USGS Landslide tsunami workshop

"Overview and recent modeling for landslide tsunami generation and propagation"

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ABSTRACT

The modeling of tsunami propagation and coastal impact is usually performed on the basis of a long-wave 2D horizontal propagation model, combined with a relevant initial tsunami source. For the more frequent co-seismic tsunamis, the source is typically parameterized using Okada's (1985) idealized method, which calculates the surface deformation of a homogeneous elastic half-space, traversed by an oblique fault plane subjected to slip. Due to both the short duration of earthquakes and the near incompressibility of water, the theoretical seafloor deformation calculated this way is simply reproduced on the ocean surface as a zero-velocity initial elevation (i.e., a hot start). For co-seismic tsunamis, large tsunami-genesis typically occurs for fairly shallow depth earthquakes of large magnitude (e.g., Mw > 8). In general, co-seismic tsunami generation and impact also depends on the detailed earthquake slip distribution, which might require using multiple "Okada" sources.

By contrast, landslide tsunamis, which are also typically triggered by earthquakes (albeit, whose magnitude may be much smaller, e.g., Mw > 7) depend much more on the geometric, submergence, material, and kinematics characteristics of the landslide, than on the earthquake itself. In view of this, in order to achieve a realistic modeling, the detailed time history of the two-way landslide interactions with the water/free surface flow, during slide motion, has to be carefully modeled in order to properly calculate relevant landslide tsunami sources. To this effect, three different approaches have been proposed in the literature.

In the *first approach*, both the detailed landslide kinematics and deformation (if any), as well as tsunami generation, are modeled (sometimes in fully coupled mode) within the same model, which usually requires using a full three-dimensional (3D) multi-material/multi-physics Navier-Stokes solver, or a subset of these equations, such Euler or fully nonlinear potential flow equations (e.g., Grilli and Watts, 1999, 2001; Mader, 2001; Mader and Gittings, 2002; Grilli et al., 2002, 2010; Enet and Grilli, 2003, 2005; Panizzo and Dalrymple, 2004; Liu et al., 2005; Gisler et al., 2006; Yuk et al., 2006; Horrillo, 2006; Kowalik et al., 2006; Fructus and Grue, 2007; Yim et al., 2008; Abadie et al., 2009, 2010; Weiss et al., 2009). In these various models, the landslide kinematics may either be specified as a one-way coupling (e.g., for a rigid body, Grilli and Watts, 1999, 2001; Grilli et al., 2002; Enet and Grilli, 2003, 2005; Liu et al., 2005; Yim et al., 2008, and others), or for solid or deformable slides, calculated as a two-way coupling, part of he solution (e.g., Panizzo and Dalrymple, 2004; Gisler et al., 2006; Weiss et al., 2009; Abadie et al., 2009, 2010).

In the *second approach*, a time dependent landslide kinematics is calculated and/or specified directly within the long wave propagation model, from a cold start. This can be either done as a bottom or a lateral boundary condition (e.g., Tinti et al., 2001, 2006; Ataie-Ashtiani and Jilani 2007; Fuhrman and Madsen, 2009; Cecioni and Bellotti 2010a,b), or by solving the landslide as a second coupled fluid layer, subject to a long-wave approximation (e.g., Jiang and Leblond, 1992, 1993; Heinrich, 1992; Imamura et al., 1995; Assier Rzadkiewicz et al., 1997). Due to the limited physics represented in long-wave models, this approach is more applicable to modeling deeply submerged underwater landslides, which do no cause steep or breaking waves on the surface, rather than more violent subaerial landslides.

Finally, in the *third approach*, detailed landslide kinematics and interactions with the water and free surface flows are calculated in a (more recently fully 3D) landslide source model, whose physics can be similar to that in the first approach (i.e., full Navier-Stokes) or a subset of it (e.g., Euler or potential flow equations). Landslide simulations are performed up to a time beyond which tsunami-genesis becomes negligible on the free surface and then introduced as an initial source (i.e., hot start as a free surface deformation with depth-averaged velocity) into a long wave propagation model (e.g., Watts et al., 2003; Lynett and Liu, 2002, 2005; Grilli et al., 2006; Løvholt et al., 2008; Tappin et al., 2008; Geist et al., 2009).

In order to both simplify and speed-up this latest approach, which might be needed in emergency or repetitive forecasting situations, Grilli and Watts and Watts et al., 2005, further developed idealized semi-empirical tsunami sources for underwater landslides or slumps, based on "curve-fitting" results of a series of fully nonlinear potential flow simulations of rigid Gaussian-shape bodies sliding down a plane slope, from various submergence depths. This approach was both numerically and experimentally validated based on 2D (Grilli and Watts, 2005) or 3D (Enet and Grilli, 2003, 2005, 2007) laboratory experiments. Figure 1 shows a typical surface elevation for such a semi-empirical underwater landslide source, which can be quickly generated on the basis of a few geometrical and material slide parameters and used in 2D horizontal propagation models as a cold start. Note, to this effect, a depth-averaged velocity is also associated to such surface elevations, based on simple mass conservation requirements.

Finally, since the late 1990's, in part as the result of the intense and comprehensive landslide tsunami work that followed the 1998 PNG landslide tsunami disaster, it became increasingly clear that, landslide tsunamis being typically made of shorter waves than co-seismic tsunamis, dispersive effects needed to be included in long wave propagation models for achieving their accurate numerical simulations. This led a number of investigators to apply Boussinesq models, with extended nonlinear and dispersive properties, that had been developed at the time for coastal wave modeling, to landslide tsunami simulations (e.g., Watts et al., 1993; Lynett and Liu, 2002, 2005; Tappin et al., 2008; Løvholt et al., 2008; Geist et al., 2009), often with greater success than when using the standard NSW tsunami propagation models (e.g., Tappin et al., 2008).

The various aspects of landslide tsunami source and propagation modeling briefly discussed above are further developed and illustrated in the presentation made during the workshop.

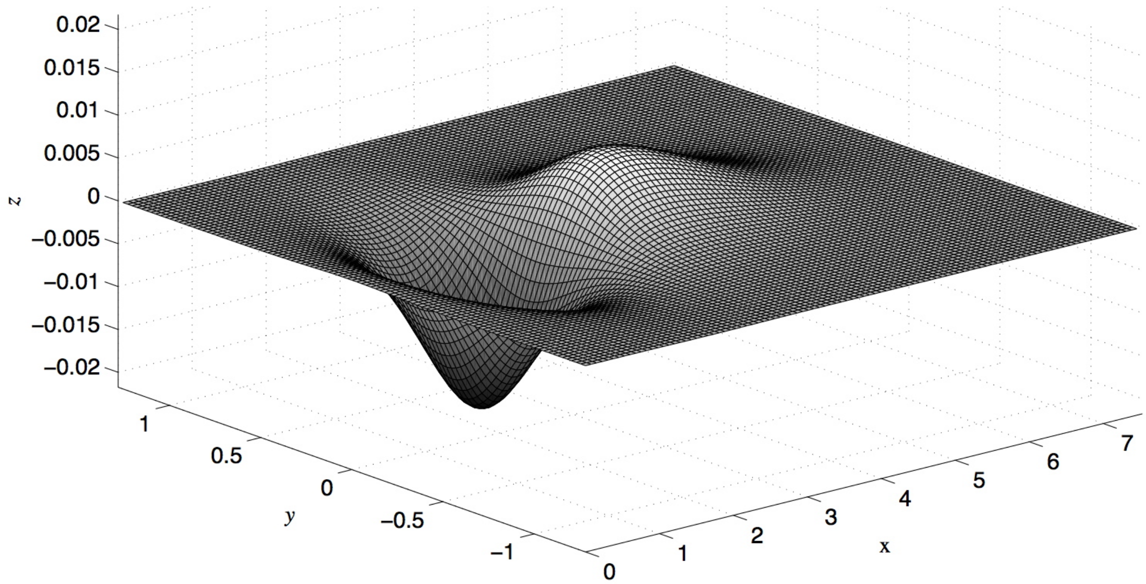

Fig. 1: Example of initial free surface elevation $\eta(x,y)$ for a landslide tsunami source, from empirical tsunami source elevation (Grilli and Watts 2005; Watts et al., 2005).

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USGS/NRC Landslide Tsunami Workshop

Overview and recent modeling work for landslide tsunami generation and propagation

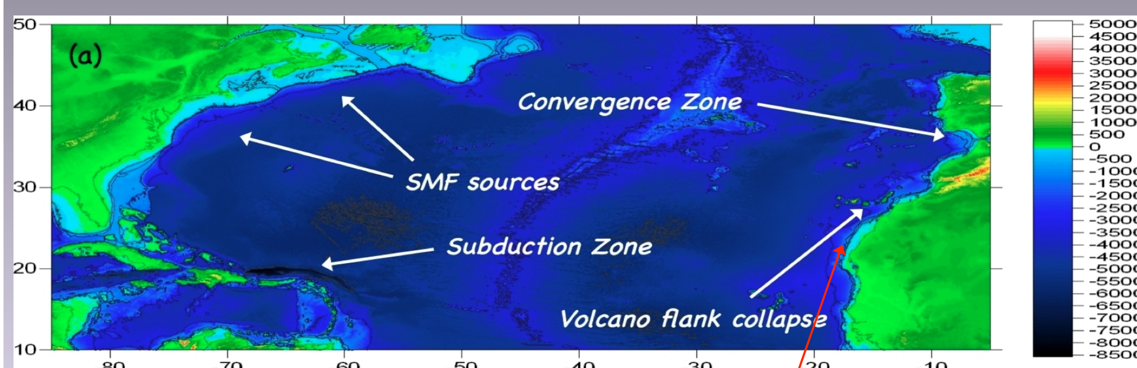
By S. Grilli, University of Rhode Island

[NTHMP UoD-URI project : "Modeling Tsunami Inundation and Assessing Tsunami Hazards for the U.S. East Coast"]

URI: Stephan Grilli, Stephan Abadie, Jeff Harris, Chris Baxter, Tayebeh Tajalli-Bakhsh, Teresa Krause

UoD: James Kirby, Fengyan Shi, John Callahan

Tsunami sources affecting the US East Coast



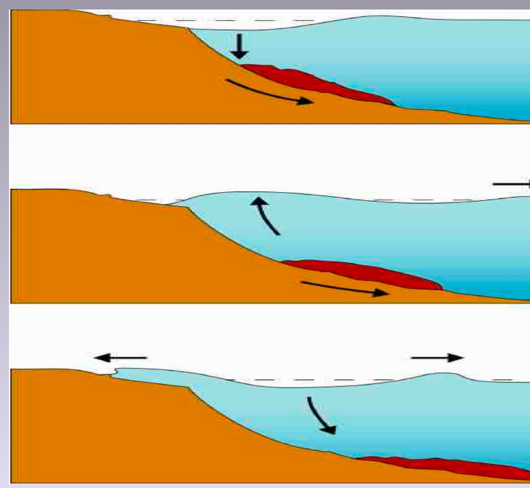
NTHMP modeling work

Landslide tsunami generation mechanism

Seismic triggering (as low as Mw = 6-7 ?) => ground accel. (PHA), triggers landslide motion (SMF) => tsunami source

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

Tsunami => Coastal runup and inundation



Methodology in NTHMP work

- Tsunami propagation and coastal impact/inundation using fully nonlinear and dispersive Boussinesq model FUNWAVE (Cartesian/spherical grid, TVD scheme; MPI implementation (highly scalable); nested grids)
- Tsunami sources are defined using the usual approach for co-seismic cases (i.e., Okada) and, for landslides, based on different model results:

  -> For rigid/expanding submarine slides/slump : 3D-BEM-FNPF model or Non-Hydrostatic sigma coordinate (muti-layer) model (NHWAVE)

  -> For subaerial slides : multi-material 3D-NS model THETIS simulates rigid <-> deforming <-> fluid-like slides and wave generation

  [Can also be used for submarine slides.]

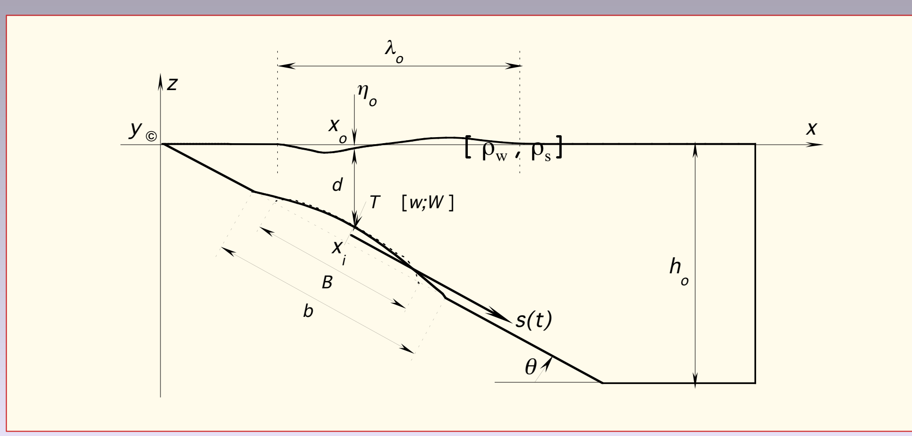
  -> Probabilistic slope stability analyses (Monte Carlo) to identify and parameterize relevant underwater slides (see Chris Baxter's talk)

Many observations of past slides

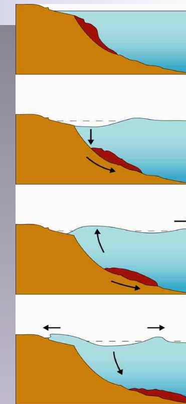
- "Paleo-slides" off of Los Angeles : [Borrero et al., 2001]: complex shapes and material properties, variety of mechanisms (~Homa's Palos Verdes slide 2)   => idealization for modeling and experiments

Landslide Tsunami generation

- Governing parameters : Geometry (width, thickness, length), slope angle, bulk density, cohesiveness/internal friction, initial submergence, mechanism (slide/slump)



Landslide tsunami generation modeling



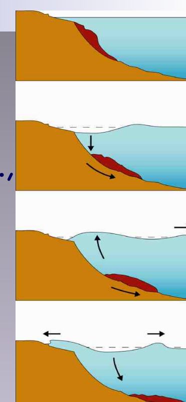
- Two-fluid NSWE model

(e.g., Jiang and Leblond, 1992, 1993; Heinrich, 1992; Imamura et al., 1995; Assier Rzadkiewicz et al., 1997; George, 2011…)
(OK for deep "debris flows")

- Multi-material, multi-physics NS solver or a subset of these equations (e.g., Euler, FNPF)

(e.g., Grilli and Watts, 1999, 2001; Mader, 2001; Mader and Gittings, 2002; Grilli et al., 2002, 2010; Enet and Grilli, 2003, 2005; Panizzo and Dalrymple, 2004; Liu et al., 2005; Gisler et al., 2006; Yuk et al., 2006; Horrillo, 2006; Kowalik et al., 2006; Fructus and Grue, 2007; Yim et al., 2008; Abadie et al., 2009, 2010; Weiss et al., 2009)
(OK for shallow/deep solid or deforming slides)

Landslide tsunami generation modeling



- Rigid slide, inviscid/viscous fluid, prescribed motion
(2D: Grilli et al., 1999-2005; 3D: Grilli et al., 2001-; Liu et al., 2005; Horrillo, 2006; Yim et al., 2008;…)
- Rigid slide, viscous fluid, non-prescribed motion
(2D, 3D: Abadie et al., 2006-2011)
- Deforming slide, viscous fluid, non-prescribed motion
fluid, (2D, 3D: e.g., Panizzo and Dalrymple, 2004; Gisler et al., Abadie et al., 2006-; Horrillo 2006-; Weiss et al., 2009; …)
- Long-wave propagation model with cold start or lateral/bottom bottom boundary conditions for slide kinematics
(e.g., Tinti et al., 2001, 2006; Lynett and Liu, 2002, 2005; Watts et al., 2003; Ataie-Ashtiani and Jilani 2007; Fuhrman and Madsen, 2009; Cecioni and Bellotti 2010a,b ; Ma et al., 2011;…)

Landslide tsunami generation modeling

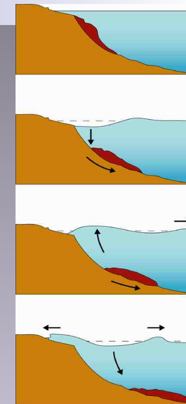
- Model coupling : 3D landslide source model or equivalent parameterization (NS, Euler, potential,…) used to initialize 2D long wave propagation model

(e.g., Watts et al., 2003; Grilli et al., 2006; Løvholt et al., 2008; Tappin et al., 2008; Geist et al., 2009 ; Abadie et al., 2007-)

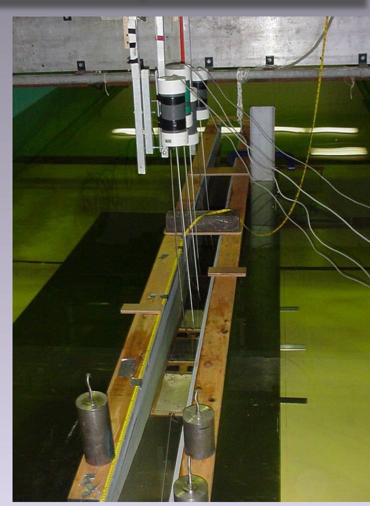
-> to simplify and speed-up source definition :

Idealized semi-empirical sources (elevation + velocity) are developed based on "curve fitting" many 3D simulations (Grilli and Watts, 1999-2005; Watts et al., 2005), with numerical and experimental validation, with laboratory benchmark cases (2D: Grilli and Watts, 2005; 3D: Enet and Grilli, 2003, 2005, 2007)

Used later by others,…

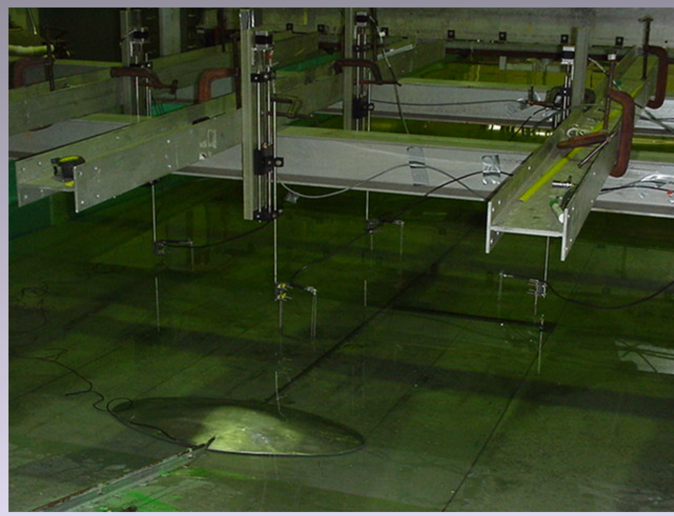


Landslide Tsunami Generation Experiments



[2D: Grilli and Watts, 2000, 2001, 2002]

Landslide Tsunami Generation Experiments



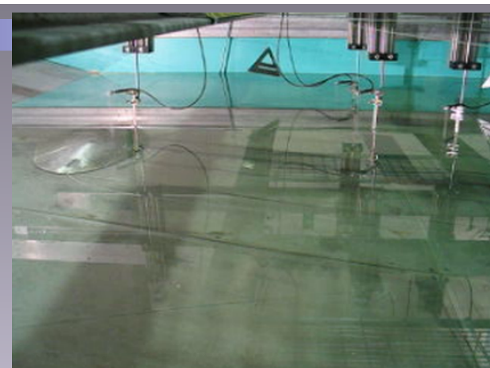
[3D: Enet and Grilli, 2003, 2005, 2007-> New NTHMP benchmark]

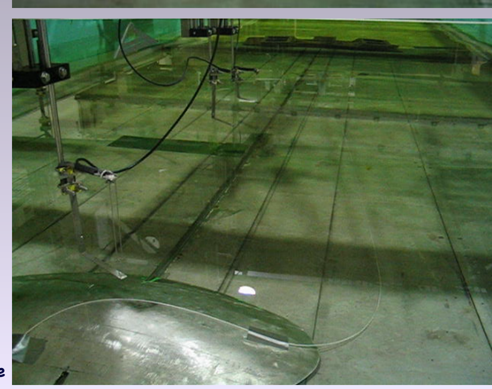
Rigid streamlined slide

- Gaussian shape slide:

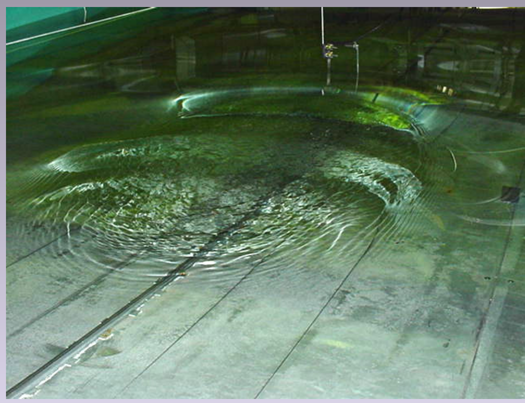
$$\zeta(\xi,\nu)=\frac{T}{1-\varepsilon}\left\{\operatorname{sech}\left(\frac{2C\xi}{b}\right)\operatorname{sech}\left(\frac{2C\nu}{w}\right)-\varepsilon\right\}$$

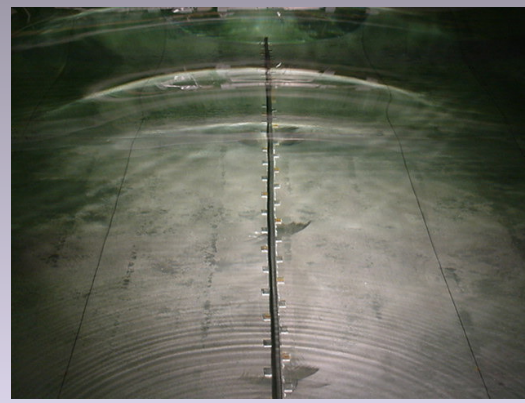
- 3D-laboratory experiments and fully nonlinear inviscid computations (Enet and Grilli, 2003-07) => very good agreement
- Waves are directional in slide direction of motion => significant coupling and energy focusing



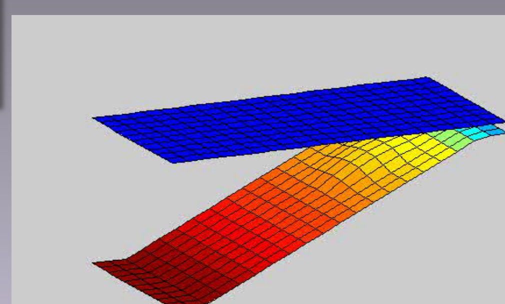


Free surface for submergence *d* = 60/120 mm

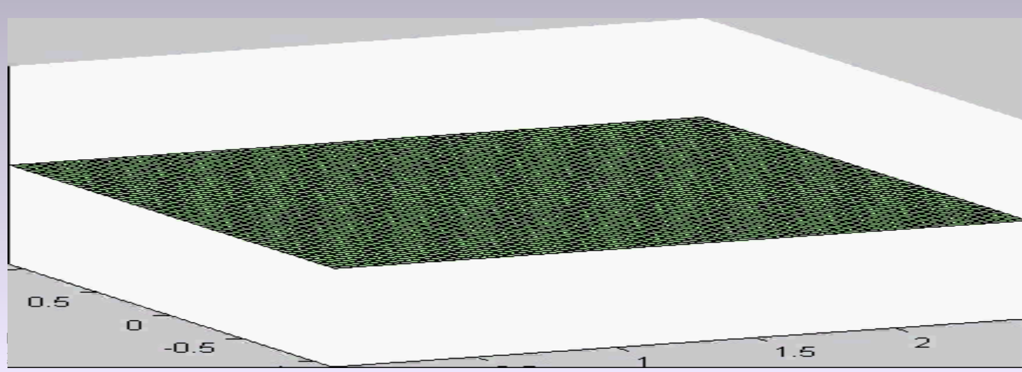




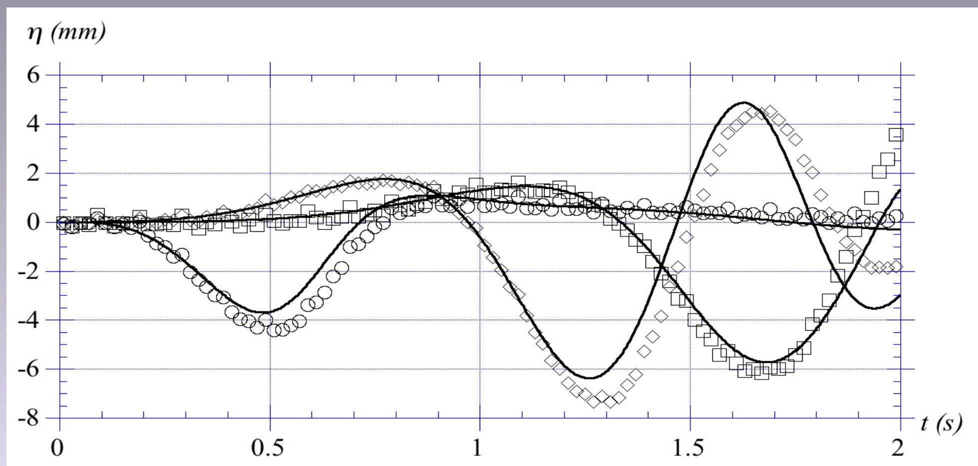
Rigid slide/inviscid 3D-BEM-FNPF model



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



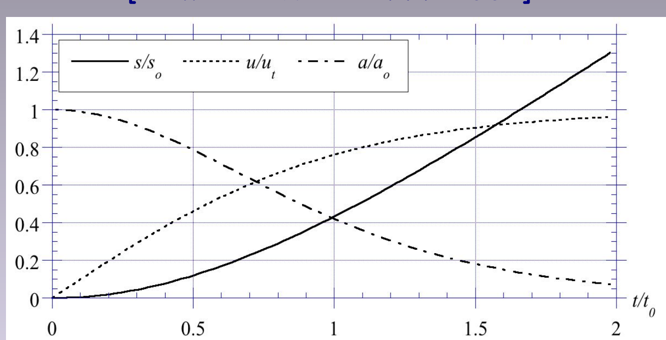
Computations vs. measurements at wave gages



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

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 $\gamma = \rho_b/\rho_w$

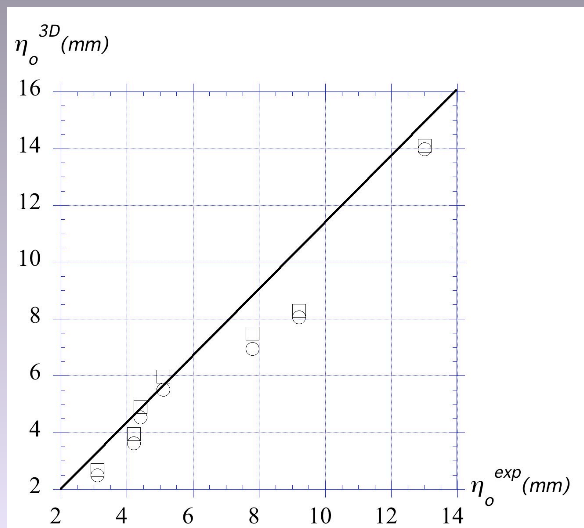
Curve fitting of numerical results -> η_o "maximum depression at initial location"

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

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

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

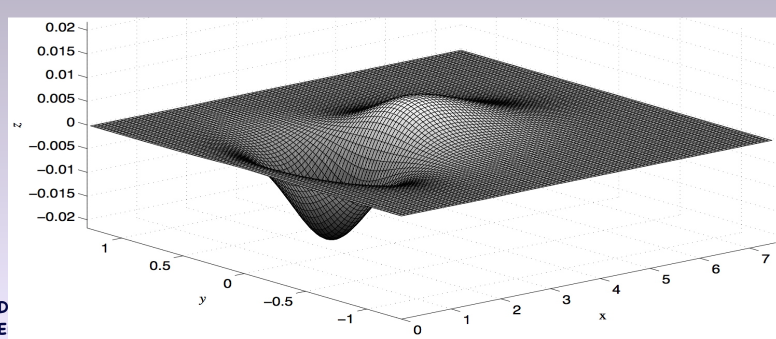
With $R^2 = 0.961$

Rigid slide/inviscid 3D-BEM-FNPF model

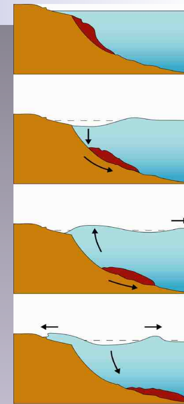
- Definition of semi-empirical tsunami sources for rigid underwater slides or slumps, based on many FNPF simulations for a wide variety of governing parameters :

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

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



Landslide tsunami generation modeling



- Conclusions of parametric modeling studies:

(Grilli and Watts, 1999, 2005; Grilli et al., 2002; Watts et al., 2005)

-> 2D/3D simulations for many underwater slides and slumps (varying parameters), both rigid and deforming (specified)

-> for given submergence on a medium slope, to a 1st order, initial acceleration governs tsunami generation (mainly function of slope, and slide density and geometry).

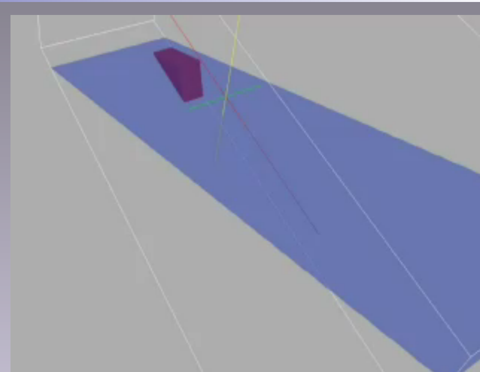
-> Main tsunami generation occurs over short time ($t < t_o$), during the acceleration period.

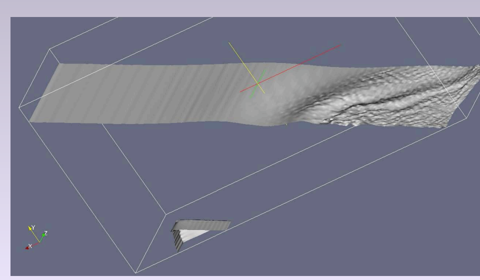
-> Slide shape and deformation do not significantly affect (1^{st}-order) slide center of mass motion (Bing model.; Watts and Grilli, 2003)

-> Slide shape/deformation play a 2^{nd}-order role on tsunami generation.

Rigid, non-streamlined slide/viscous fluid

- Multi-fluids 3D-Navier Stokes-VOF model (THETIS) (Abadie et al.; 2005-)
- Slide ⇔ Newtonian fluid
- Rigid slides ⇔ infinite viscosity
- Penalty method solves slide-water coupling, even for rigid slide.
- No slide motion is specified => water-slide forces are implicitly calculated (PLIC- or TVD-VOF)
- MPI implementation for large clusters
- Example: Liu et al. (2005) benchmark
  => very good agreement with experiments for both slide motion and waves

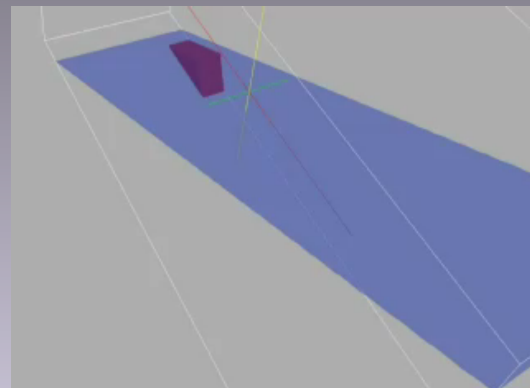


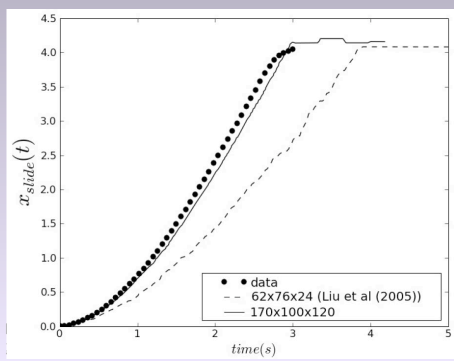


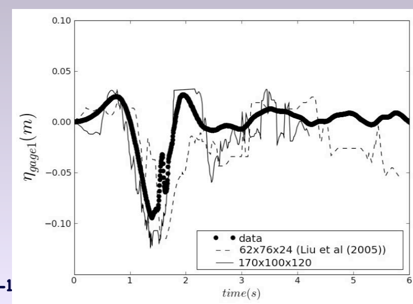
Rigid, non-streamlined slide/ viscous fluid

- Multi-fluids 3D-Navier Stokes-VOF model (THETIS) (Abadie et al.; 2005-)
- Example: Liu et al. (2005) benchmark

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



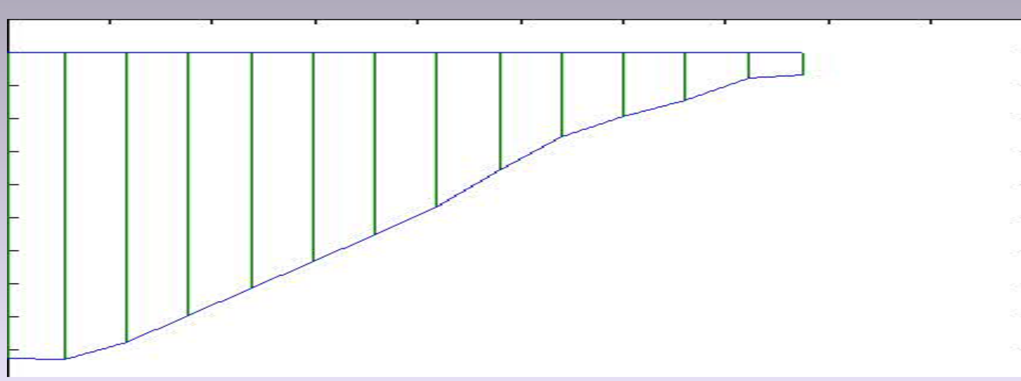




Rigid slide/inviscid 3D-BEM-FNPF model

- Significant 3D-slide-water motion coupling above slide => non-uniform horizontal and vert. velocities

  => 2D-Long wave model works away from slide after some time



Modeling landslide tsunami propagation/dispersion !

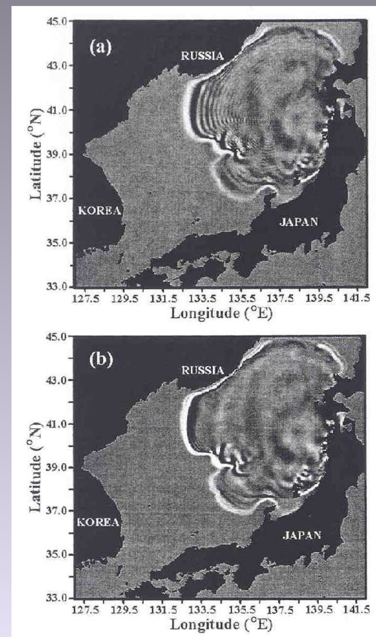
- Simulation of 1983 Nihonkai-Chubu tsunami in Japan Sea. Model results of Yoon (2002): (a) Dispersive models (Boussinesq equations); and (b) NSW long-wave propagation are used.

  => Tsunami front is modified by *dispersion.*

- For landslide tsunamis, smaller area of generation => shorter more dispersive waves require using a dispersive model for propagation.

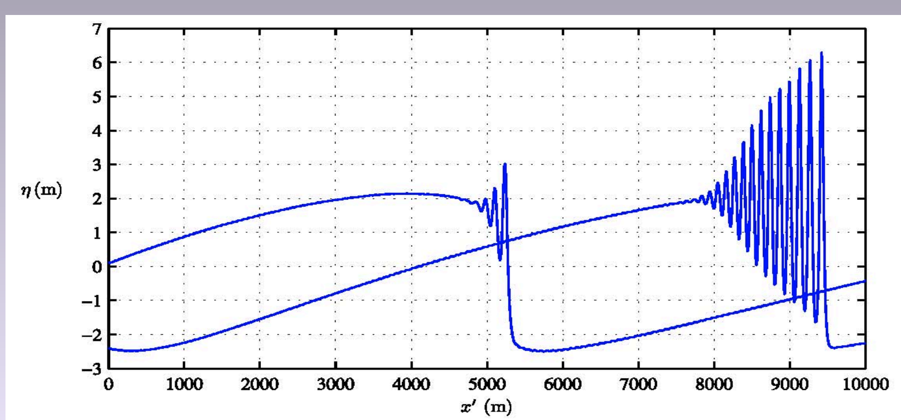
  => 1999: first application of fully nonlinear and dispersive model (FUNWAVE) to landslide tsunami propagation (PNG 1998)

- Many others since (e.g., Watts et al., 2001, 2003; Lynett and Liu, 2002, 2005; Tappin et al., 2008; Løvholt et al., 2008; Geist et al., 2009)



Dispersive effects in many transoceanic tsunamis may be significant

- Madsen et al. (2008) : Long wave shoaling on slope with Bouss. model.



- Madsen et al. (2008) : 12/26/04 observations

- Madsen et al. (2008) : 12/26/04 observations

- Madsen et al. (2008) : 12/26/04 observations

FUNWAVE origin and history

- Boussinesq (1892): Mildly nonlinear and dispersive long wave equations over a flat bottom (i.e., Boussinesq eqs.)
- Peregrine (1967): extension of BE to varying bottom
- Nwogu (1993), Madsen (1993): extension of BE dispersive properties to match linear dispersion in deep water
- Wei, Kirby, Grilli, Subramanya (1995): extension of BE to full nonlinearity in *a/h* (similar to NSWE) to leading order in dispersion $O\,[(kh)^2]$

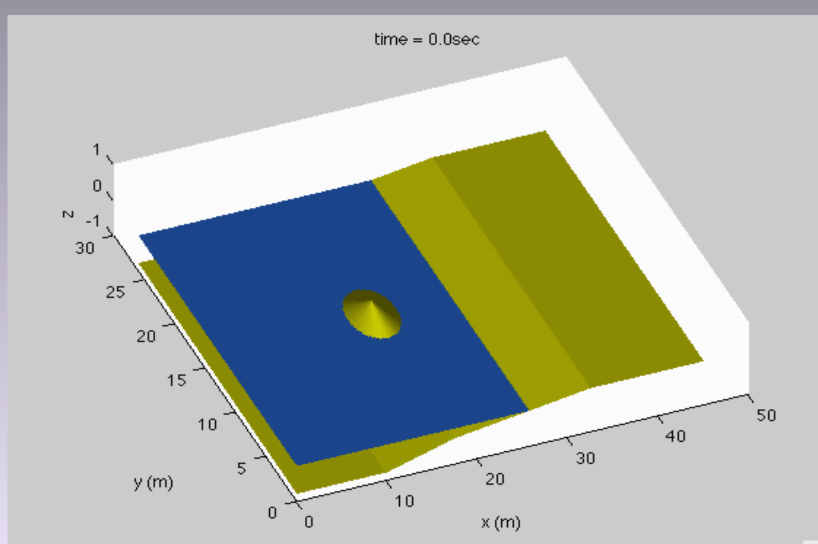
$$\eta_t + \nabla\cdot\left\{(h+\eta)\left[u_\alpha + \left(z_\alpha + \frac{1}{2}(h-\eta)\right)\nabla\left(\nabla\cdot(hu_\alpha)\right) + \left(\frac{1}{2}z_\alpha^2 - \frac{1}{6}\left(h^2 - h\eta + \eta^2\right)\right)\nabla\left(\nabla\cdot u_\alpha\right)\right]\right\} = 0$$

FUNWAVE origin and history

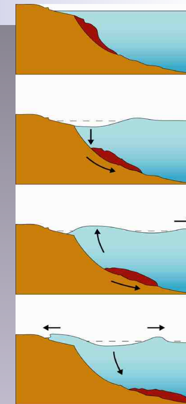
- Kennedy et al. (2000), Chen et al. (2000): inclusion of improved parameterization of dissipation from breaking waves and bottom friction, and shoreline runup.
- Kirby et al. (2006-2011) : spherical coordinates plus Coriolis.
- Pophet et al. (2008); Shi and Harris (2010) : efficient MPI code
- Shi et al. (2011): following OSU's (2009) workshop, new TVD implementation for better shoreline runup modeling. Inclusion of some horizontal vorticity terms.

  -> model now referred to as FUNWAVE-TVD

- Improvement of FUNWAVE runup and inundation using TVD (Example: Experimental Benchmark form OSU's 2009 workshop)



Landslide tsunami generation modeling



- Landslide tsunami modeling case studies:

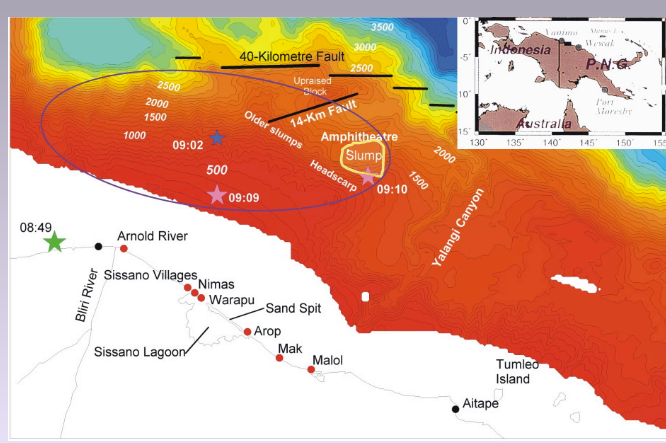
-> historical, e.g., PNG 1998; Unimak, 1946; Grand Banks, 1929; Skagway,...

-> predictive, e.g., Cumbre Vieja (e.g., Ward and Day, 2001; Pérignon, 2006; Lovholt et al., 2008; Abadie et al., 2008-2011); Currituck (Geist et al., 2009;...)

Many others...

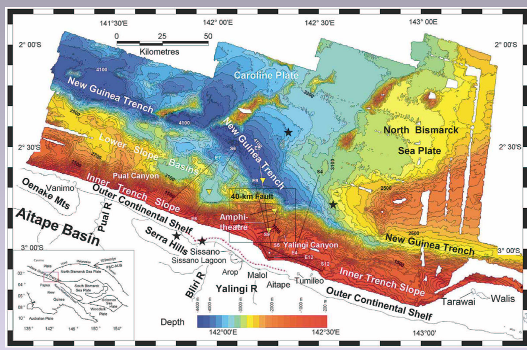
PNG 1998 Case Study: propagation simulation

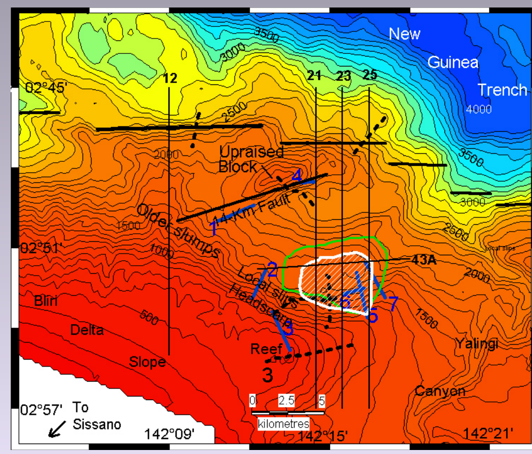
- July 17th, 1998: A modest earthquake (Mw = 7.1) off of Papua New Guinea (PNG) north shore triggers a tsunami that floods Sissano lagoon with over 16 m inundation/runup and kills 2000 people.



PNG 1998 Case Study: geological map (2003)

- PNG 1998: Very complex geology (see Homa's talk) (Tappin, 2003)

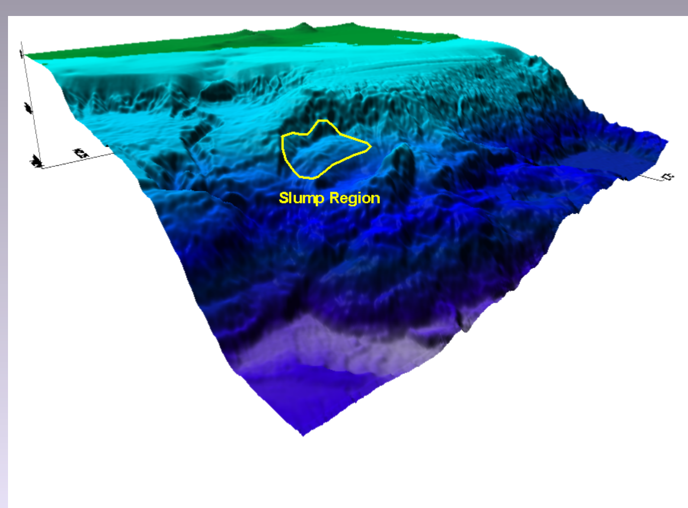




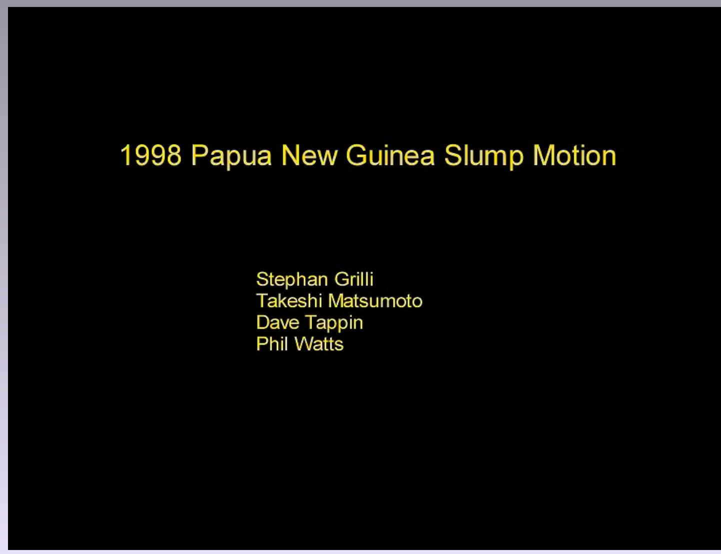
-> 1500 m deep, 6 km^3 slump

PNG 1998 Case Study: geological data

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

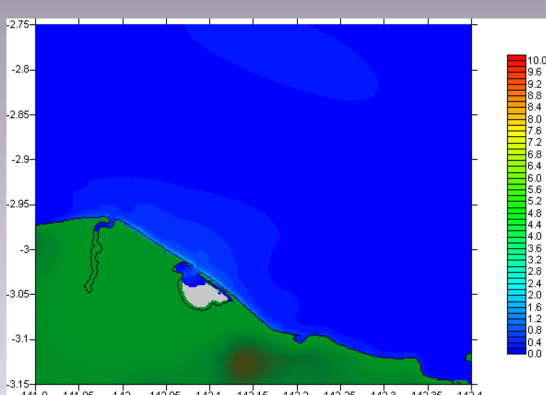


PNG 1998 Case Study: geological data

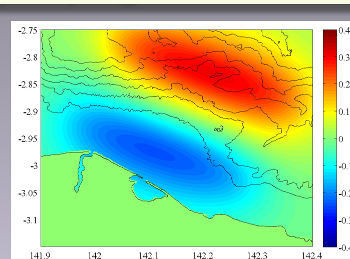


PNG 1998 Case Study: propagation simulation

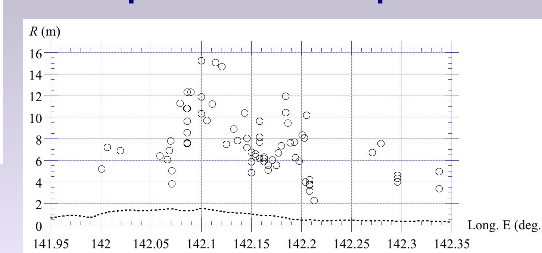
Earthquake tsunami elevation



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

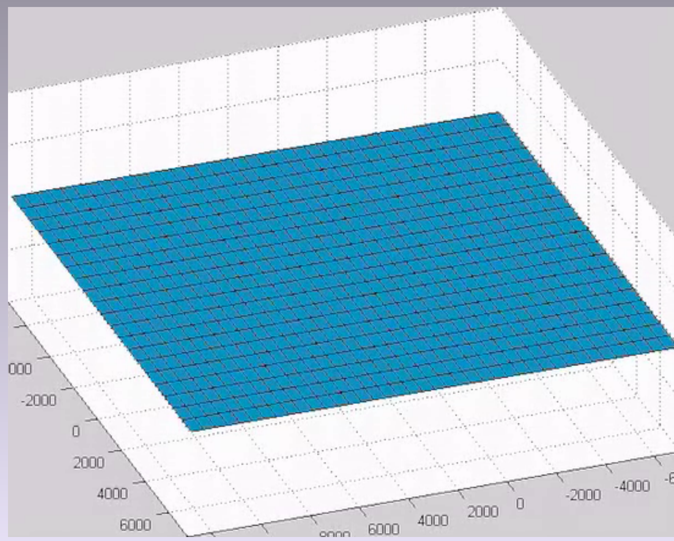


Earthquake tsunami runup

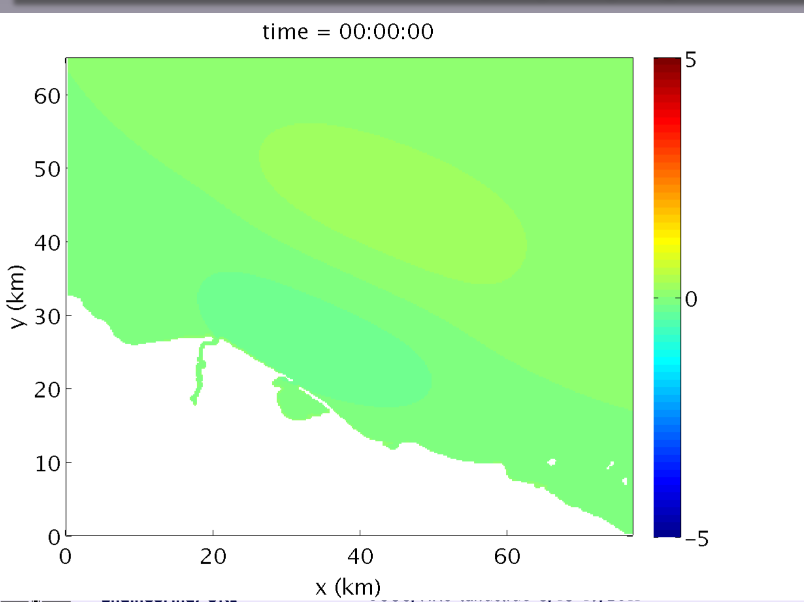


(see Tappin et al., 2008)

PNG 1998 Case Study: 3D source simulation

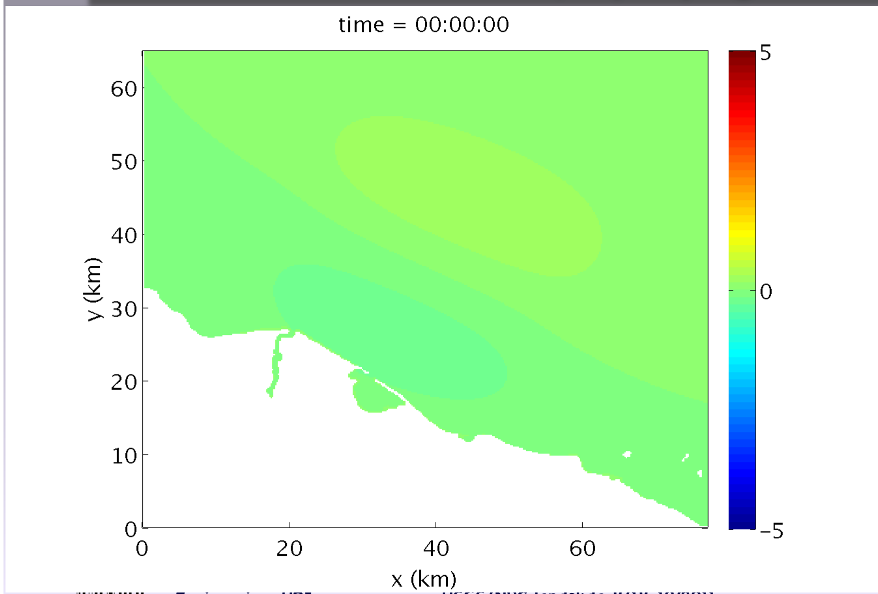


PNG 1998 Case Study: propagation simulation



(FUNWAVE Dispersive simulation, 50 m grid)

PNG 1998 Case Study: propagation simulation



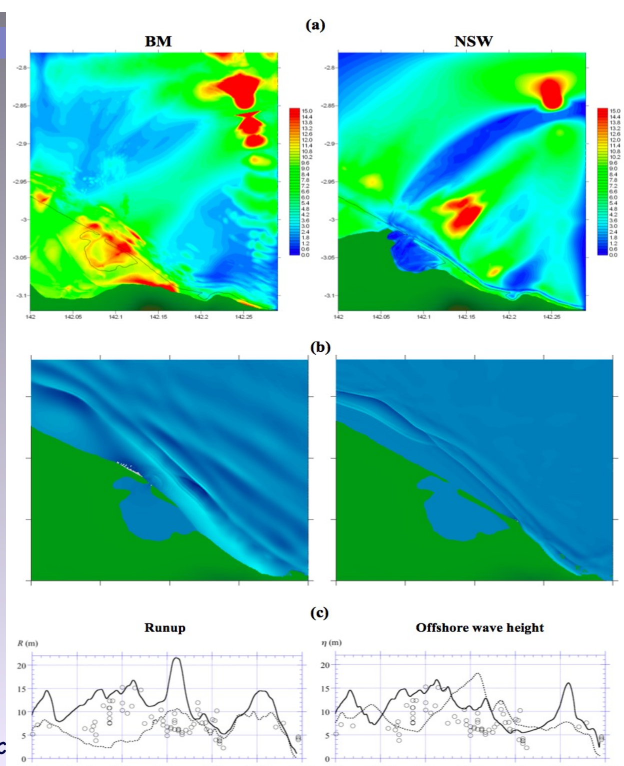
(FUNWAVE Non-Dispersive simulation, 50 m grid)

FUNWAVE simulations

Dispersive vs. non-dispersive solution (PNG 1998)

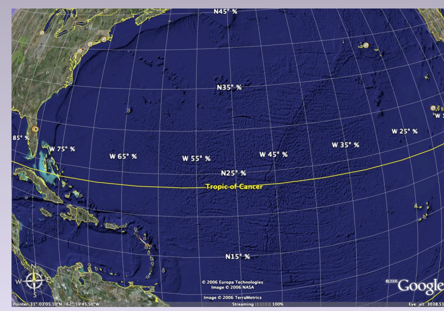
Same slump source, same code, bathymetry, and dissipation parameters

(Tappin et al., 2008 (NHESS))



Case study: Cumbre Vieja/ La Palma Flank Collapse

[Ward and Day (2001); Grilli et al., (2005); Pérignon (2006); Lovholt et al., 2008; Abadie et al. (2008-2011)]

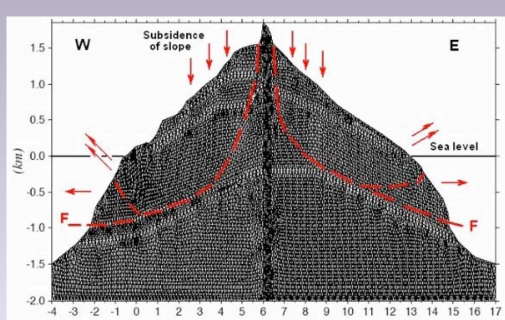


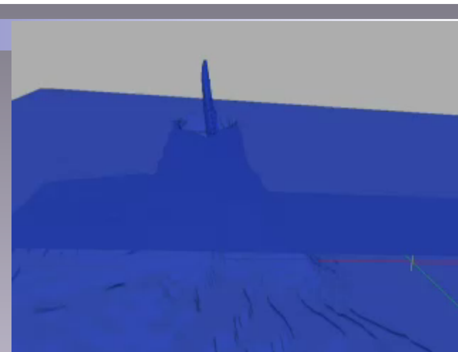
Case study: Cumbre Vieja Flank Collapse

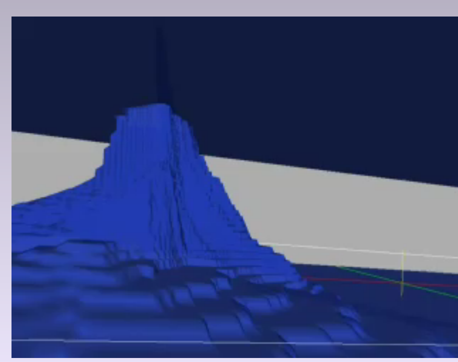
- Multi-fluids 3D-Navier Stokes-VOF model (THETIS) (Abadie et al.; 2006-11)
- Slope stability analysis (FLAC 2D; 2D-FEM)

-> Most likely scenario of 80 km^3

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







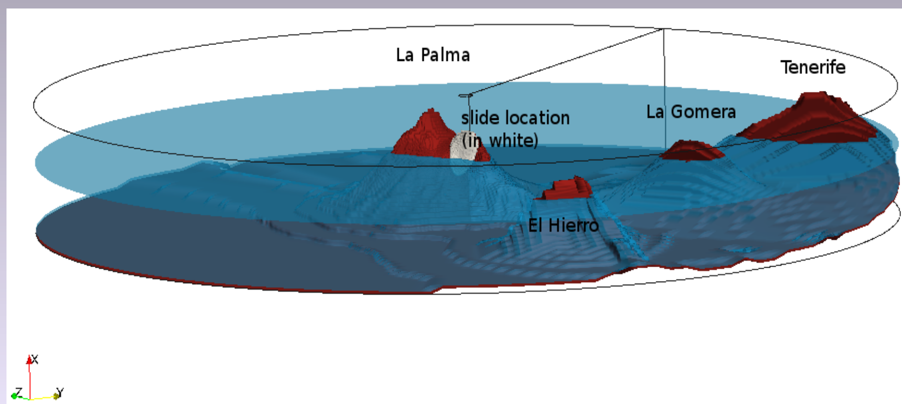
[U. of Bordeaux]

Case study: CVV Flank Collapse

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

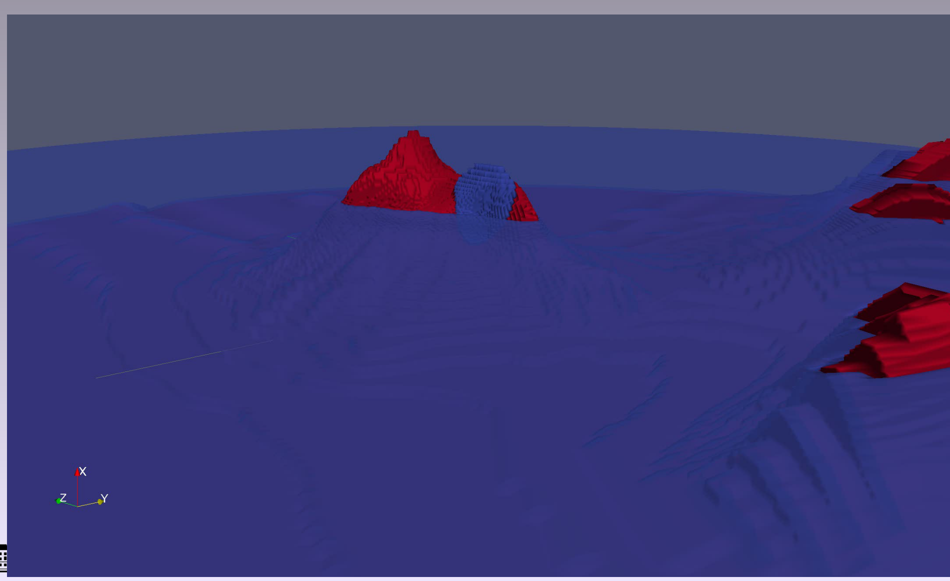
For lack of better information, slide is assumed to behave as an inviscid fluid with constant density => worst case scenario.

- If known, an arbitrary rheology can be used.



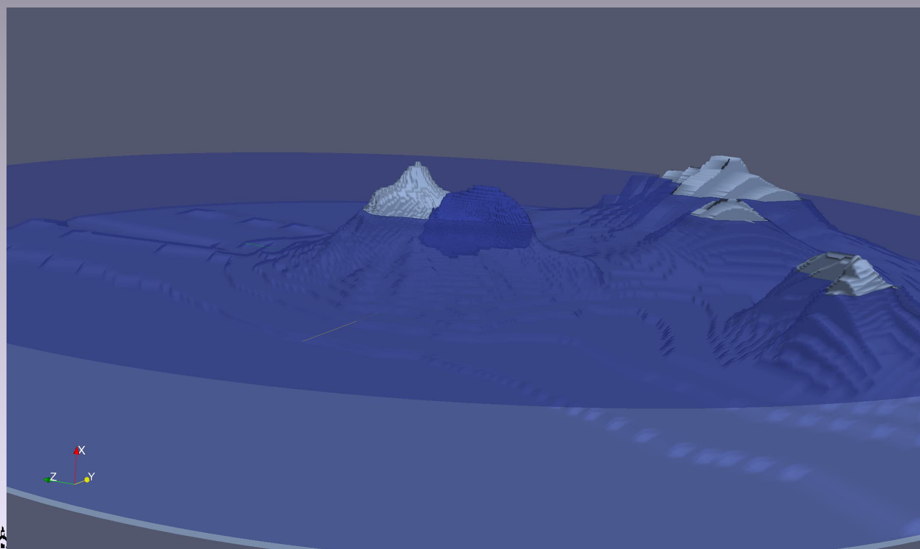
Case study: CVV Flank Collapse

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



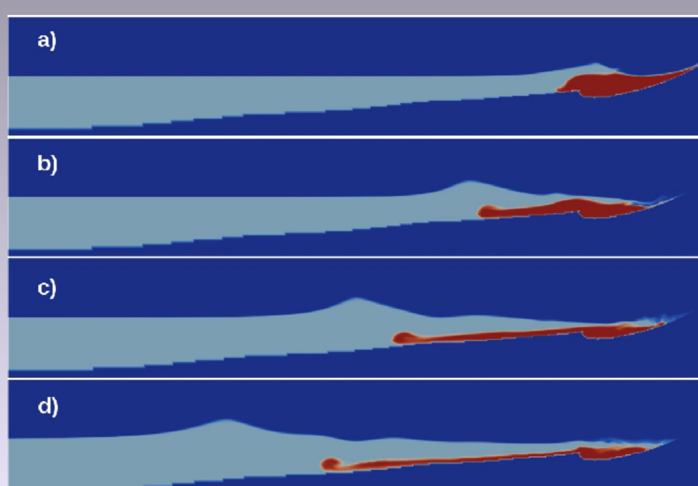
Case study: CVV Flank Collapse

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



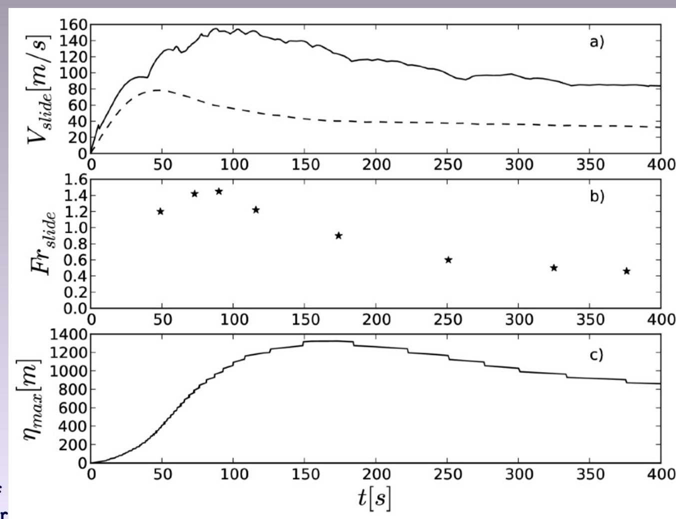
CVV Flank Collapse : 2D sensitivity analysis

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



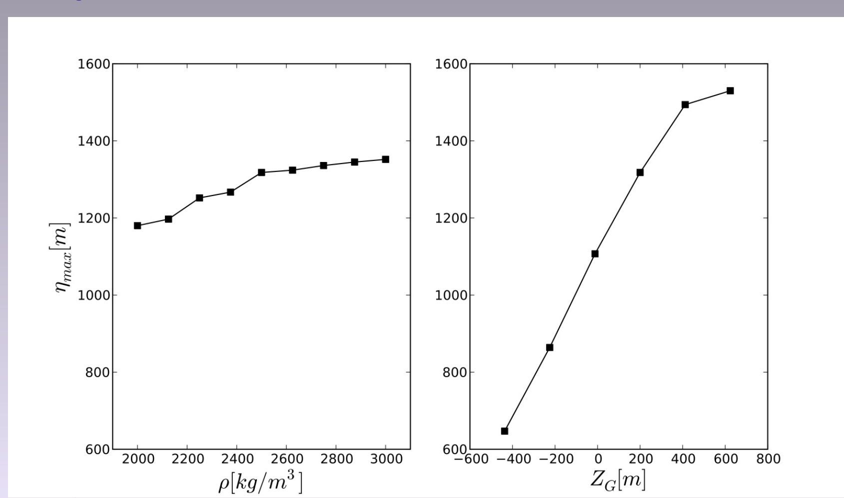
CVV Flank Collapse : 2D sensitivity analysis

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



CVV Flank Collapse : 2D sensitivity analysis

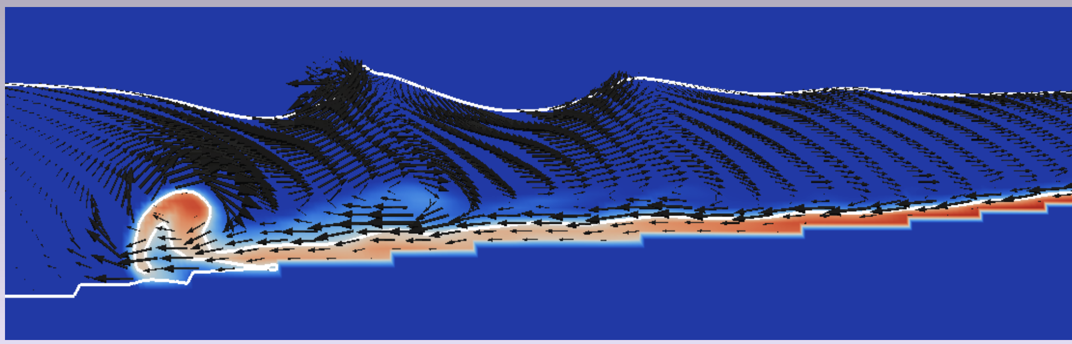
- Source + near-field propagation : THETIS 80 km^3 CVV source :
  Max. leading wave elevation vs. slide density and center of mass height



CVV Flank Collapse : 2D sensitivity analysis

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

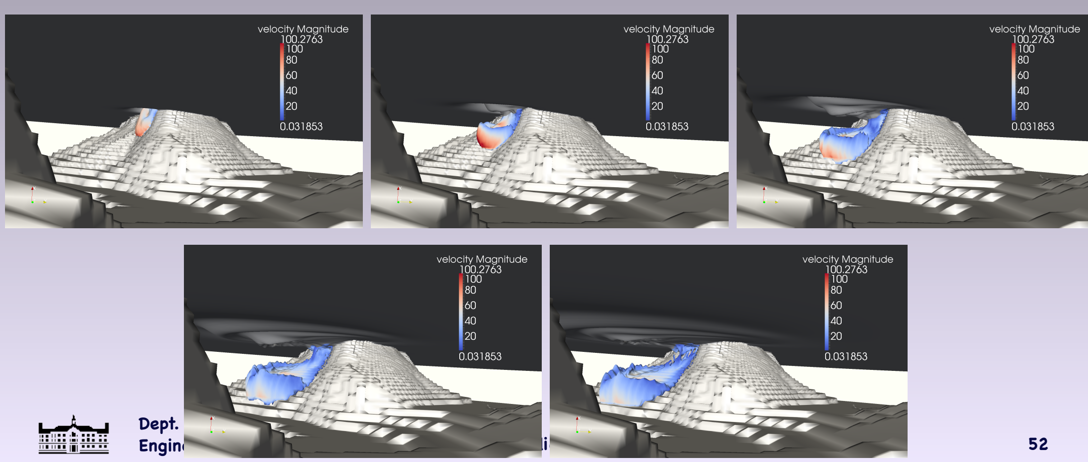
Detailed velocity field around slide tip at t = 396 s, showing the strong current generated in the water by the slide motion and Kelvin-Helmholtz instabilities along the slide/water interface.



Case study: CVV Flank Collapse

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

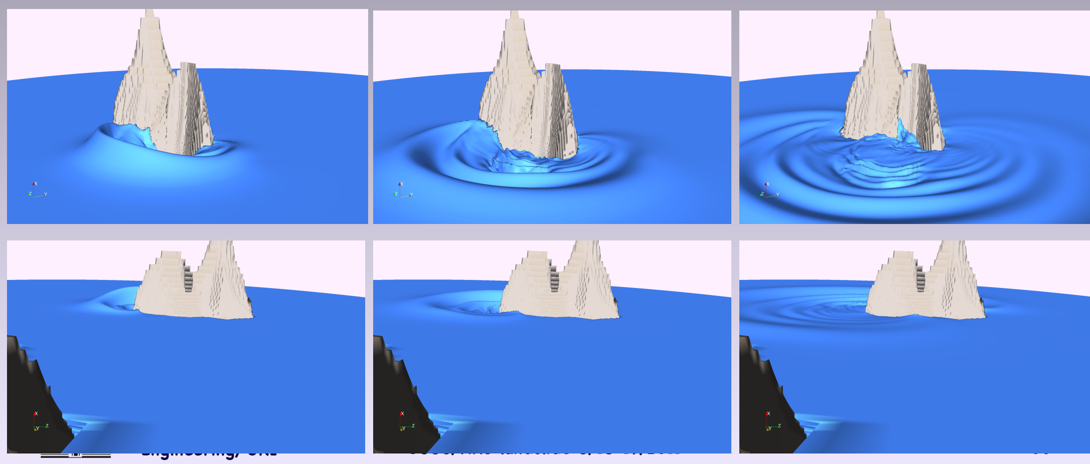
Underwater view of air/water and water/slide interfaces (water volume fractions equal to 0.5 and 0.9, respectively) at t =: a) 50 s, b) 100 s, c) 150 s, d) 200 s, e) 250 s, f) 300 s



Case study: CVV Flank Collapse

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

Time series of surface elevation snapshots showing runup and edge-wave propagation. South-Western view at t =: a) 192 s, b) 290 s, c) 474 s. Eastern view at *t* = d) 192 s, e) 290 s, f) 474 s.

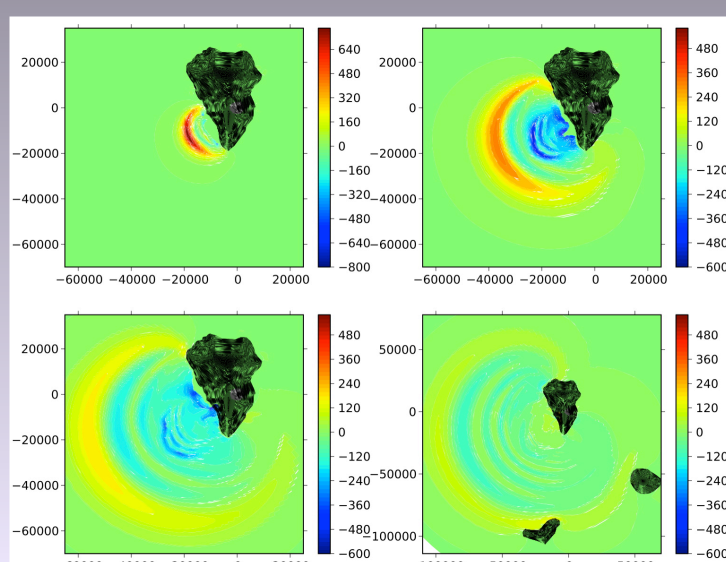


Case study: CVV Flank Collapse

- 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

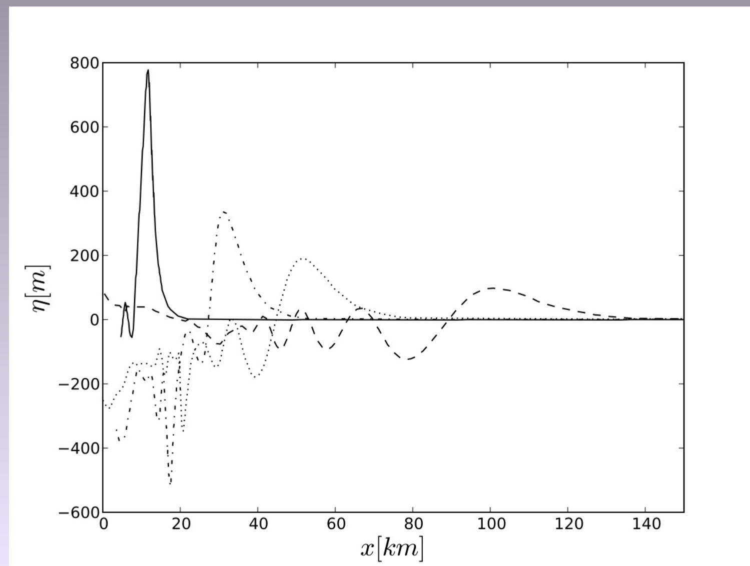
=> Main direction of propagation 20 deg. off W



Case study: CVV Flank Collapse

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

3D Slide in 20 deg. from W plane:
- Surf. Elevation at t = 101,232,340,558s



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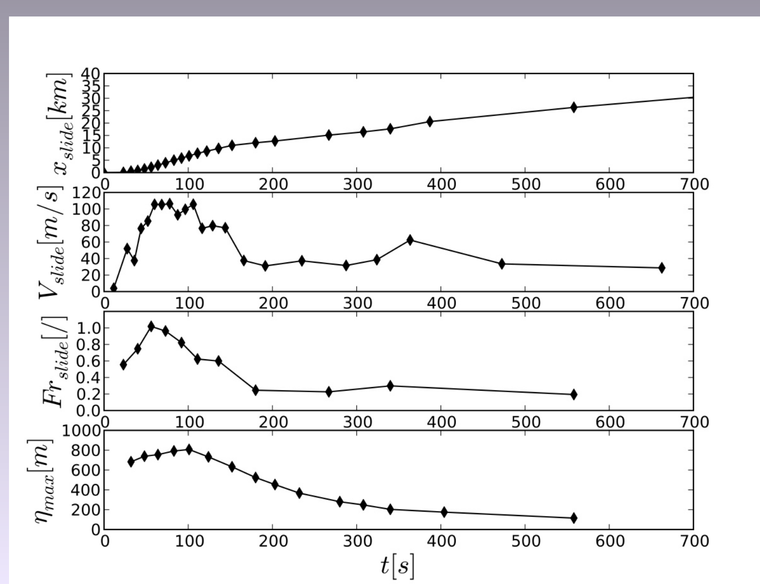
Case study: CVV Flank Collapse

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

3D Slide in 20 deg. from W plane:
- Tip runout
- Tip velocity
- Tip Froude Nb.
- Max. wave elev.
- Flow total energy reaches an asymptotic value at about t = 200 s representing 35% of the slide energy loss



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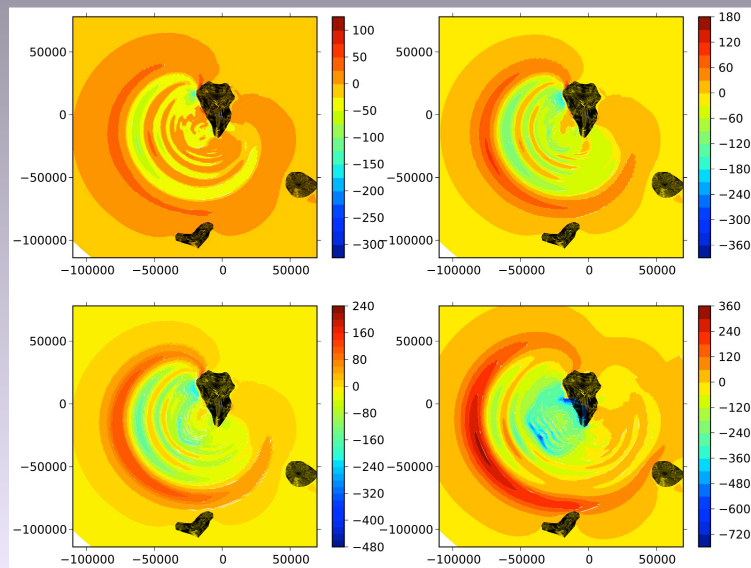
Case study: CVV Flank Collapse

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

Surface elevation (m) : t = 450 s



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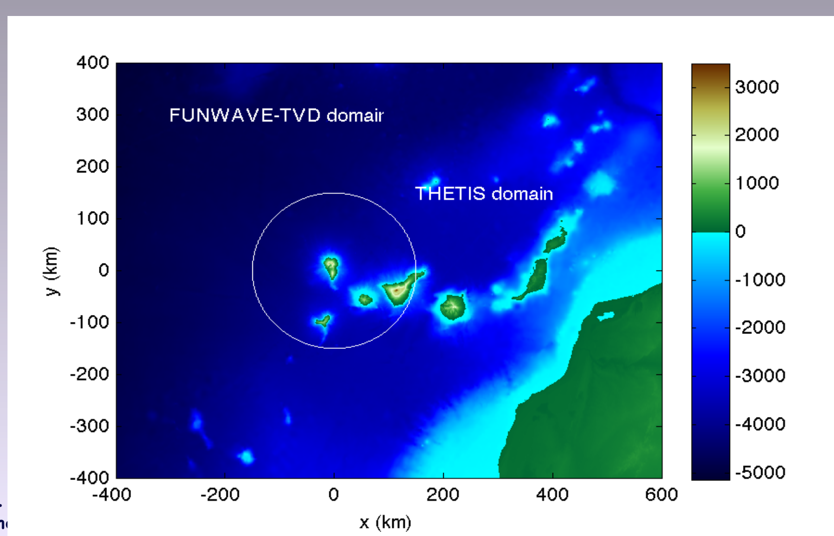
Case study: CVV Flank Collapse

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



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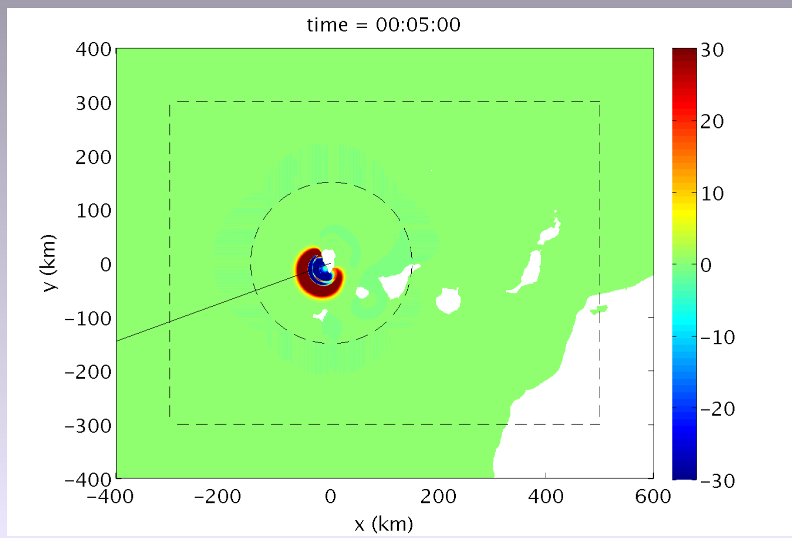
Case study: CVV Flank Collapse

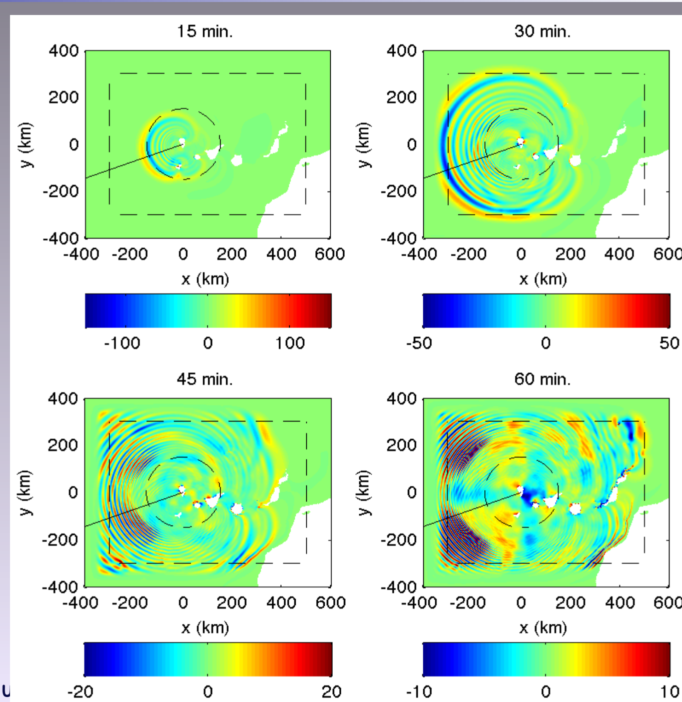
- Regional/Transoceanic/East coast propagation : 2D-horiz Fully Nonlinear Boussinesq model FUNWAVE in various nested grids (80 km^3 CVV source)



Case study: CVV Flank Collapse

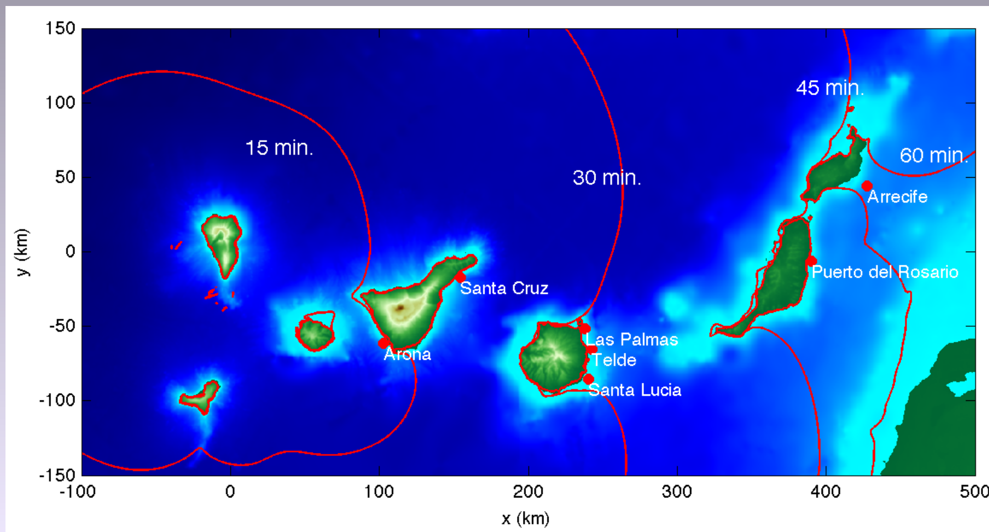
- Regional/Transoceanic/East coast propagation :

-> 2D-horizontal Fully Nonlinear Boussinesq model FUNWAVE in various nested grids (80 km^3 CVV source)



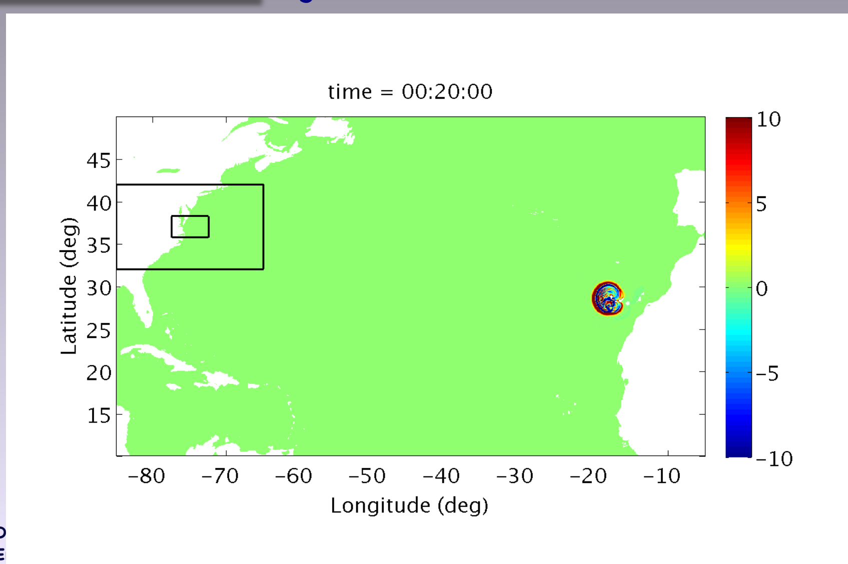
Case study: CVV Flank Collapse

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



Case study: CVV Flank Collapse

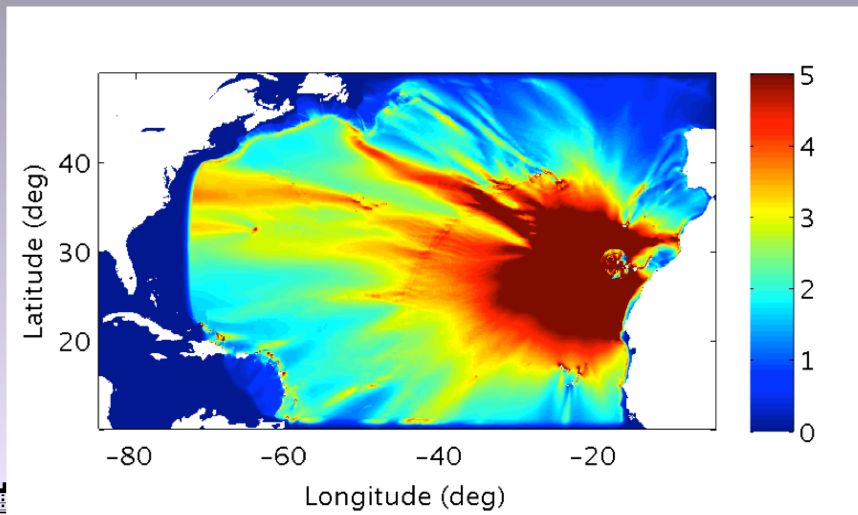
- Regional/Transoceanic/East coast propagation : 2D-horiz Fully Nonlinear Boussinesq model FUNWAVE in various nested grids (80 km^3 CVV source)



Case study: CVV Flank Collapse

- Regional/Transoceanic/East coast propagation :

2D-horiz Fully Nonlinear Boussinesq model FUNWAVE in various nested grids
(80 km^3 CVV source)



Case study: CVV Flank Collapse

- Regional/Transoceanic/East coast propagation :

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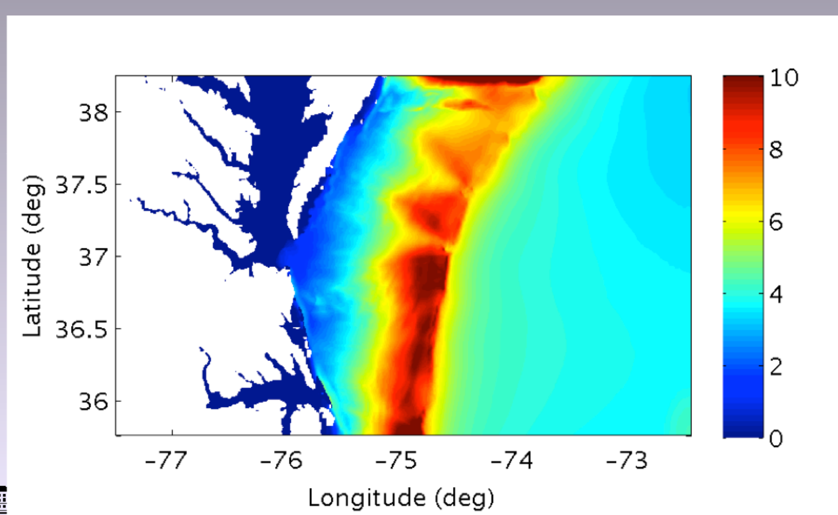
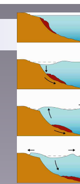


Conclusions/modeling discussion points



Co-seismic tsunamis :

- Source: Nearly instantaneous; fault kinematics has little effect on tsunami generation (only final deformation)
- Tsunami waves: large-scale cross-fault deformation :

=> long, linear, non-dispersive waves

=> Dissipation does not initially matter

- Modeling: Simplified source model (e.g., Okada) is often adequate, with specified initial water surface elevation. 2D horiz. propagation with LSW or NSW eqs.

-> see caveat regarding dispersion

Landslide tsunamis :

- Source: Initial kinematics matters more than final deformation => function of slide volume, density, slope (initial acceleration)
- Tsunami waves: smaller-scale source, strong vertical accelerations, larger vertical displacement :

=> dispersive, possibly nonlinear, waves

=> wave breaking and dissipation may matter (especially for subaerial slides or low submergence underwater slides)

- Modeling: Complex source model (3D-FNPF or 3D-NS-VOF, multi-fluids) is required, together with detailed geome-chanical and geological properties.

-> 2D horiz. propagation with BM or FNBM equations.

Aleutian 1946 case study

- Fryer et al., 2003 : hypothetical 200 km^3 slide -> Unimak Island :