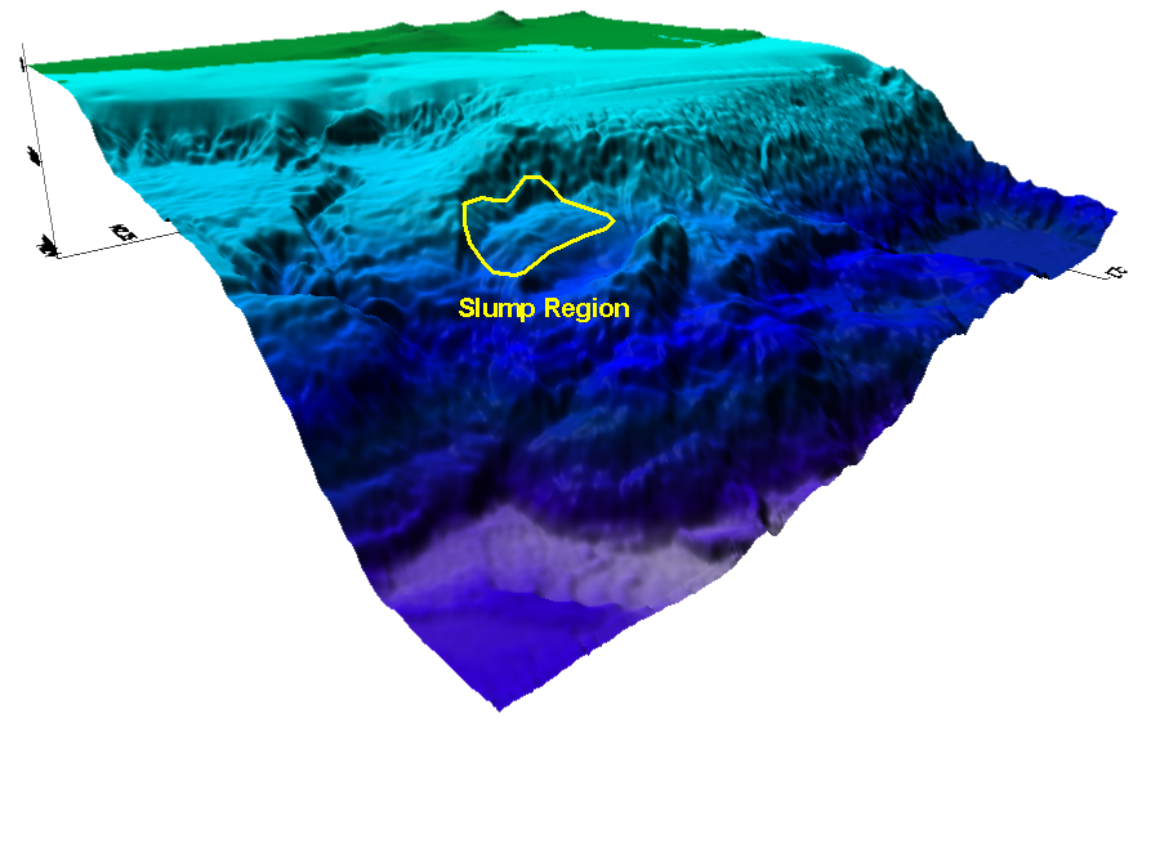
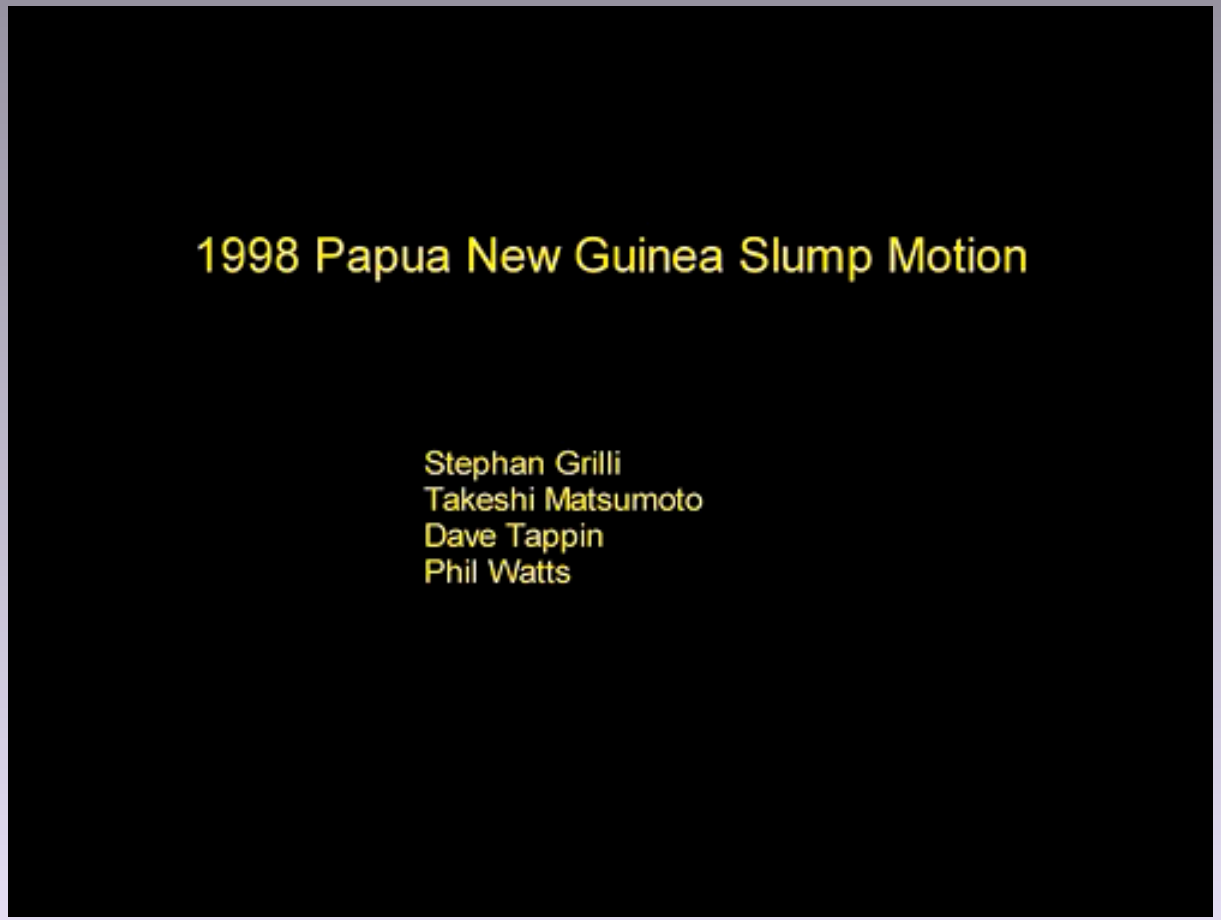
PNG 1998 Case Study: geological data

- Tappin, Watts and Grilli, (1999-2003) :

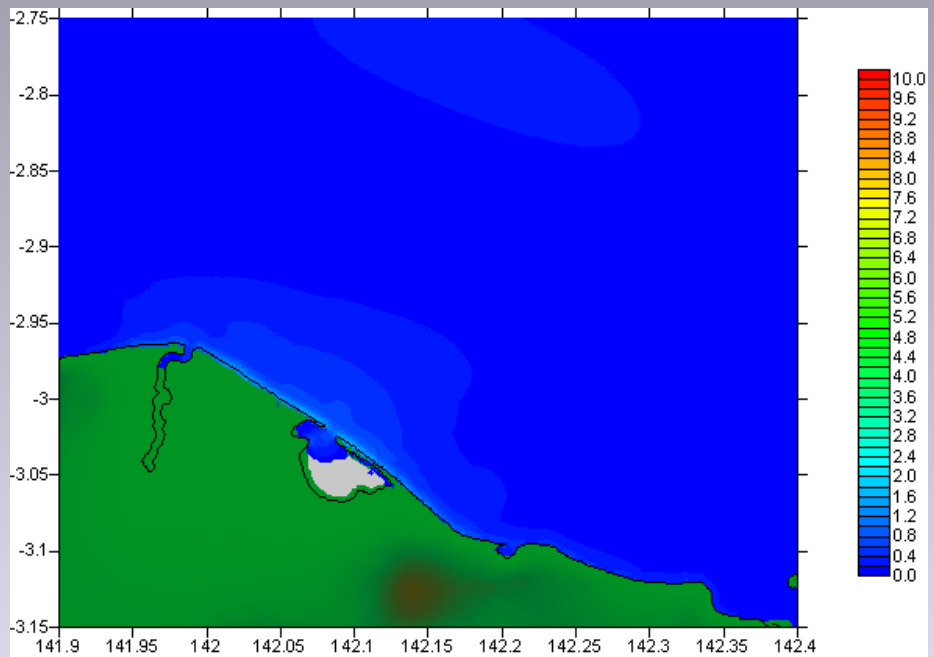


PNG 1998 Case Study: geological data

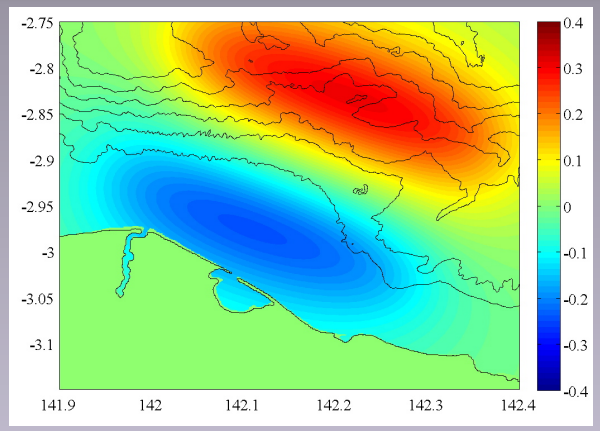


PNG 1998 Case Study: propagation simulation

Earthquake tsunami elevation

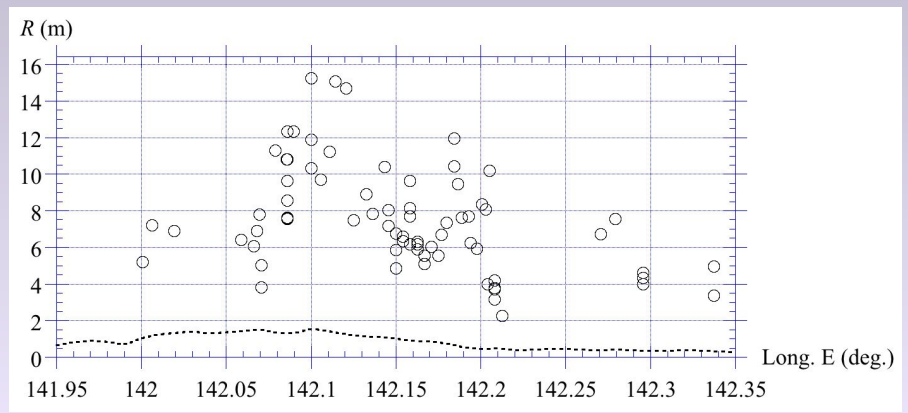


(see Tappin et al., 2008)



Initial co-seismic source
Mw = 7.1
(Okada, 1985)

Earthquake tsunami runup



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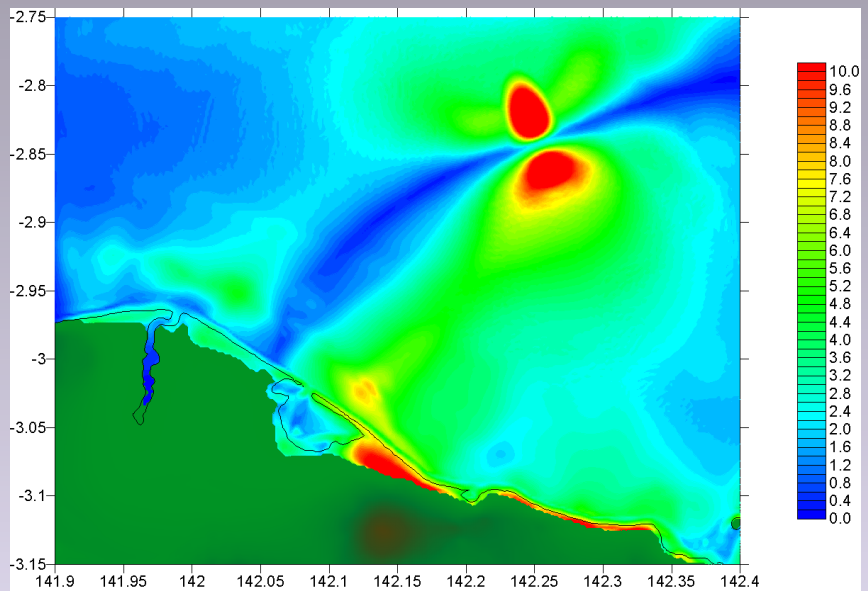
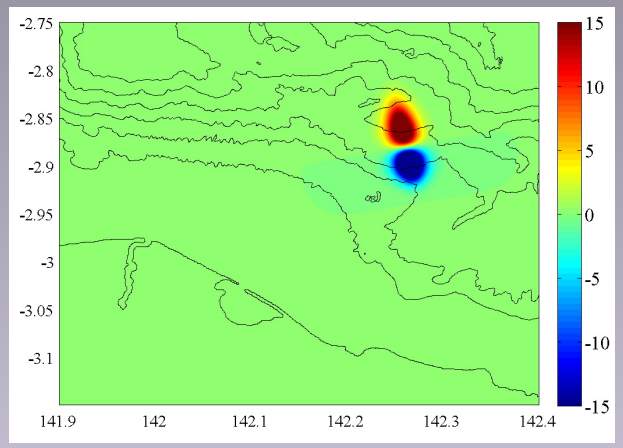
PNG 1998 Case Study: propagation simulation

Landslide tsunami elevation (m)

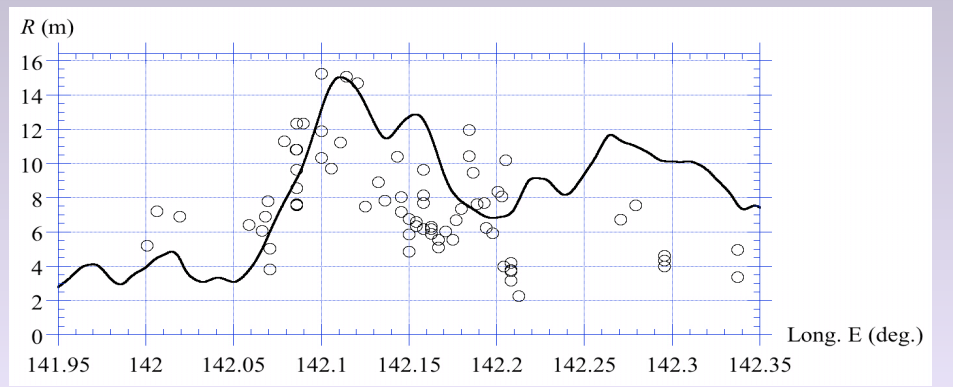


(2003 results;
see Tappin et al., 2008)



Initial slump source (m) (Tappin et al, 2002-2008)

Landslide tsunami runup



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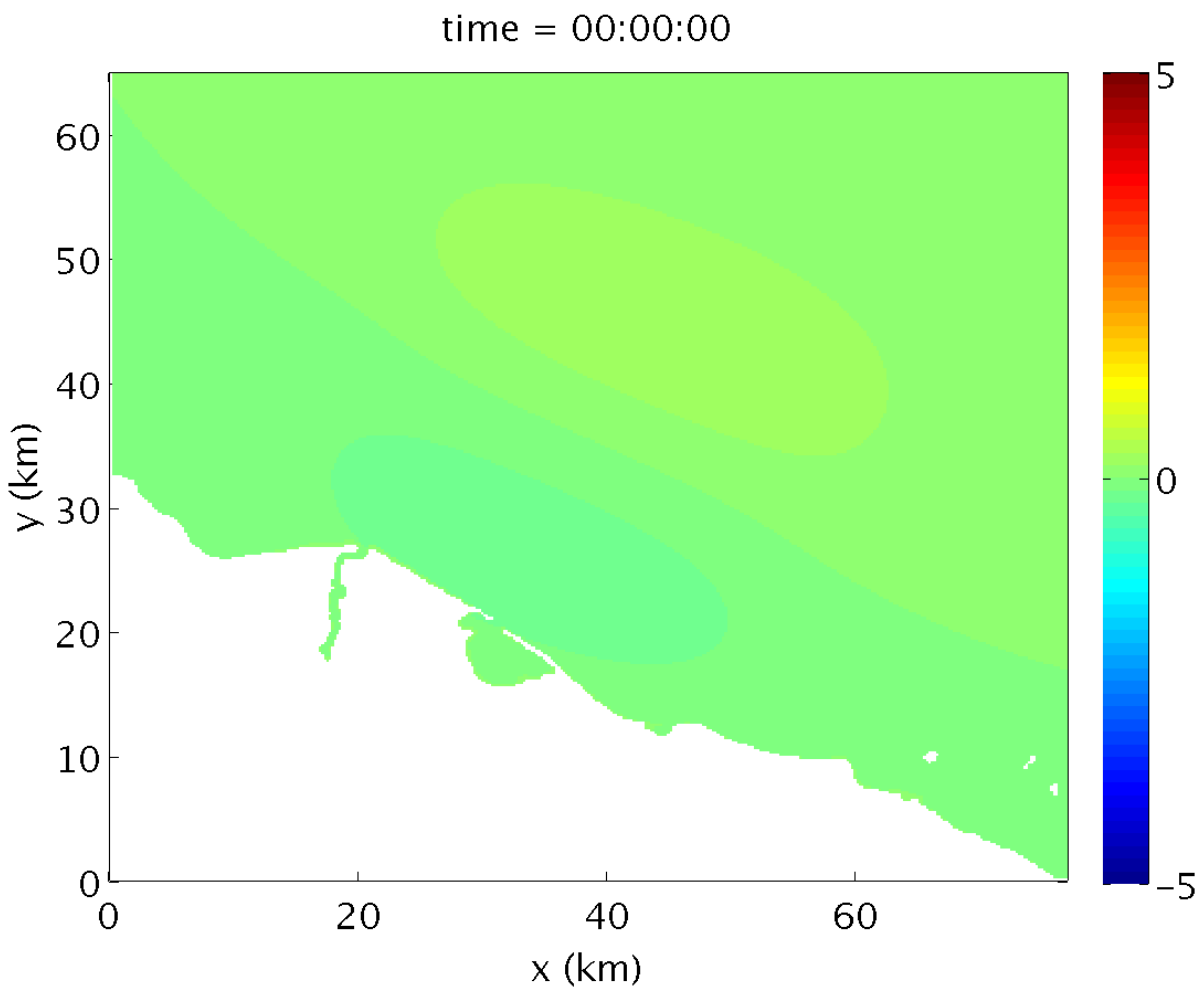
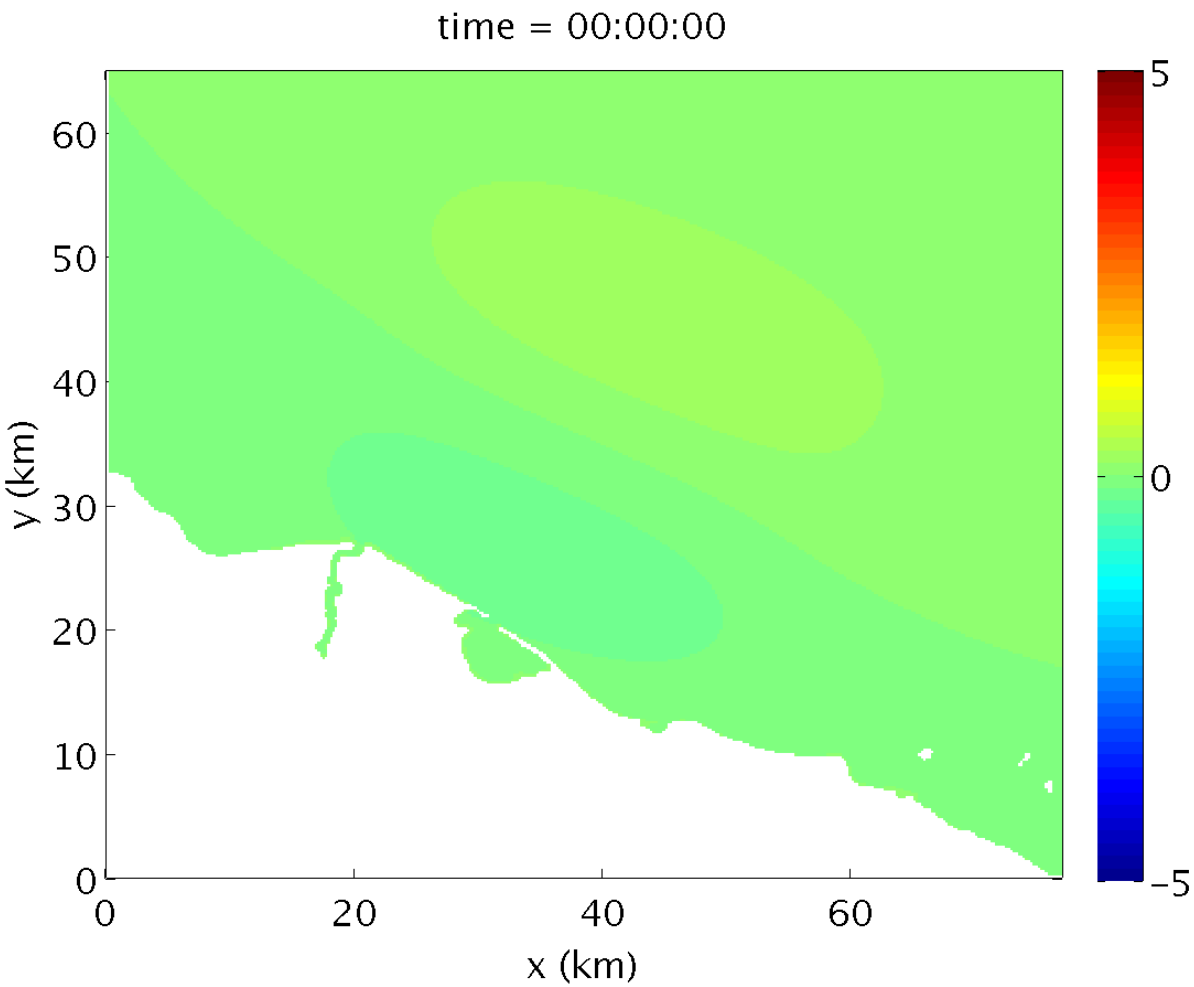
PNG 1998 Case Study: propagation simulation



(FUNWAVE Dispersive simulation, 50 m grid)

PNG 1998 Case Study: propagation simulation



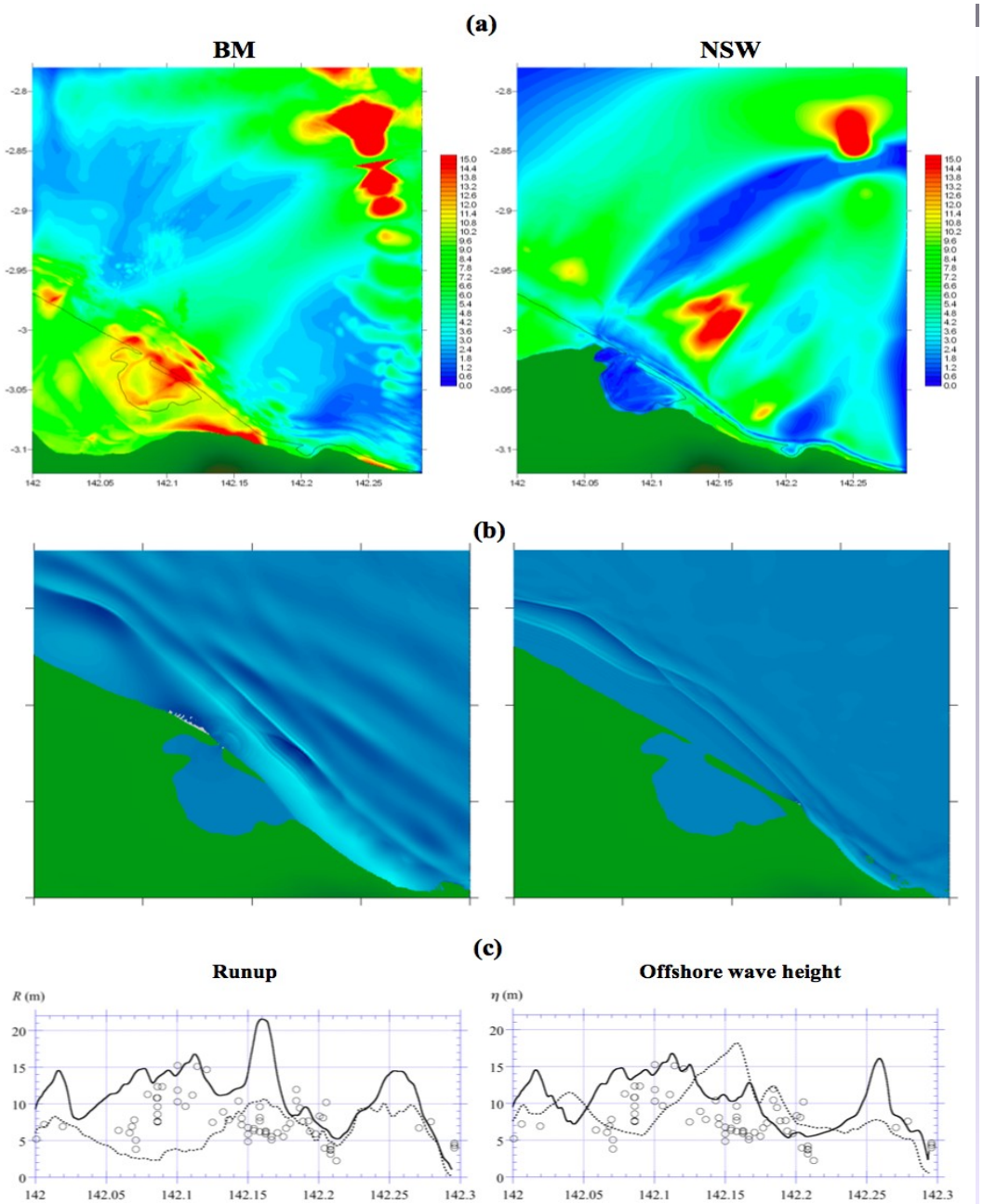
(FUNWAVE Non-Dispersive simulation, 50 m grid)

FUNWAVE simulations

Dispersive vs. non-dispersive solution (PNG 1998)

Same slump source, same code, bathymetry, and dissipation parameters

(Tappin et al., 2008 (NHESS))



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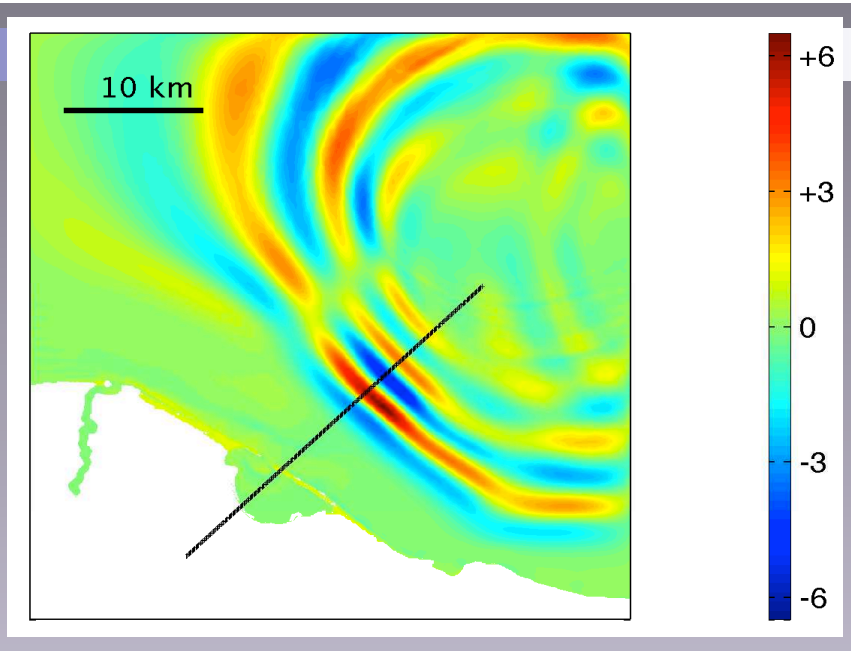
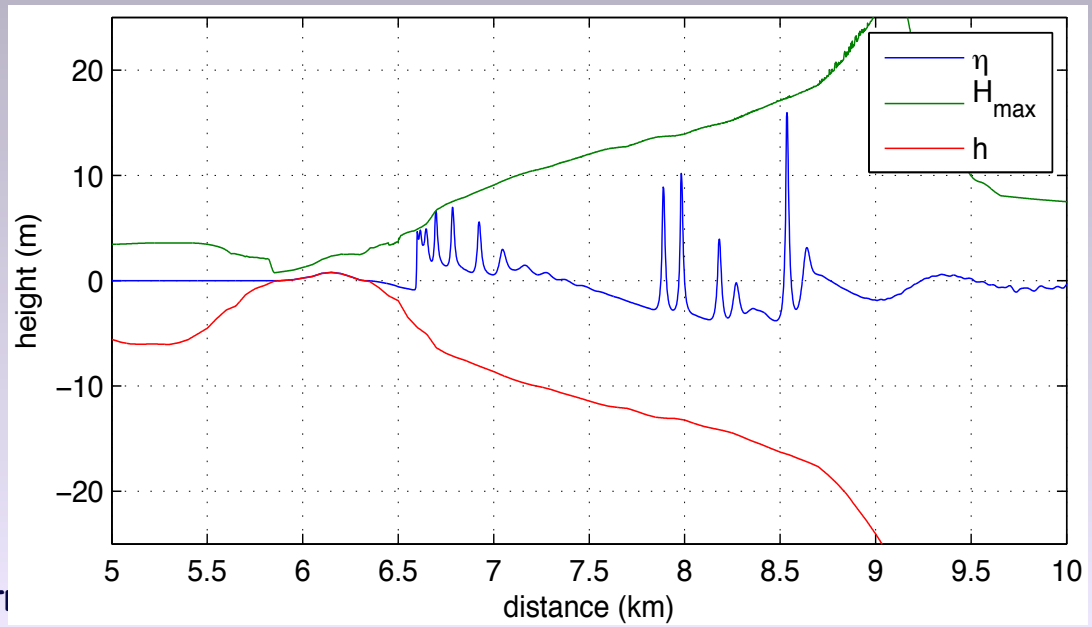
FUNWAVE-TVD simulations

Recent higher-resolution simulations

(Grilli et al., 2012 (ICCE12))





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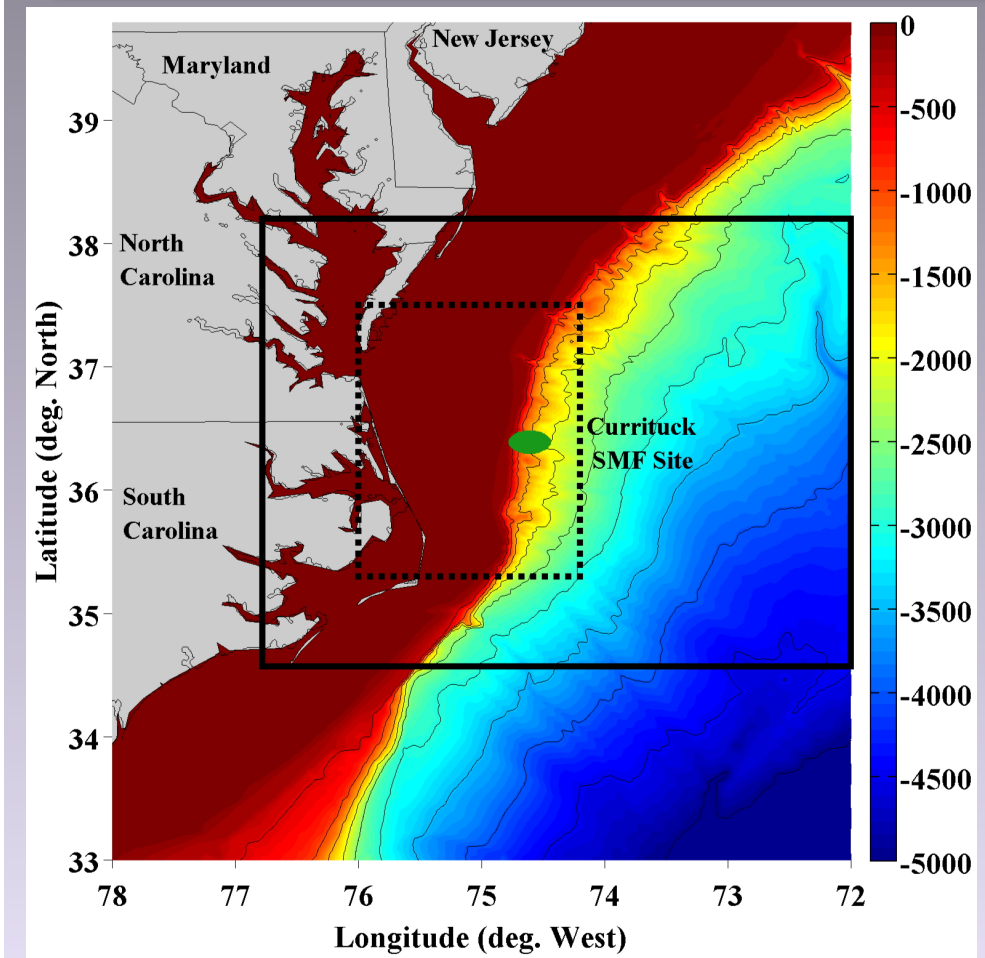
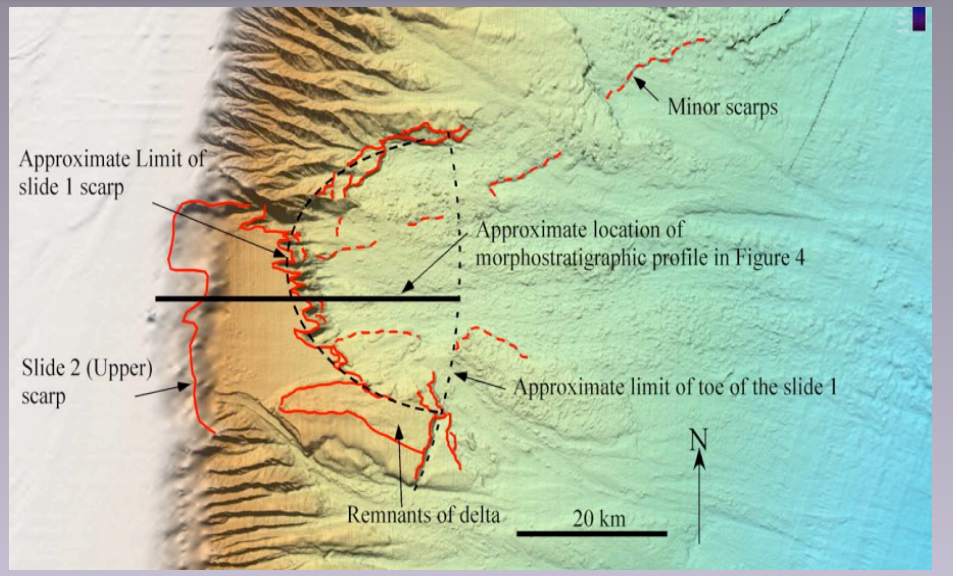
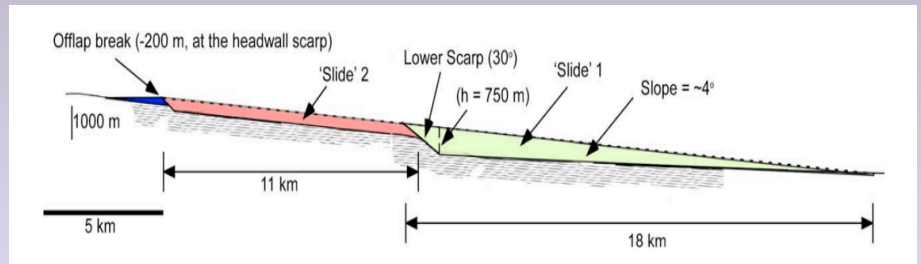
NTI

Case study of US East Coast slide: Currituck







[Grilli et al., 2015 (Nat. Haz.)]

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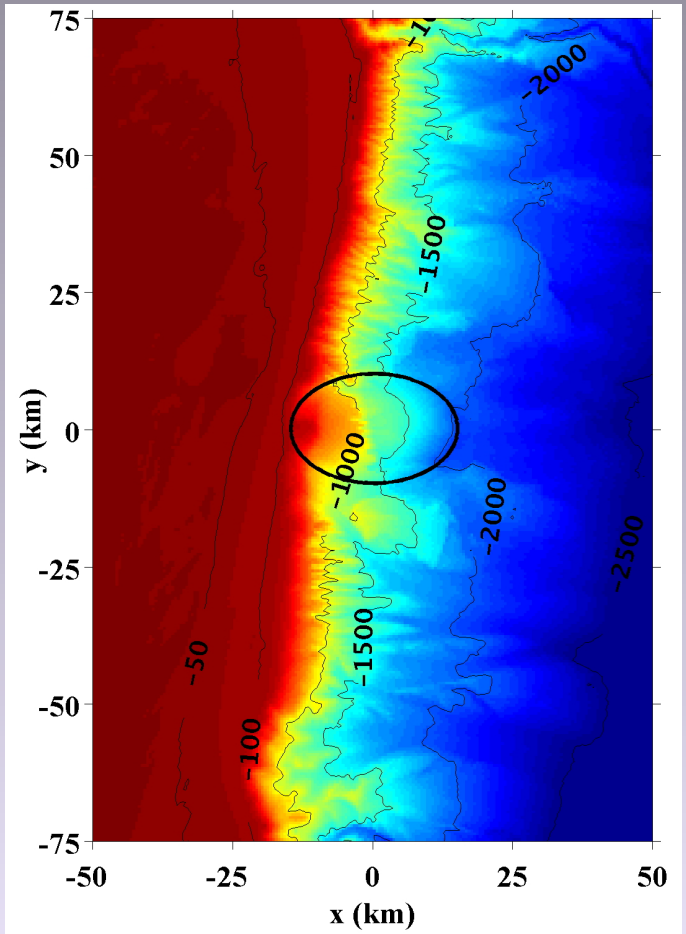
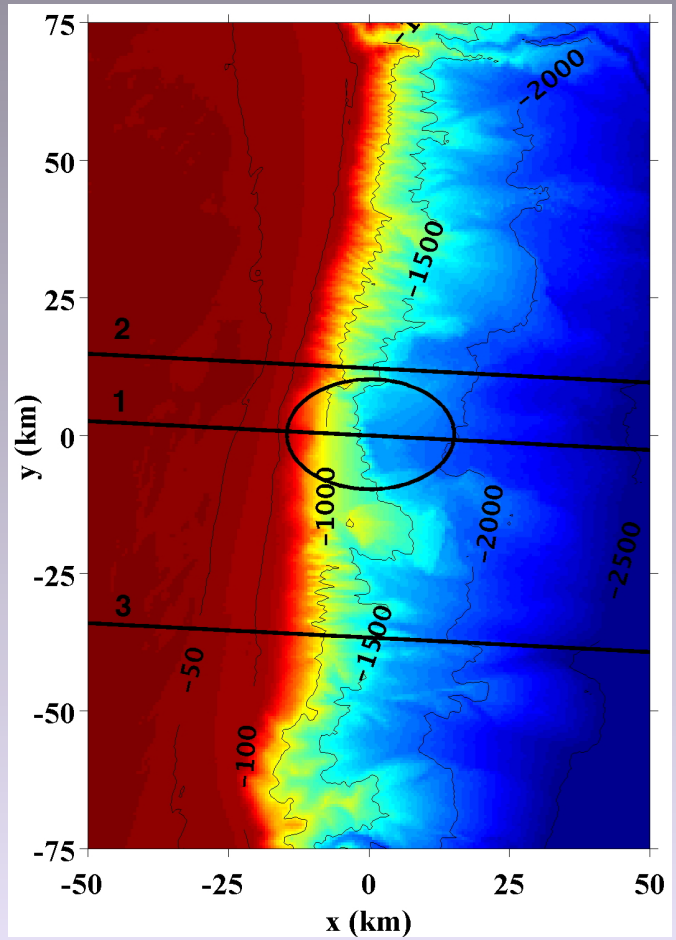
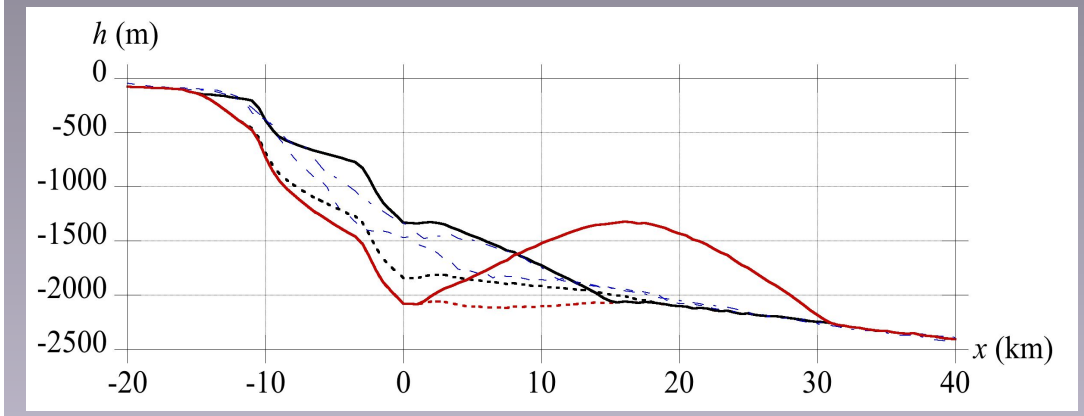
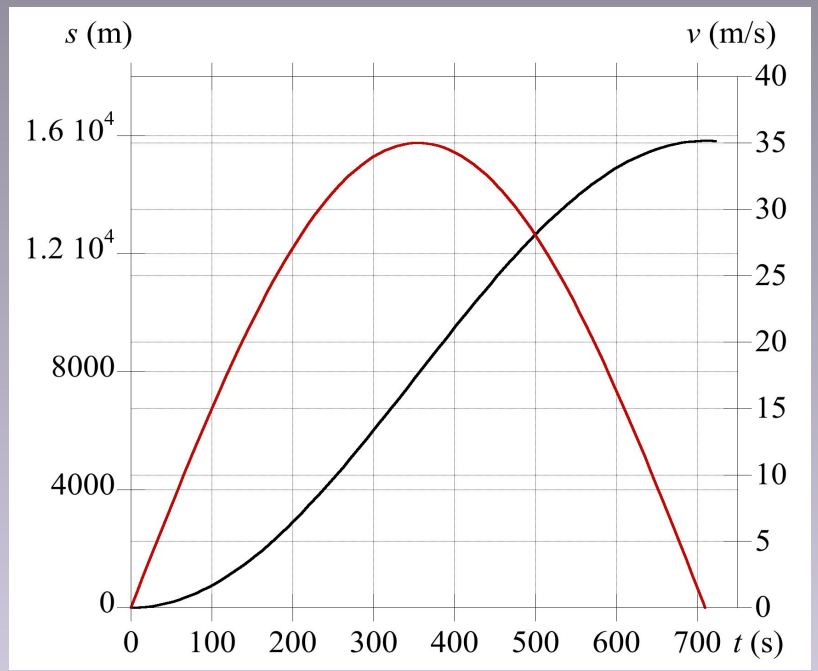
Currituck: slide geometry reconstruction





Currituck: slide geometry and kinematics





$$\zeta(\xi,\chi) = \frac{T}{1-\varepsilon}\max\left[0,\ \operatorname{sech}(k_b\xi)\operatorname{sech}(k_w\chi) - \varepsilon\right]$$

$$k_b = \frac{2}{b}\operatorname{acosh}\frac{1}{\varepsilon}$$

$$k_w = \frac{2}{w}\operatorname{acosh}\frac{1}{\varepsilon}$$

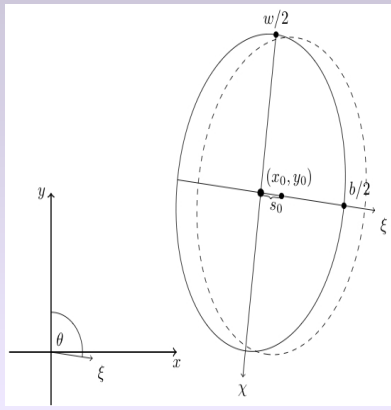
$$s(t) = \begin{cases} 0 & t < t_i \\ s_0\left(1-\cos\left\{\dfrac{t-t_i}{t_0}\right\}\right) & t_i \le t < t_i + \pi t_0 \\ 2s_0 & t_i + \pi t_0 \le t \end{cases}$$

$$\xi = (x-x_0)\cos\theta - (y-y_0)\sin\theta - s(t)$$

$$\chi = (x-x_0)\sin\theta + (y-y_0)\cos\theta$$

$$h(x,y,t) = h_0(x,y) + \zeta\{\xi(x,y),\chi(x,y),t\} - \zeta\{\xi(x,y),\chi(x,y),t_i\}$$

$$\frac{dh}{dt}(x,y,t) = \frac{d}{dt}\left\{\zeta\{\xi(x,y,s(t)),\chi(x,y)\}\right\}$$



$$s_0 = \frac{R\Delta\phi}{2} \quad \text{and} \quad t_0 = \sqrt{\frac{R}{g}\frac{\gamma + C_m}{\gamma - 1}}$$

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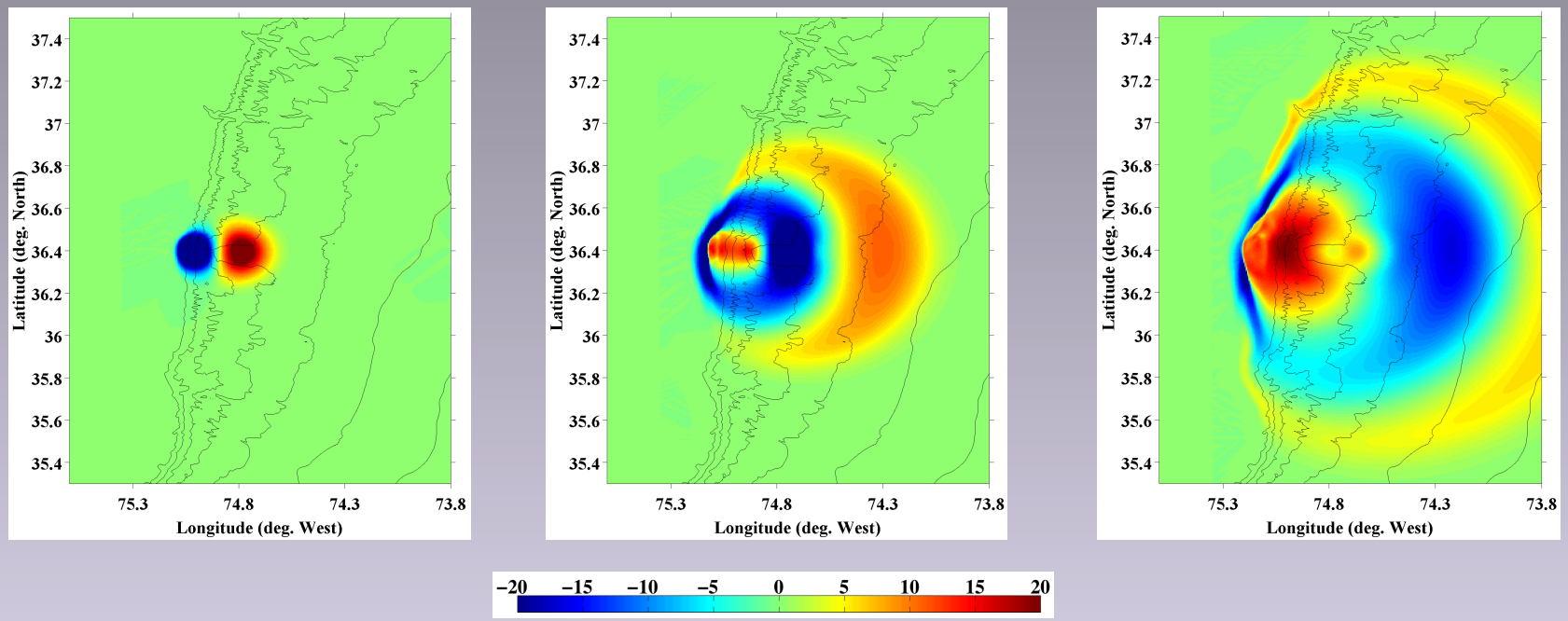
Currituck: NHWAVE tsunami source generation



NHWAVE (C_d = 0; 500 m grid; 3 sigma levels). Instantaneous surface elevation (color scale is in meters) after: (l) 125 s; (m) 500 s; and (r) 800 s (13.3 min.)

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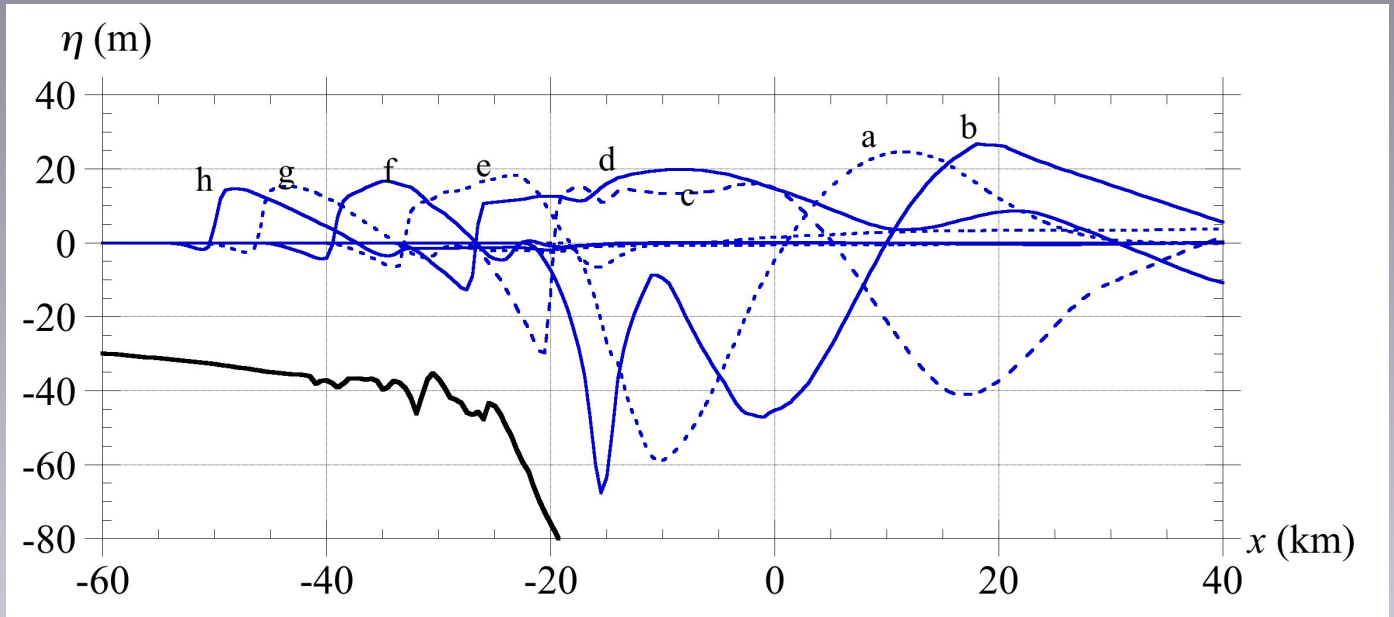
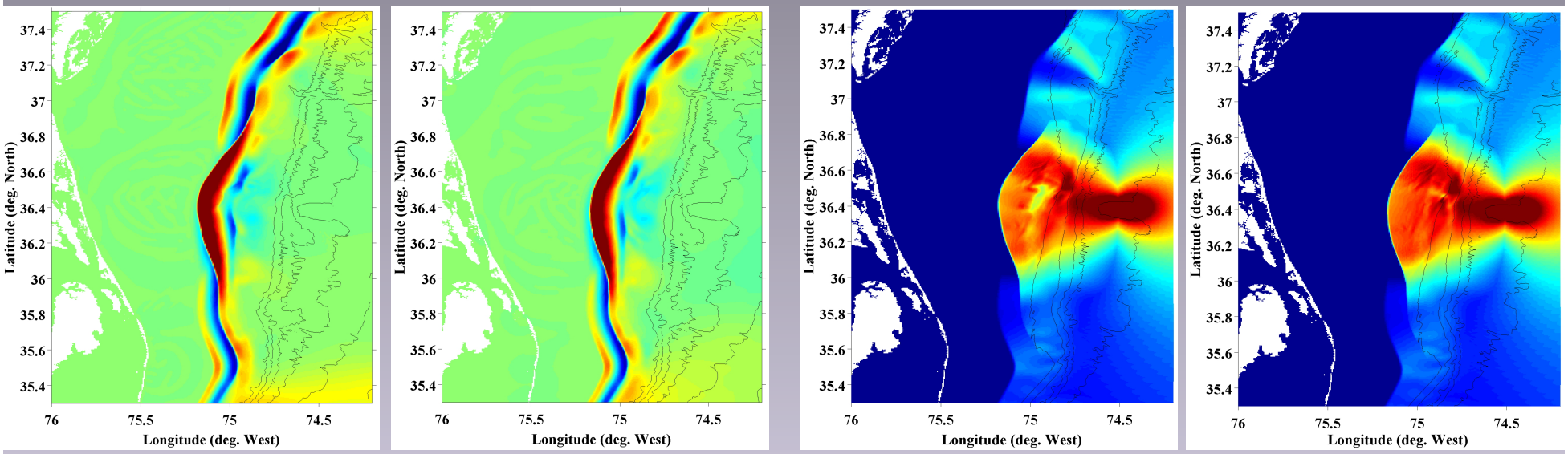
Currituck: NHWAVE early propagation



NHWAVE instantaneous surface elevation (---) after: (a) 125 s; (b) 250 s; (c) 500 s; (d) 800 s (13.3 min); (e) 1100 s; (f) 1400 s; (g) 1700 s; (h) 2000 s (33.3 min). Results are shown along an E-W transect through the SMF center (36.39 N lat.), as a function of the distance to the center of the SMF.

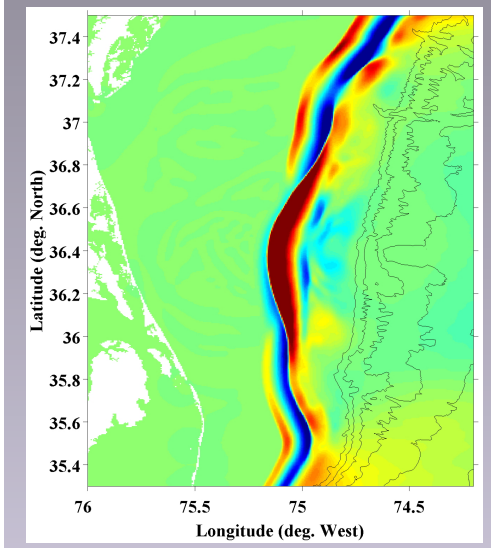
Currituck: NHWAVE/FUNWAVE early propagation



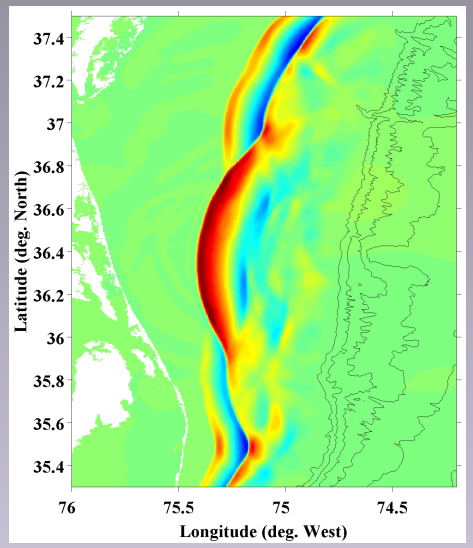
NHWAVE (33′) FUNWAVE (33′) NHWAVE (max to 33′) FUNWAVE (same)

[FUNWAVE is initialized form NHWAVE results at 13′ (on same 500 m grid)]

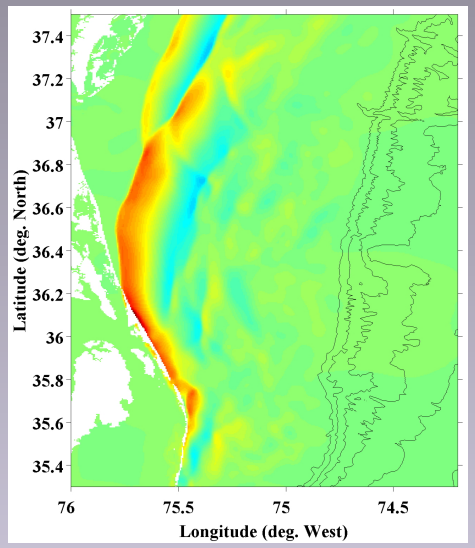
Currituck: FUNWAVE propagation shelf/coastal



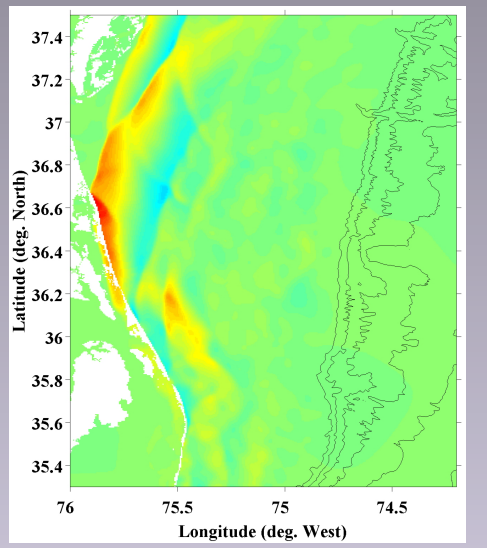
FUNWAVE (33′)



FUNWAVE (49′)



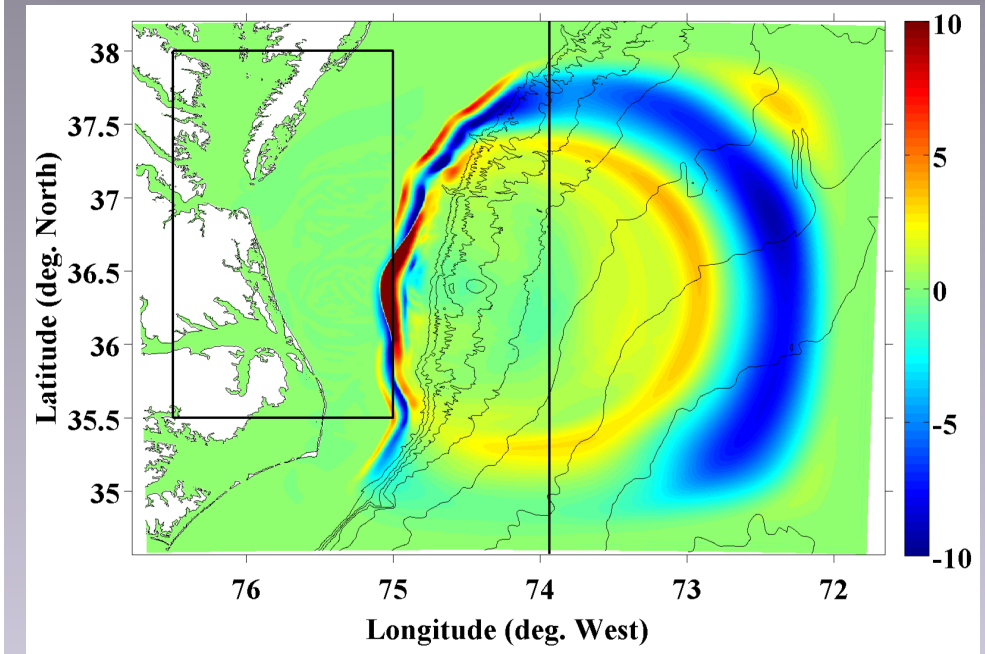
FUNWAVE(82′)

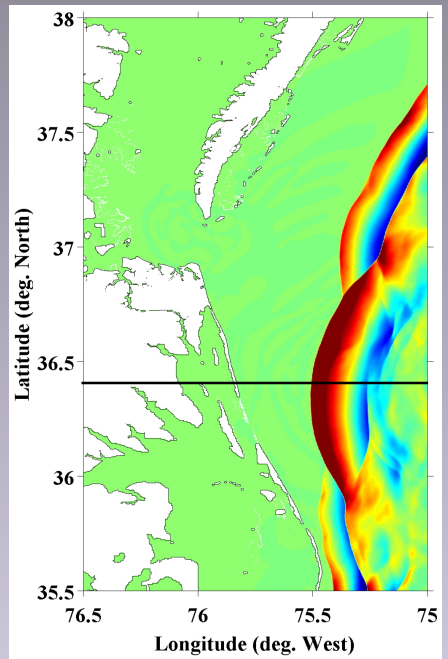


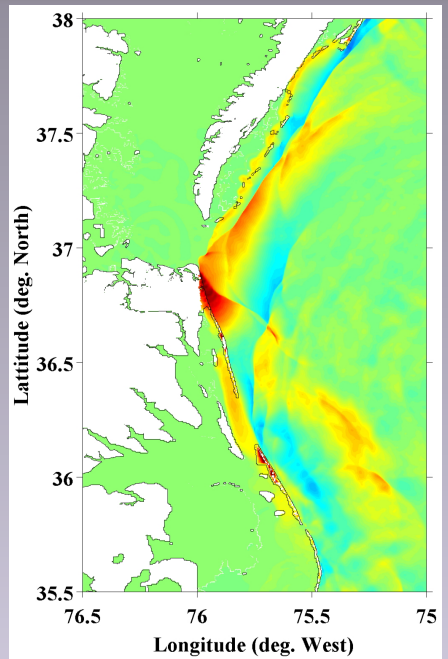
FUNWAVE (99′)

[FUNWAVE is initialized form NHWAVE results at 13′ (on same 500 m grid). After that, bottom friction coefficient is C_d = 0.0025]

Currituck: FUNWAVE shelf/coastal nested grid



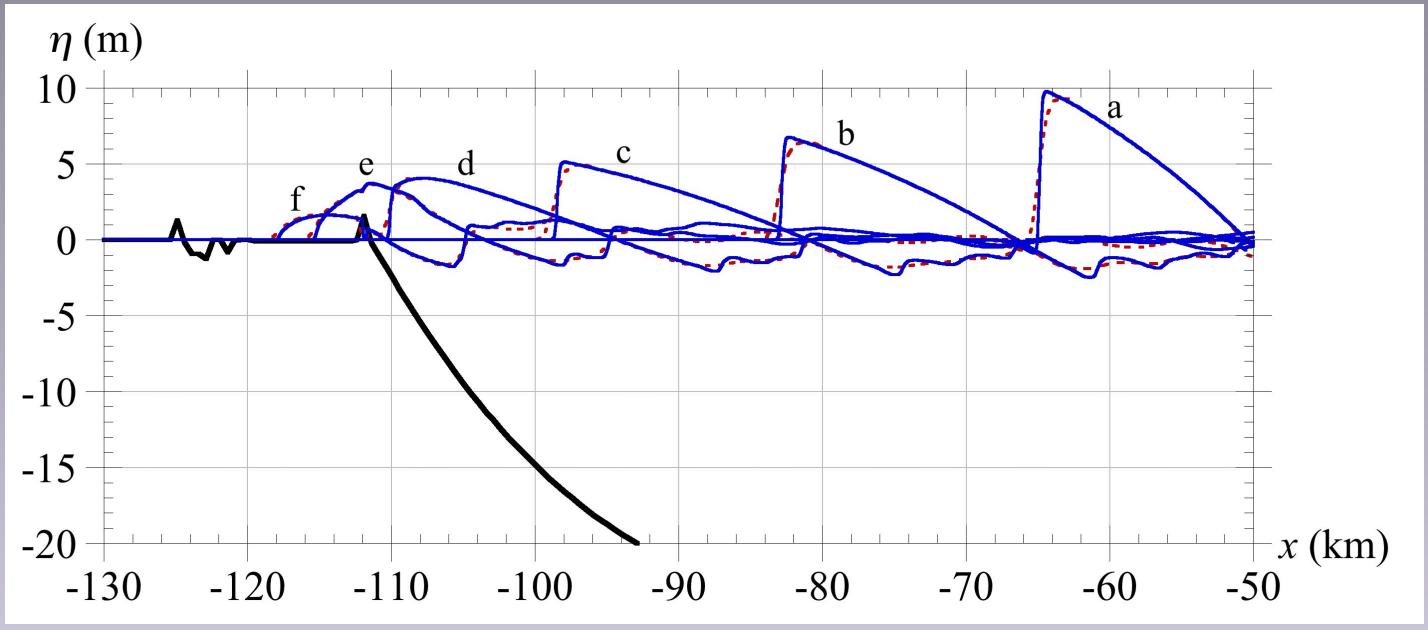




FUNWAVE (27′) FUNWAVE (57′) FUNWAVE (117′)

[FUNWAVE is initialized form NHWAVE results at 13′ (on same 500 m grid). After that, bottom friction coefficient is C_d = 0.0025. Nested grid is 125 m.]

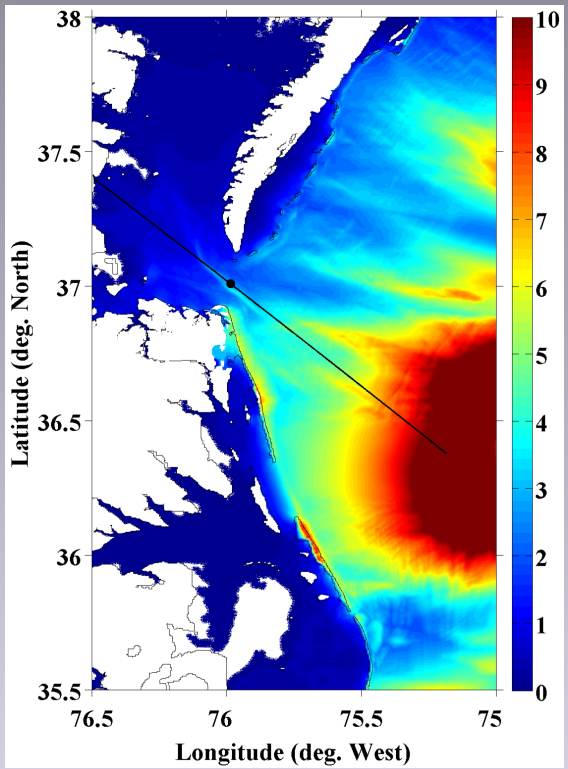
Currituck: FUNWAVE shelf/coastal nested grid

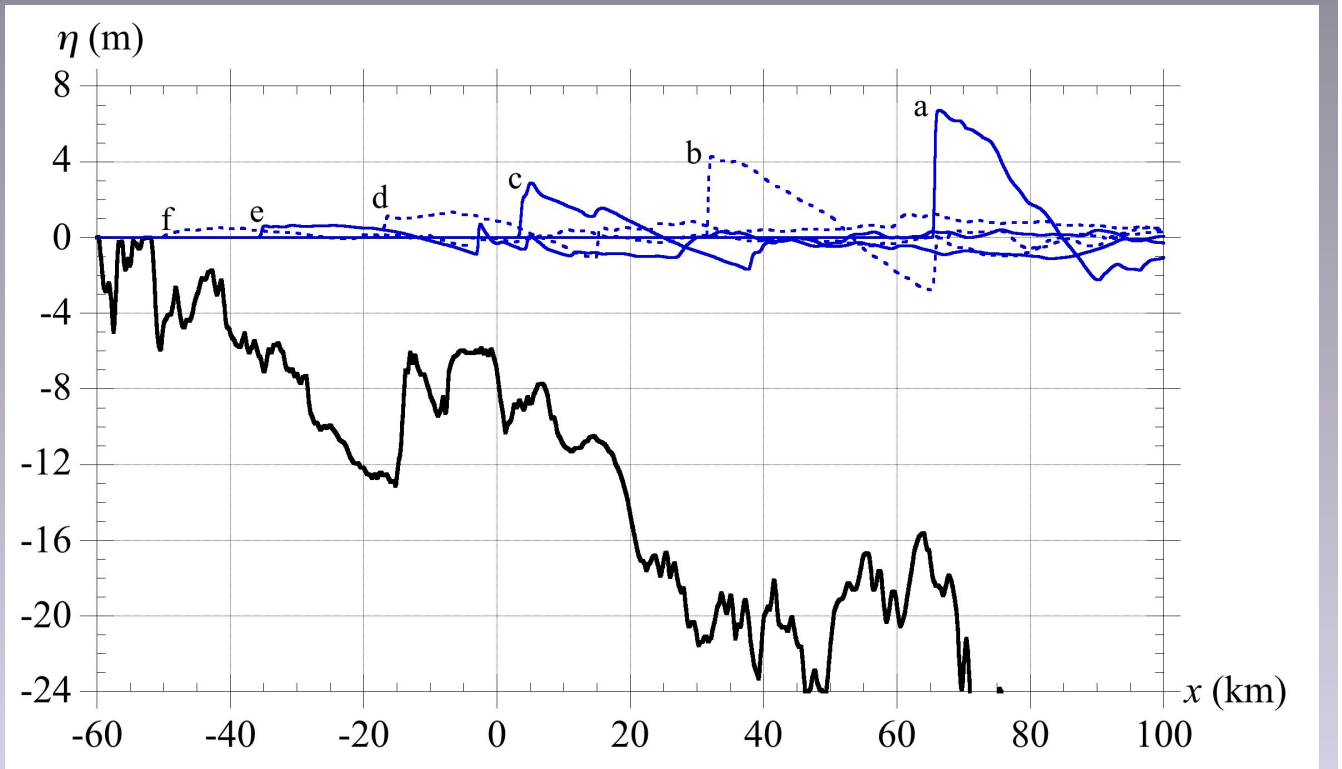


FUNWAVE transects from 42′ to 117′: 125 m (solid); 500 m (dash) (mesh is still not fine enough for undular bores to appear)

[FUNWAVE is initialized form NHWAVE results at 13′ (on same 500 m grid). After that, bottom friction coefficient is C_d = 0.0025. Nested grid is 125 m initialized from BC time series from 27′ on.]

Currituck: FUNWAVE/Chesap. Bay in nested grid





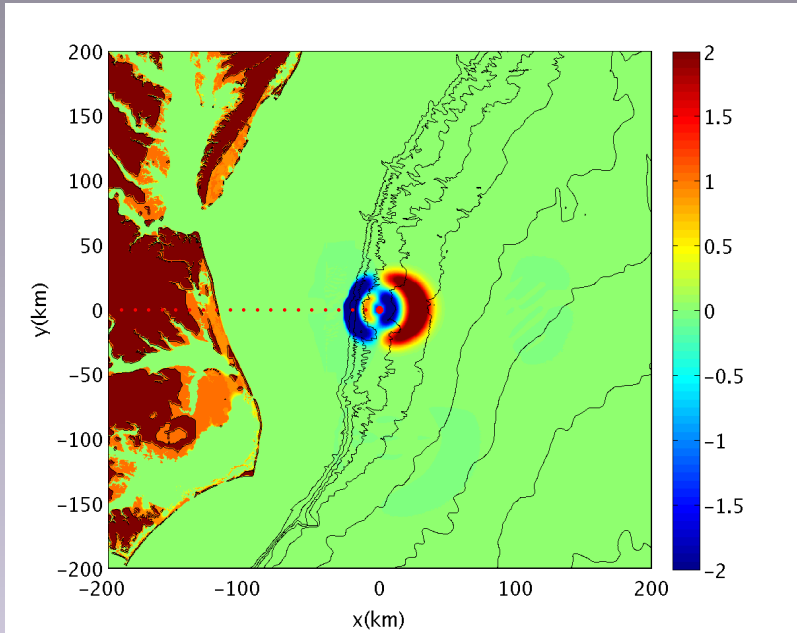
MAX in 125 m grid

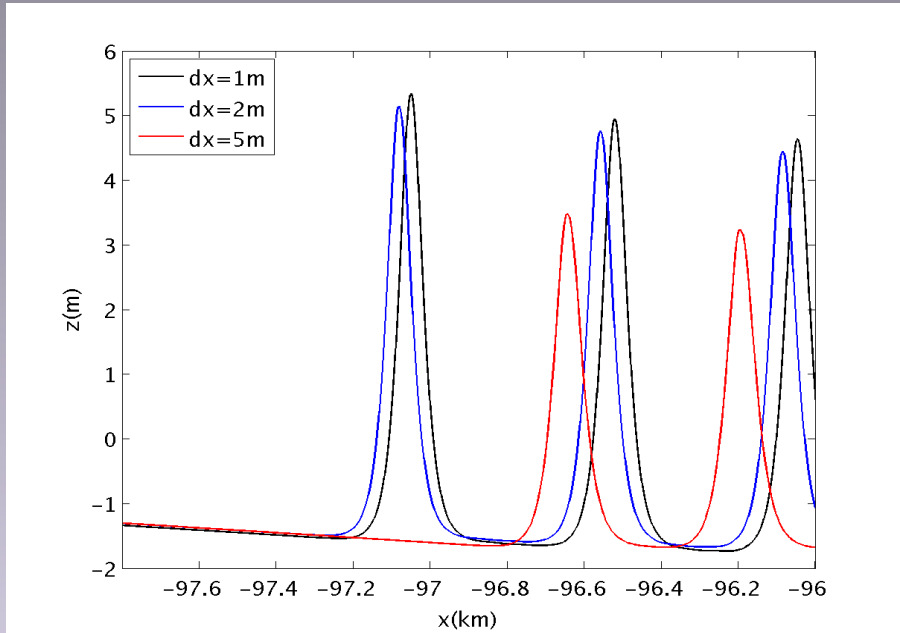
Transects in Chesap. Bay from 57′ to 201′

FUNWAVE transects: 125 m (solid); 500 m (dash) (mesh is still not fine enough for undular bores to appear)

URI UOD

Currituck: FUNWAVE 1D transect/undular bores





1D grids at 5, 2, 1 m => E/W Transects. Mesh is fine enough for undular bores to appear -> shorter wavelength breaking waves. Don't affect inundation too much but provide high momentum flux from breaking waves (Grilli et al., ICCE12)

URI UOD

Thank you