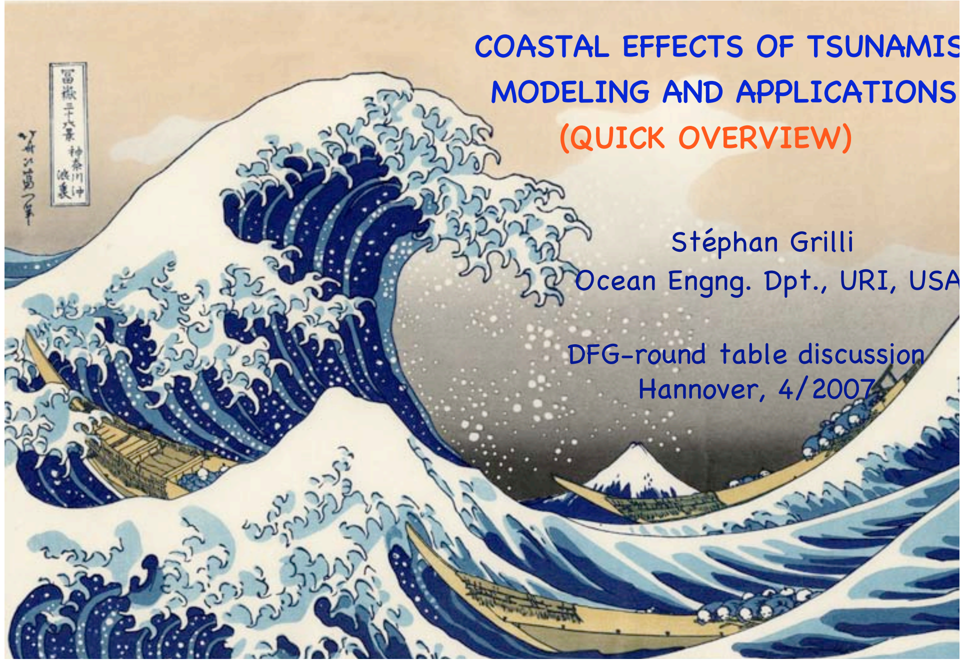


COASTAL EFFECTS OF TSUNAMIS MODELING AND APPLICATIONS (QUICK OVERVIEW)

Stéphan Grilli
Ocean Engng. Dpt., URI, USA

DFG-round table discussion
Hannover, 4/2007

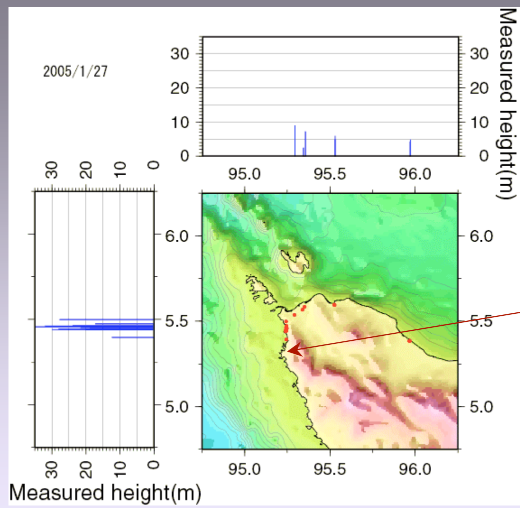
Tsunamis :

"Large waves caused by seismic activity"

Ex: 1946 Aleutian Tsunami:
Scotch Cap light house => wave runup, 42 meters minimum

"=> Coastal impact can be huge"

[Photographs by Henry Hartman]



Ex. 12/26/04:
Now up to 49 m !
Further south

[Yuichi Namegaya, Earthquake Research Institute, the University of Tokyo, Japan, 1/05]

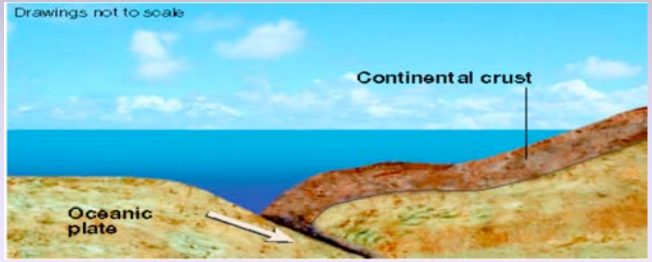
Tsunami projects at URI

- long waves (sol. waves,...) : modeling/exper. of shoaling/breaking/runup (1989-)
  -> modeling/exper. of wave-induced sediment transport (2003-)
- landslide tsunamis : numerical modeling/experiments of (1998-) :
  => Cohesive slides and slumps (1998-2006)
  => Non-cohesive slides (2005-) (French/EC collaboration)
  => Earthquake triggering of Submarine Mass Failure (SMF model./exp.) (NSF-PIRE project with TUB; 2005-2009)
- US East Coast tsunami risk (FMGlobal) : (Maretski et al., 2007)
  => Monte Carlo analysis of landslide tsunami risk -> runup (2005-2006)
  => Follow-up: Cumbre Vieja collapse; Puerto Rico (2007-)
- 12/26/04 co-seismic tsunami : modeling of detailed coastal impact in Thailand (including Phi Phi); contribution to Thai warning system (2005-)
- Tsunami warning by remote sensing : (2006-) (French/TSUMOD collaboration)

Tsunamis : two main generation mechanisms

1. <u>*Co-seismic displacement*</u> : For large earthquake moment magnitude (M_w > 8), slipping motion of a subduction zone may cause large upwards motion of ocean bottom along a fault (e.g., 12/26/04) => *overlying tsunami source*

[Nature 1/27/05 Vol. 433]

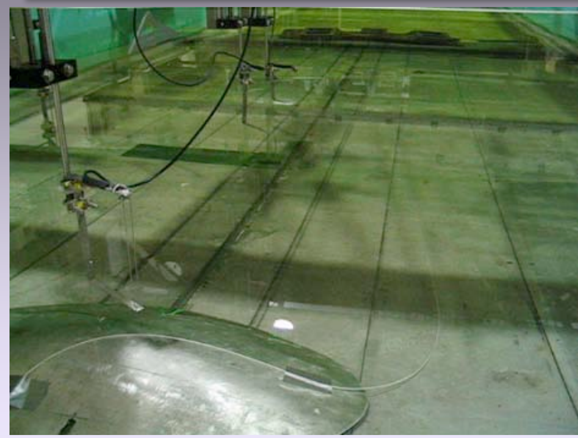


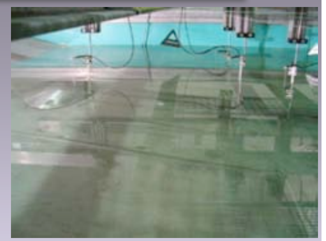
Tsunamis : two main generation mechanisms

2. <u>*Landslide tsunamis*</u> : Even for moderate earthquakes (M_w = 6-7), seismic shaking can destabilize sediment on a continental slope, causing Submarine Mass Failure (SMF) (e.g., PNG, 1998) => *directionally focused tsunami source*

"Unstable slope":

Landslide tsunami generation : Mechanism





[Enet and Grilli, 2001-2003; NSF project; URI wavetank (3.6 x 1.8 x 30 m)]

Tsunami Hazard

- <u>Tsunami amplitude</u> :
  => correlates with M_w for *co-seismic* displacement (Hammack, 1973)
  => only limited by vertical displacement for *landslide* (Murty, 1979)

- <u>Thus for moderate M_w , landslide tsunamis may pose</u> :
  => *greater threat* to coastal communities (nearby, short warning)
  => one of the *major coastal hazards* for moderate M_w , which are quite *frequent* earthquakes (Tappin et al., 1999).

Long waves: Development of 2D-Numerical Wave Tank for Fully Nonlinear Potential Flows

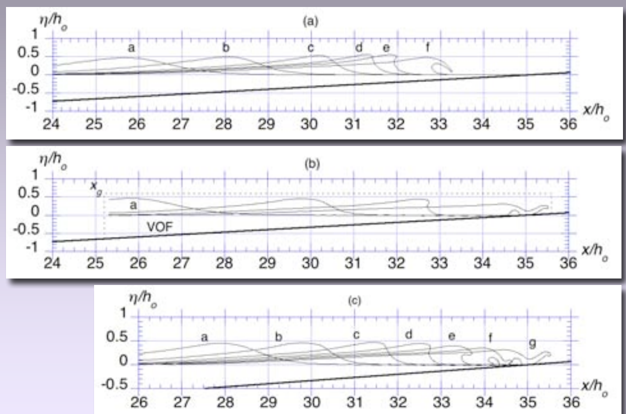
- Longuet-Higgins and Cokelet (1976) – BIE method/mixed E-L/ conformal mapping (periodic)/Runje-Kutta-ABS
- Vinje and Brevig (1981) – BIE (similar)
- Dold and Peregrine (1984-1986) – Explicit Taylor series expansions
- New, McIver, Peregrine (1985) – 2D breaker properties (u, a deep water)
- Grilli, Skourup, Svendsen (1988) – As DP in physical space
- Grilli et al. (1989-1996) – Higher-order refinements/various wave gent.
- Grilli and Horrillo (1987) - Absorbing beach/piston, exact wave gent.
- Grilli et al. (1994-1999) - Solitary and periodic wave shoaling/overturning and experimental validation
- …..

Tsunami Modeling : fore-/hind-casting

- Three components are needed :
  1. A tsunami *source* (landslide or coseismic)
  2. Model *grid(s)* (bathymetry and topography; nesting ?)
  3. A generation and propagation/runup *model*
- In hindcasting mode :
  1. comparison with *observations* (e.g., tide gage elevations)
  2. Iterative *refinement* of the source parameters

Model coupling to simulate wave breaking

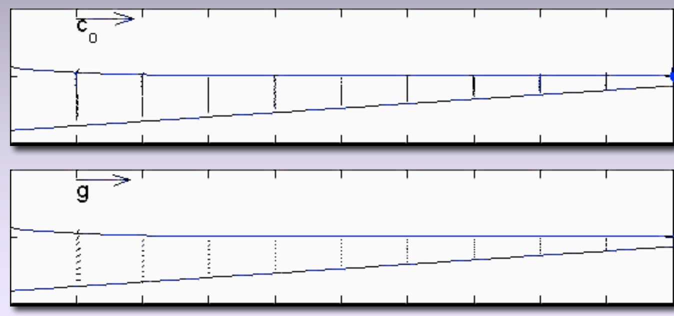
- Coupling of 2D-NWT and 2D-NS-VOF (Guignard et al., 1999) :



Ex. of earlier work with 2D-FNPF NWTs

- *Solitary wave* breaking over a slope (velocity, acceleration)

(Grilli and Subramanya, CP, 1996; Grilli et al., JWPCO 1994, 1997)



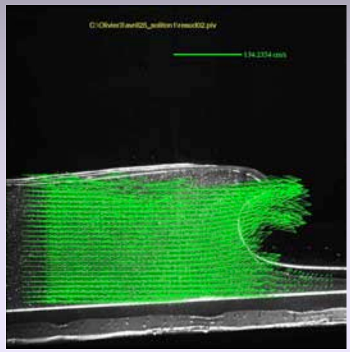
1-2 c_o

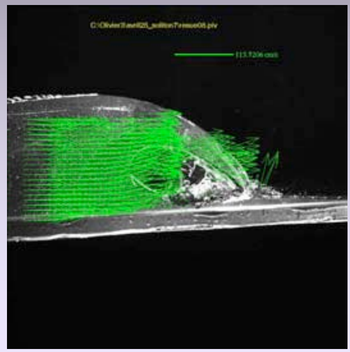
4-5 g

2D sol. wave breaking :experimental validation

- *Solitary wave shoaling/breaking* simulations were experimentally validated (Grilli et al., 1994, 1997, 1998 , 2004) :

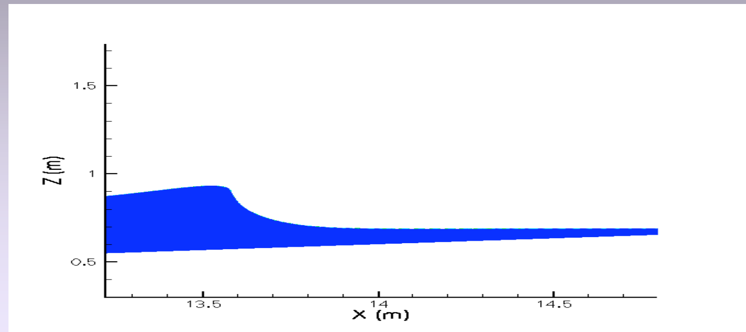
[Kimoun et al, 2004; ESIM]



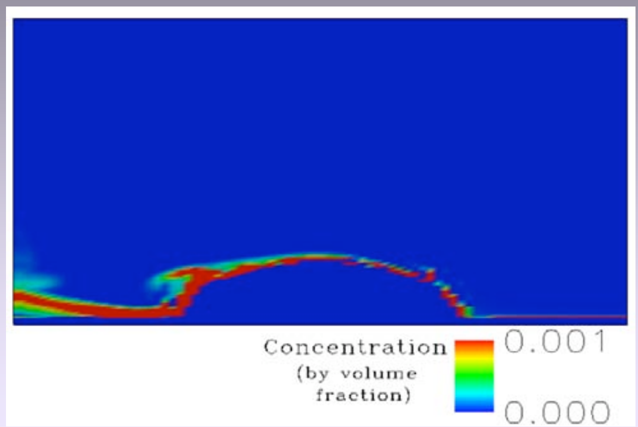


Model coupling to simulate wave breaking

- Coupling of 2D-NWT and 2D-NS-VOF (Grilli et al., 2004) with Lubin's, 2004 model. Example of NS-VOF result for sol. wave:

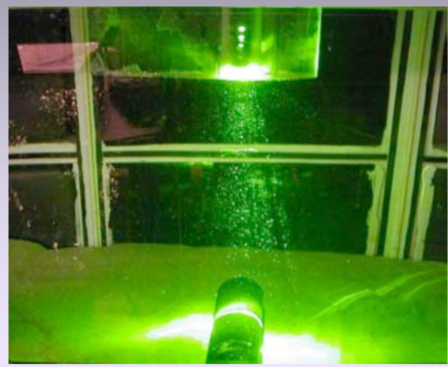


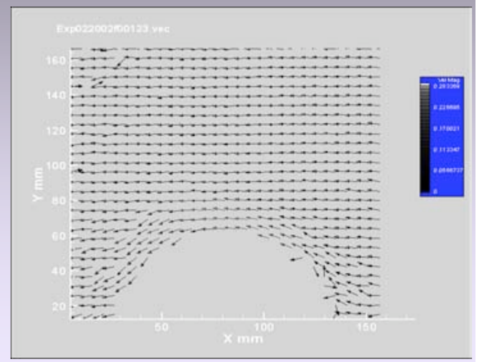
- Coupling 2D-FNPF/3D-NS-LES, with sediment transport (bed/suspended) -> Gilbert,Zedler,Grilli,Street (2005; IEEE 2007)



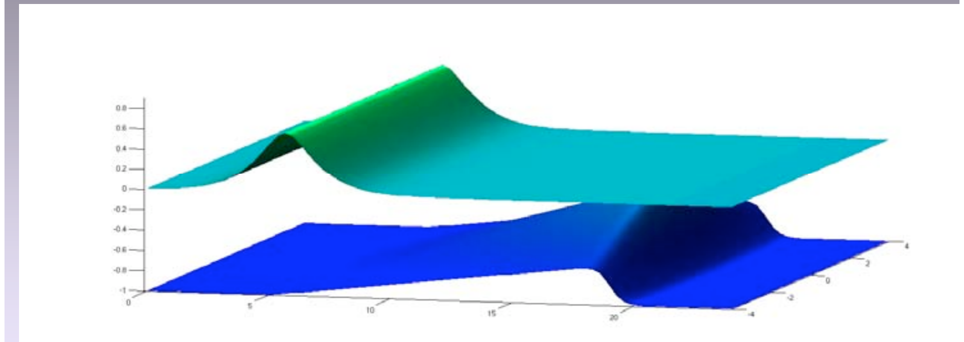
Modeling/experiments of wave-induced sediment transport (collab. ASU, Stanford)

- Particle Image Velocimetry (PIV; Fernando et al., 2002) :





3D solitary wave breaking over bottom topography



[3D-FNPF model + FMA (*N* log *N*), by Fochesato, Grilli, Dias (2004)]

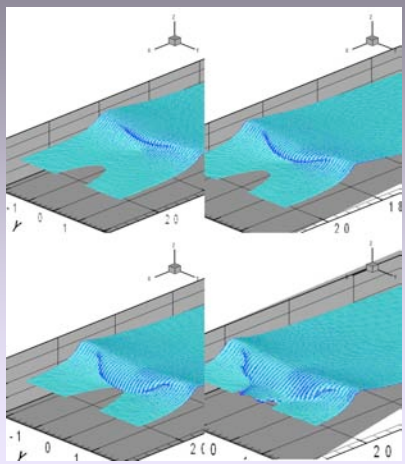
Some recent 3D-FNPF NWTs

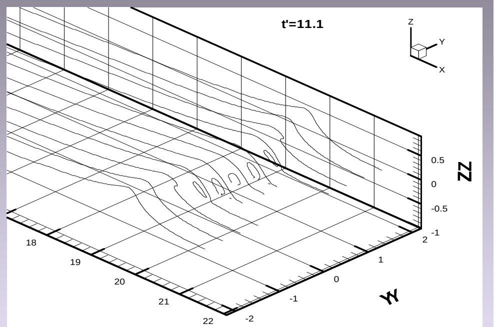
- Xue et al. (2001) – Boundary element method (BEM; bi-periodic)
- Grilli et al. (2000-2001) – 3D BEM as in 2D -> NWT
- Bateman et al. (2001) – Fourier expansions
- Bonnefoy et al. (2004), LeTouze et al. (2004) – Spectral method
- Fructus et al. (2005) – Vortex sheet method

Applications/extensions :

- Fochesato, Guyenne and Grilli (IJNMF, 2005) – Improved numerical methods to model 3D overturning/breaking waves
- Guyenne and Grilli (JFM, 2006) – 3D breaking solitary waves, on slopes
- Fochesato, Grilli and Dias (Wave Motion, 2007) – 3D wave focusing

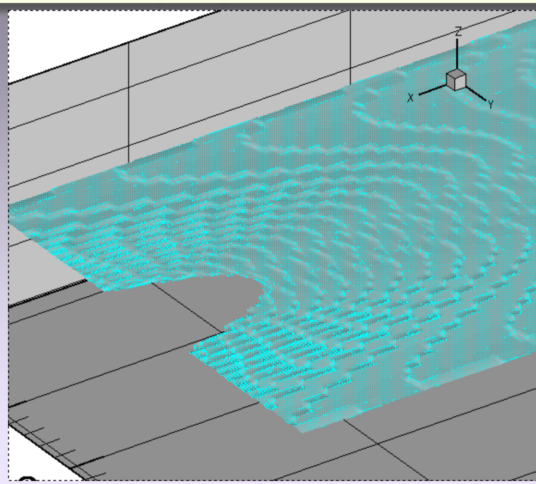
3D-NWT coupling with 3D-NS-VOF





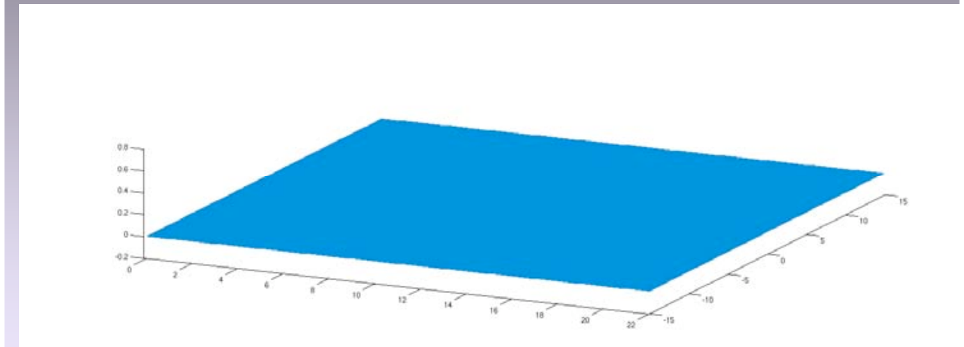
[Biausser et al., J. IJOPE, 2004]

3D-NWT coupling with 3D-NS-VOF



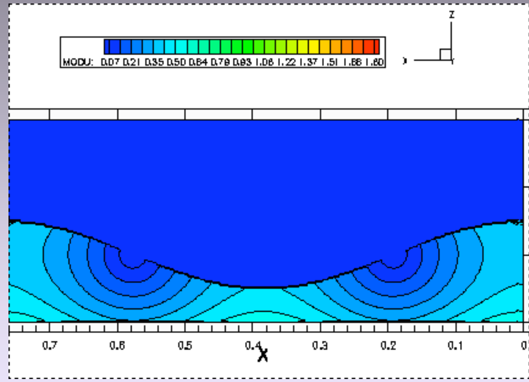
[Biausser et al., J. IJOPE, 2004]

Generation of extreme breaking waves by 3D spatial energy focusing in NWT



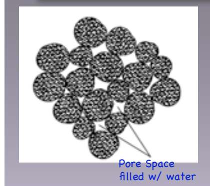
[Brandini and Grilli, 2001; Fochesato, Grilli, Dias (2004,2005,2007)]

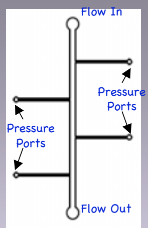
3D-NWT coupling with 3D-NS-VOF



[Biausser et al., J. IJOPE, 2004]

NSF-PIRE project (05-09) : THE ROLE OF FLUID PRESSURES IN THE TRIGGERING OF TSUNAMOGENIC LANDSLIDES





Dynamic Pore Pressure in Porous Media Modeled in a Micro-channel network

MICRO-SCALE TESTING
Experiments using mini- and micro-channels will provide data and insight into pore pressure response due to dynamic loading. Dynamic pressure pulses will be generated using a "water hammer" effect and a pneumatic actuator. The properties of the channel will be modified such that the pore pressure response can be compared to pore pressure generation in soils.
MICROFLUIDIC MODELING
Two different CFD models are currently being used to model the physical microfluidic experiments. The first one, FLUENT, is a FVM that solves the 3-D Navier-Stokes (NS) equations. The second one is a model developed by Prof. Krafczyk's team at TU-BS, which is based on the Lattice-Boltzmann equations, that also simulate the dynamic behavior of Newtonian fluids similar to the NS equations.
MACRO-SCALE TESTING
Cyclic triaxial tests of artificial soil made of uniform glass spheres, with local pore pressure measurements, will provide insight into the fundamental pore pressure generation in soils due to seismic loading. Using uniform spheres provides control of pore diameter, leading to a clearer understanding of pore pressure response for various particle sizes. Actual sediment will be used in a second phase.

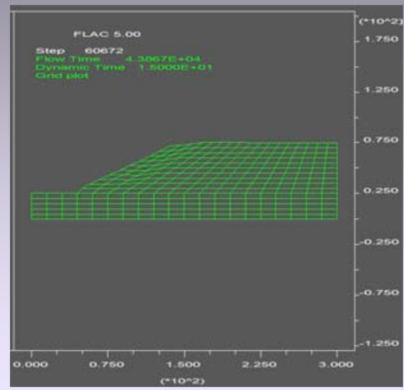
Cyclic Triaxial Tests on Idealized and Real Soils

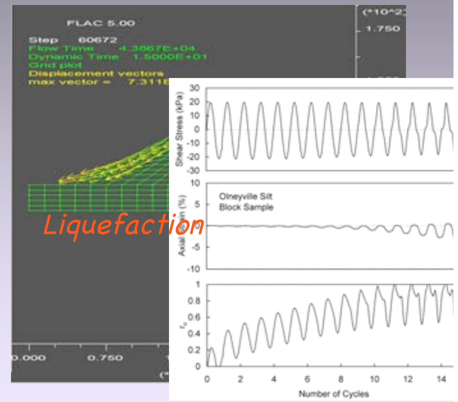
Landslide tsunami modeling: methodology 98-07

- Triggering : ??? -> NSF-PIRE ongoing project
- Kinematics : idealized (slides or slumps), as a function of governing parameters (geometry, geology, geomechanics)
  -> analytical/semi-empirical models validated by 2D/3D lab. experiments
- Landslide tsunami source : numerical model prediction (2D/3D-FNPF)
  -> semi-empirical representation of sources for fast model initialization
  -> experimental validation with large scale 2D and 3D experiments
- Tsunami propagation : long wave model (FUNWAVE: a validated fully nonlinear Boussinesq model) -> coastal runup/moving shoreline/inundation
- Cases studies : (Unimak, 1946; Kalapana, 1975; Skagway, 1992; PNG 1998,…)
  See: www.oce.uri.edu/~grilli -> for publications

NSF-PIRE project: tsunami task

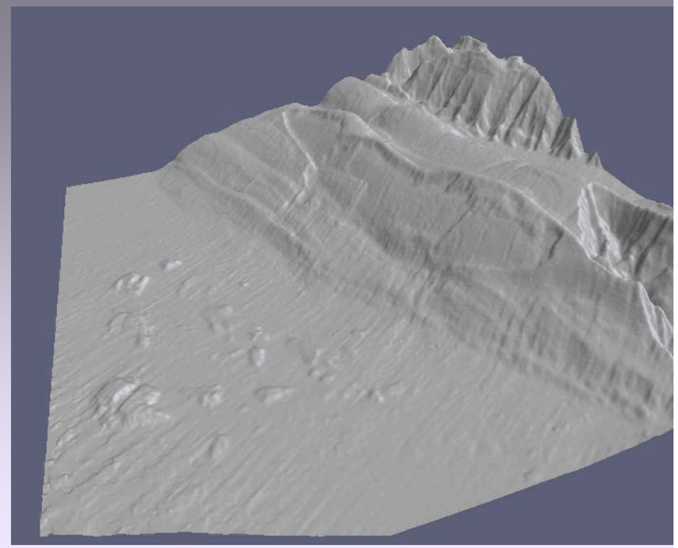
- triggering of landslide tsunamis (current project using FLAC/experiments)





Landslide Tsunami Generation off Sumatra, SEATOS 05 (Meyer et al)

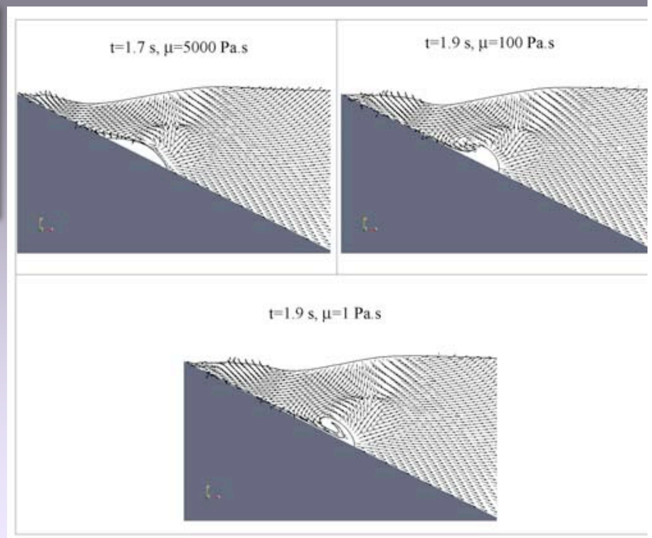
IDEALIZED Geometry and kinematics !



Landslide Tsunami Generation : Full 3D-NS three fluid simulations

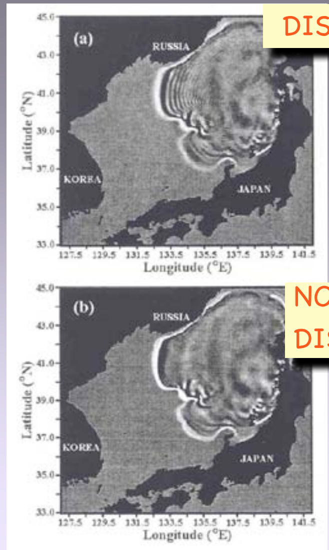
[Abadie et al., ICCE 2006; La Houille Blanche, 2007]

IDEALIZED Geometry and kinematics !



Modeling tsunami propagation

- Simulations of *Nihonkai-Chubu tsunami* of May 26, 1983 in the Japan Sea. Model results from Yoon (2002).
- *Dispersive* long-wave propagation model (Boussinesq equations) vs. *non-dispersive* model (NLSW eqs.)
- Tsunami fronts modified by *wave dispersion.*



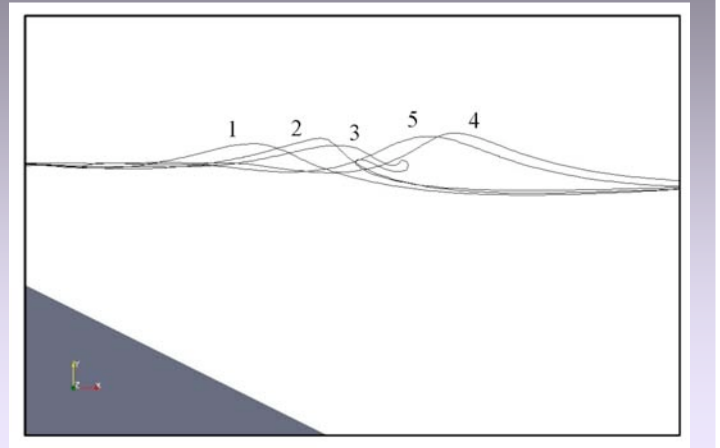
DISPERSIVE

NON DISPERSIVE

Landslide Tsunami Generation : Full 3D-NS three fluid simulations

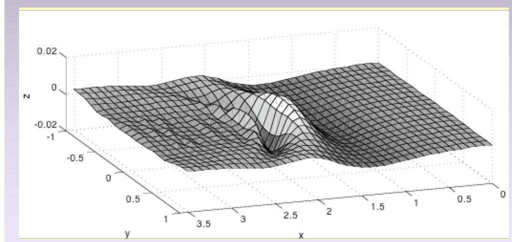
[Abadie et al., 2006,2007]

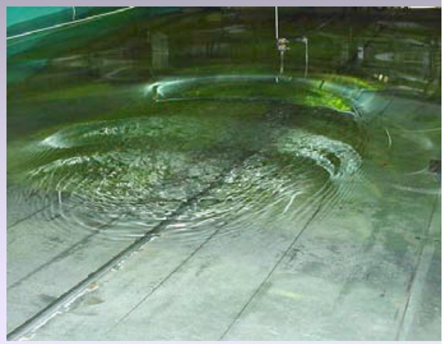
Free surface shapes !



Landslide Tsunami Generation Model

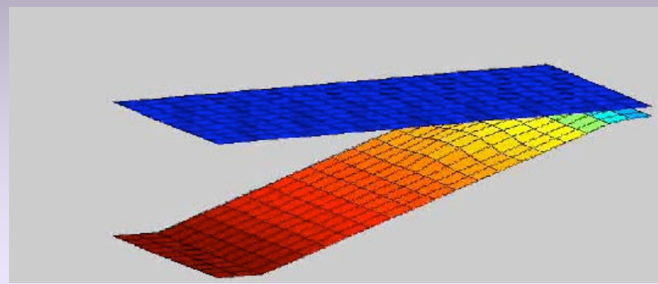
- Computed/measured tsunami Landslide surface elevation (Enet et al., ISOPE 2003; WAVE 2005; JWPCE 2007) :



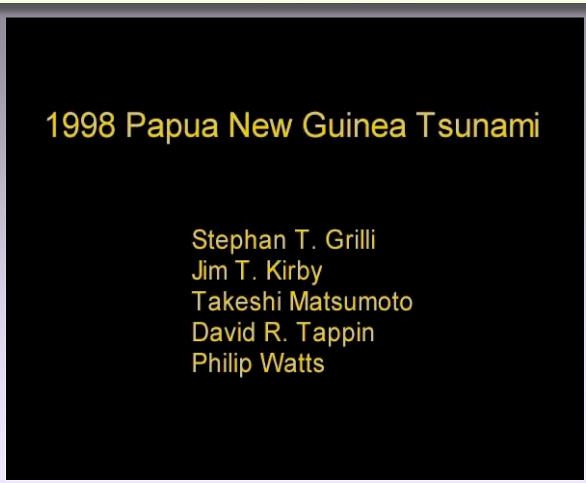


3D Landslide/slump Tsunami Generation Model

- FNPF Model to compute 3D SMF tsunami source elevation over a discretization as a function of kinematics SKETCH :

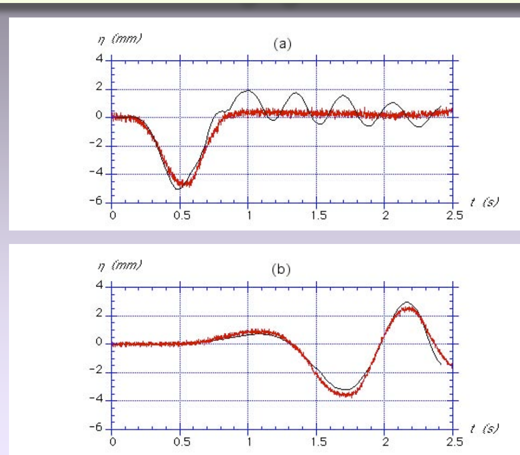


PNG 1998 Case Study: propagation simulation

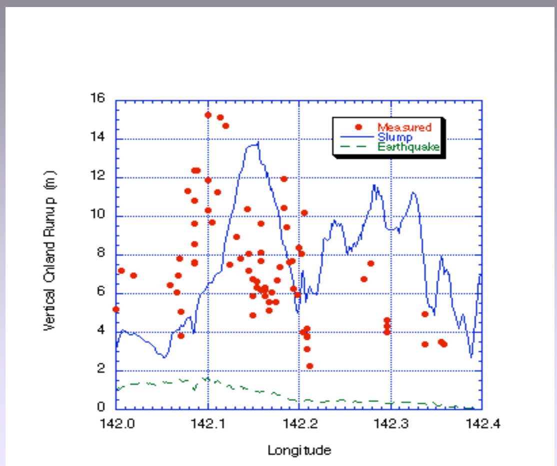


[1999-2001]

Laboratory Validation of 3D Tsunami Generation Model : gage measurements



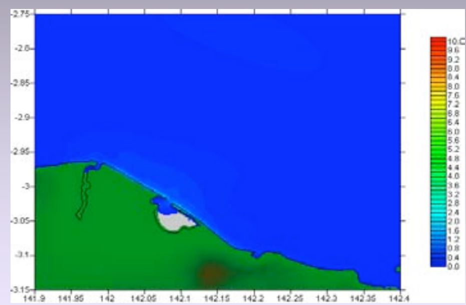
PNG 1998 Case Study: runup vs. prediction



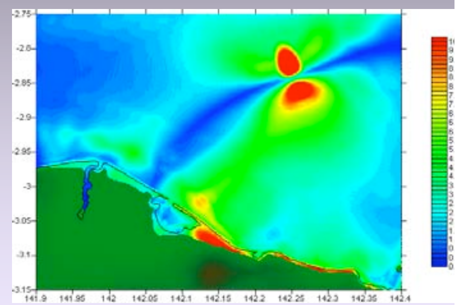
[Tappin et al., 2001]

PNG 1998 Case Study: propagation simulation

Co-seismic displacement tsunami

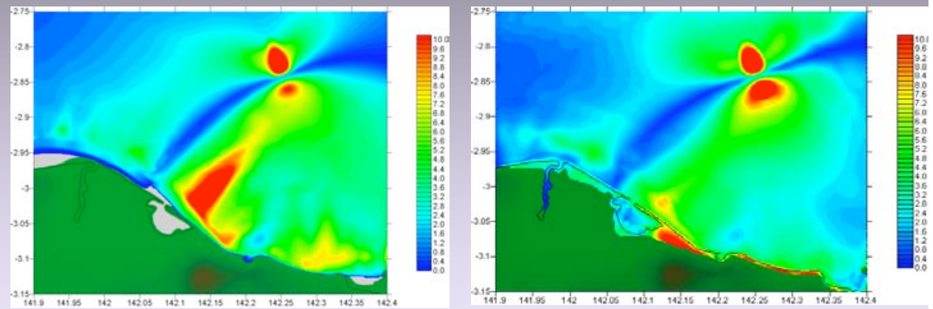


FNBM modeling of Slump generated tsunami (Tappin et al., 2001)



PNG 1998 Case Study: propagation simulation

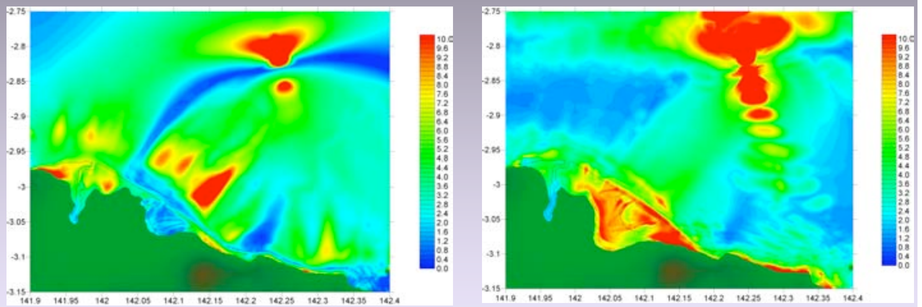
Tsunami N2 (NSW) FUNWAVE (FNBM; Wei et al., 1995



-> Dispersion matters for SMF tsunami propagation, runup, and flooding (more local; shorter wave length) (Tappin et al., 2001)

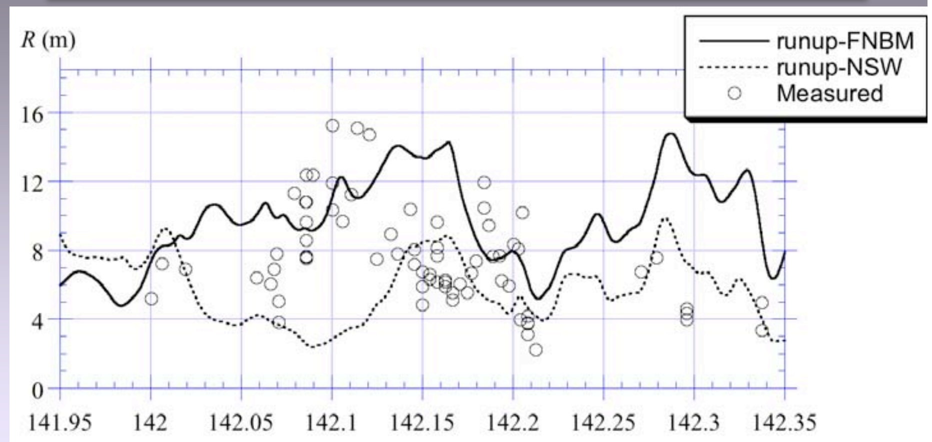
PNG 1998 Case Study: propagation simulation

FUNWAVE (NSW) FUNWAVE (FNBM)



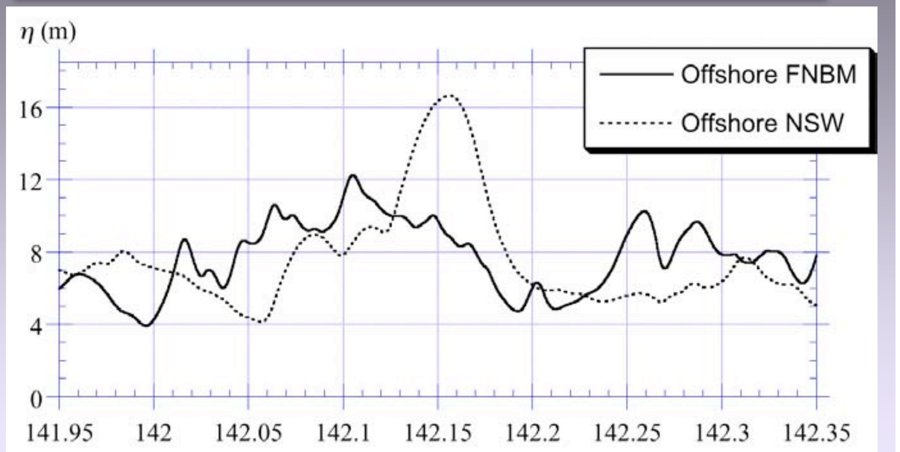
-> Tappin et al., 2007 : improved source geology and timing

PNG 1998 Case Study: runup vs. prediction



[Tappin et al., 2007]

PNG 1998 Case Study: runup vs. prediction



[Tappin et al., 2007]

12/26/04 tsunami source and modeling

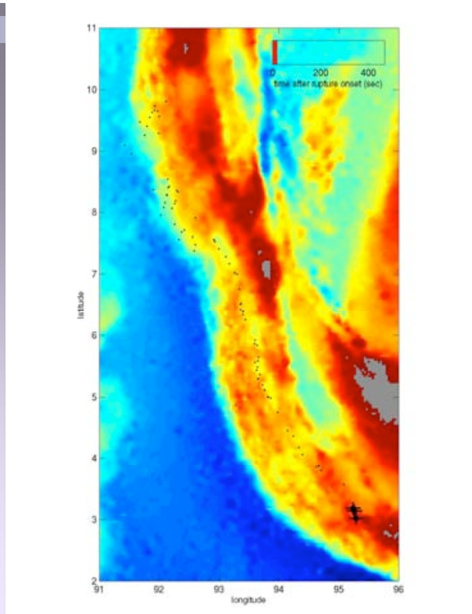
- Overview of 12/26/04 tsunami event (see other talks)
- Source definition from geological and seismological constraints. Iterative source refinement to match tsunami observations but runup (tide gages, satellite transects,…)
  -> Grilli et al. (2005; 2007, JWPCE, in press)
- Detailed modeling of the event in Thailand (case study in a nested grid) : runup, coastal impact
  -> Collaboration with Thailand
  -> Ioualalen et al. (2007, JGR, in press)

12/26/04 Rupture

Rupture simulation, based on hydroacoustic measurements :

- 9.3 M_w at 58’53” GMT
- 500 s rupture time
- 1200 km rupture size (NNW)

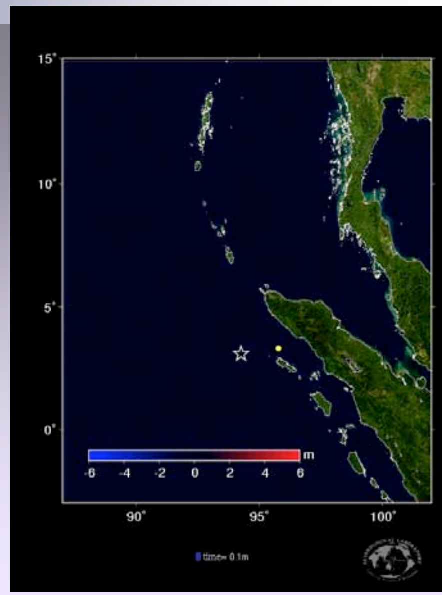
[De Groot-Hedlin, C.D.,5/05]



Seismic inversion models

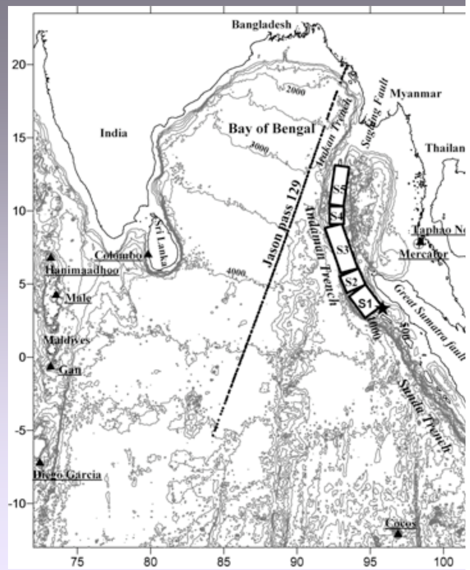
- Use *seismic wave data* measured at seismographs
- Inverse propagation *modeling* to reconstitute earthquake source parameters
- Prediction of ocean bottom *uplift* and *subsidence*

[Ammon et al., 5/05;]



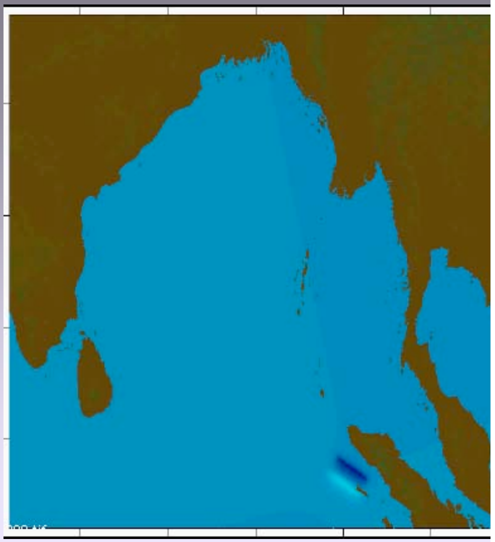
Tsunami source parameters and basin model grid

- Ocean basin simulations : FUNWAVE on 1’ x 1’ grid (1.85 km x 1.85 km)
- ETOPO 2 : bathymetry and topography merged with better coastal data from Thai Navy maps
- Rupture: simplest possible source => 5 independent segments/sources triggered at different times (0 to 600 s -> 1213 s) (Okada, 1985)

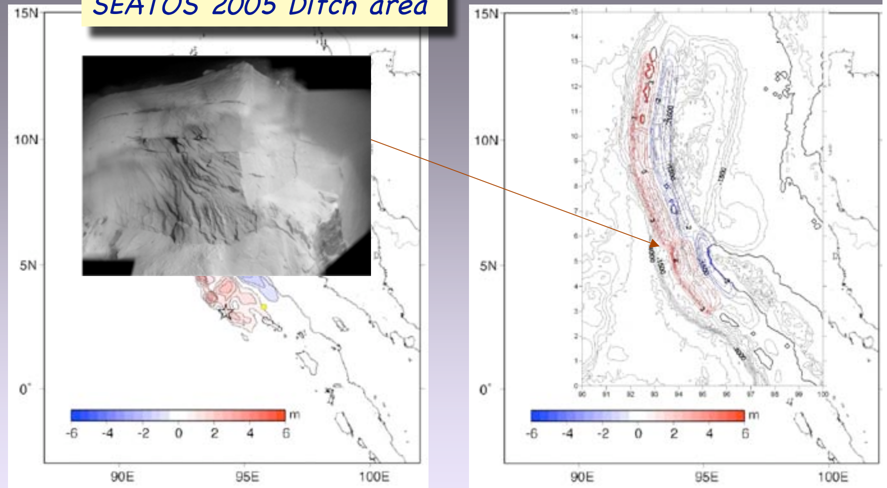


Propagation model

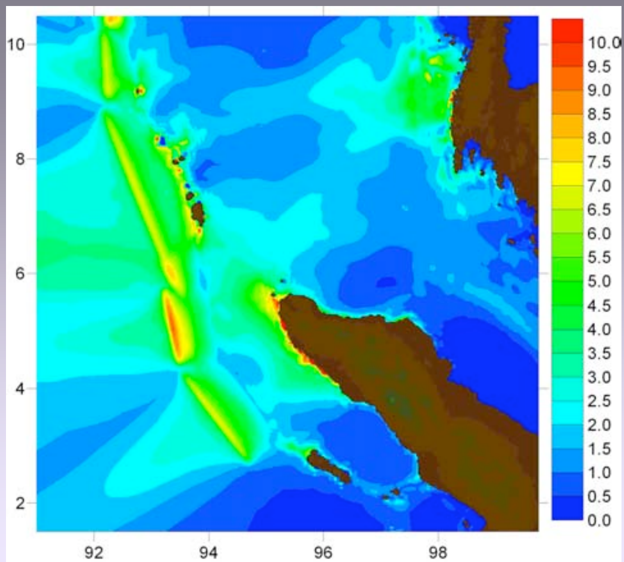
- Fully Nonlinear Boussinesq model (Wei et al, 1995…; Kirby, 2003) (FUNWAVE)
- Fully nonlinear and keeps dispersion to high-order -> Dispersion modeled where it matters
- Bottom friction and wave breaking dissipation.
- Moving shoreline algorithm -> accurate runup and inundation

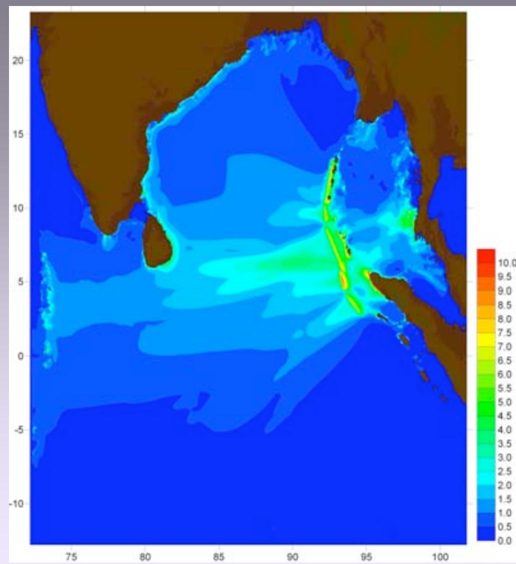


SEATOS 2005 Ditch area

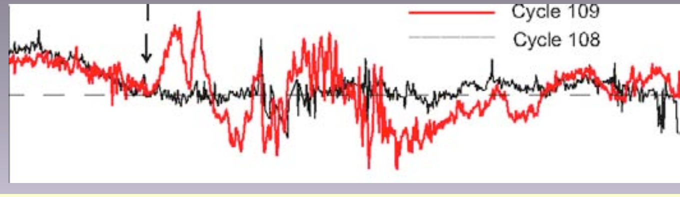


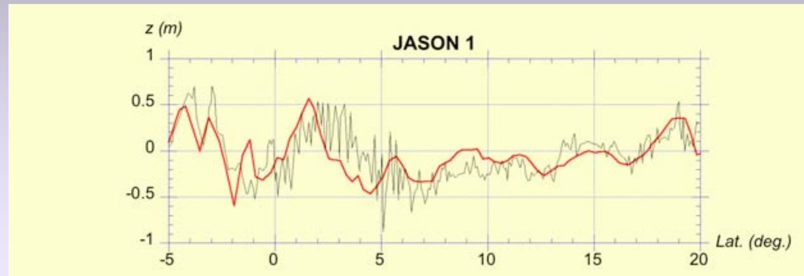
[Seismic inversion (Ammon et al., 2005) and Tsunami sources (Okada, 1985)]



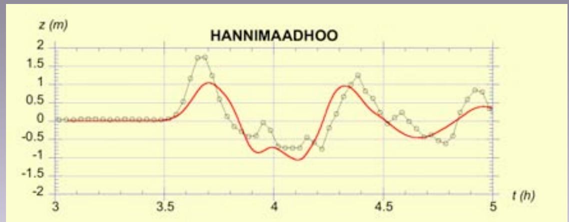


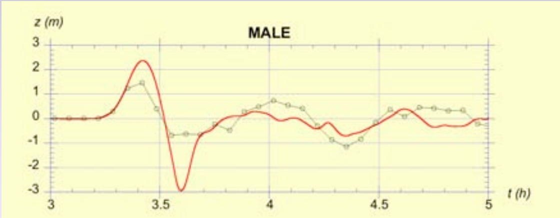
Statellite track in Bay of Bengal

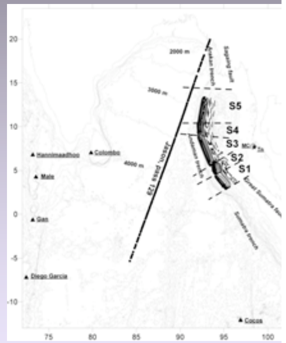




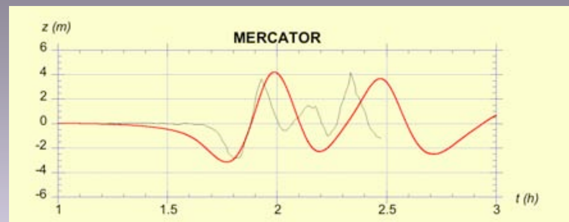
Tsunami record in West Indian Ocean

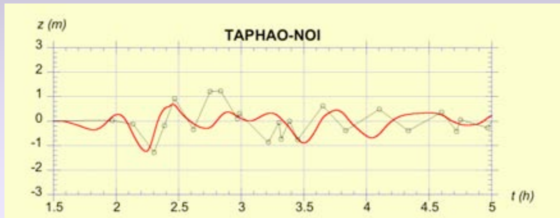


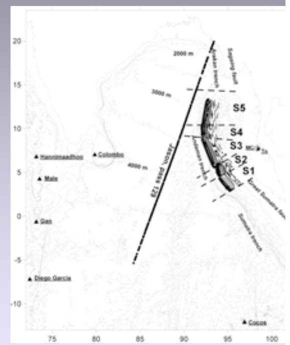




Tsunami record in Phuket





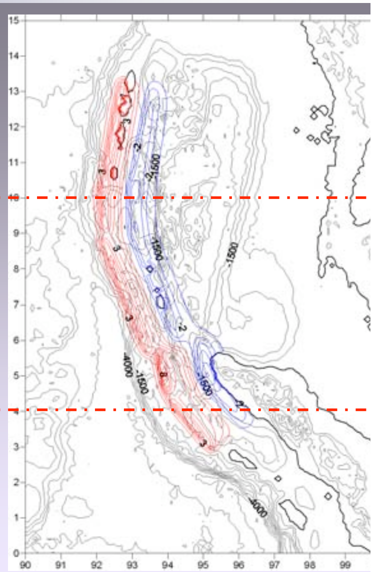


Locations	Model runup	Model (long. E, lat. N)	Field runup
Northern tip, Aceh, Indonesia	11.8 m	(95.248,5.573)	20-28 m
Upper NW, Aceh, Indonesia	10.9 m	(95.284,5.559)	12.2 m
Upper NW, Aceh, Indonesia	10.2 m	(95.307,5.567)	9.8-10.3 m
Upper NW, Aceh, Indonesia	10.2 m	(95.323,5.570)	10-11 m
Upper NW Aceh, Indonesia	23.6 m	(95.341,5.067)	5-35 m
Colombo, Sri Lanka	1.9 m	(79.883,6.812)	2.1 m (t. gage)
Galle, Sri Lanka	2.4 m	(80.475,5.974)	2-3 m
SE coast, Sri Lanka	5.5 m	(81.816,7.427)	5-10 m
Chennai, India	3.2 m	(80.285,13.552)	2.9 m
Nagappaattinam, India	2.4 m	(79.740,10.865)	2-3.5 m
Port Blair, India	5.6 m	(92.000,11.702)	5.0 m
Rangoon, Burma	1.3 m	(96.966,17.309)	NA
Kamala Bch., Phuket, Thailand	4.9 m	(98.275,7.973)	4.5-5.3 m
Patong Bch., Phuket, Thailand	4.1 m	(98.276,7.900)	4.8-5.5 m
Ko Phi Phi, Thailand	2.8 m	(98.777,7.739)	4.6-5.8 m

[FUNWAVE simulation 1′ grid with ETOPO2: runup]

Tsunami impact in Thailand: regional grid

- Regional basin simulations : 0.25′ x 0.25′ grid (450 m x 450 m)
- ETOPO 2 : bathymetry and topography merged with Thai Navy maps of Coastal Thailand.
- Rupture: Same source as for basin scale since propagation is E-W



Tsunami impact in Thailand: regional grid

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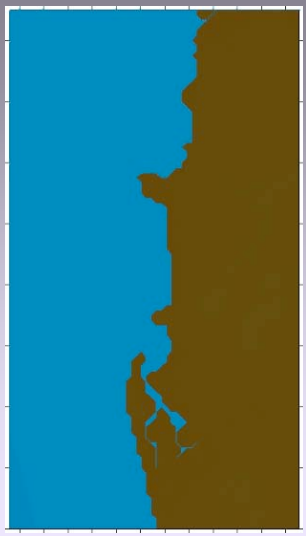
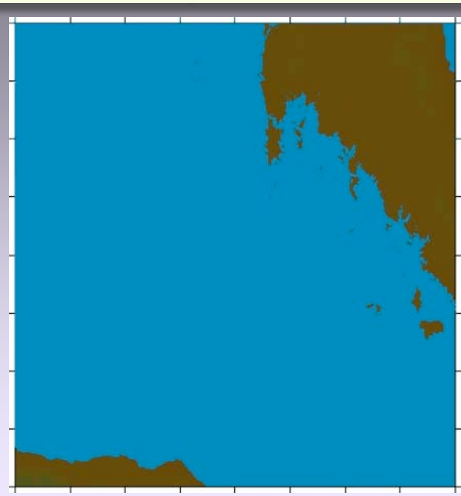
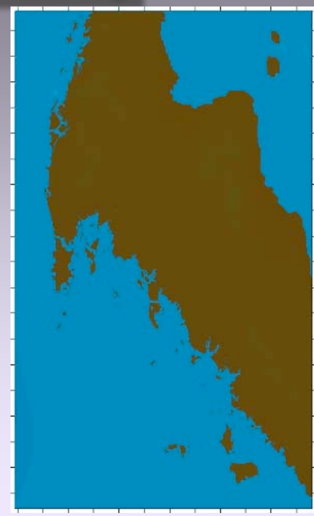
Tsunami impact in Thailand: Khao Lak



Tsunami impact in Thailand: modeling

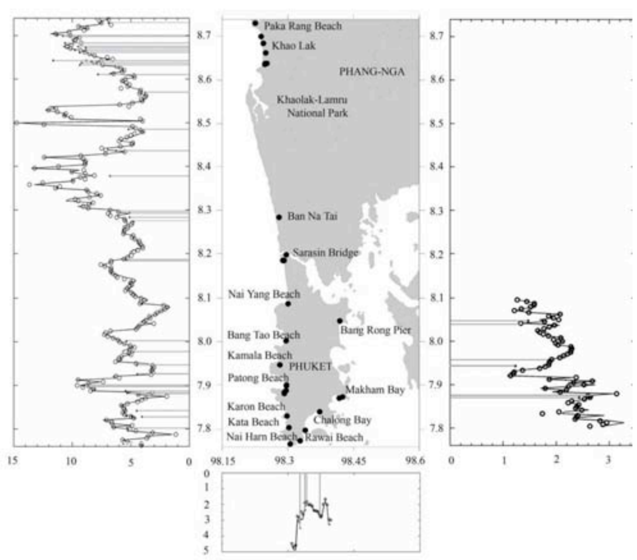




Tsunami impact in Thailand: runup

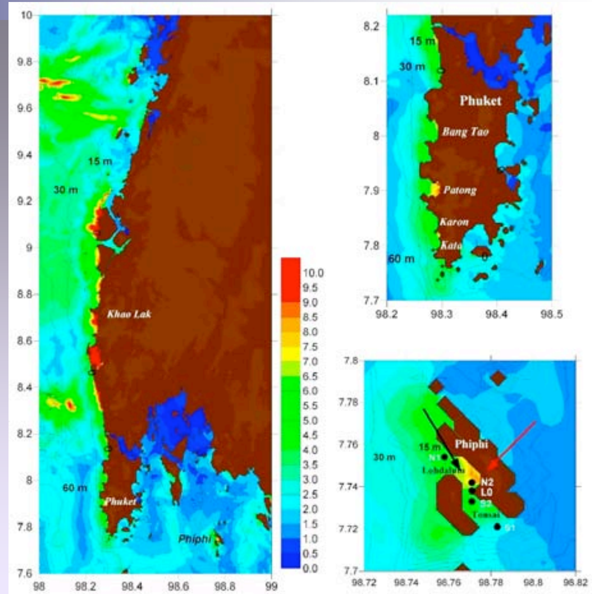
[Ioualalen et al., JGR, 2007]

Field data: Disaster Prevention Research Institute, Japan, 2005.

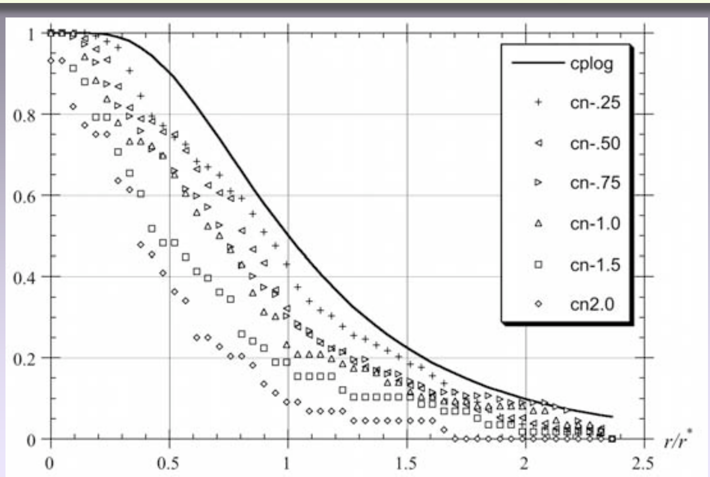


Tsunami impact in Thailand: elevation

[Ioualalen et al., JGR, 2007]



Tsunami impact in Thailand: runup grid effects

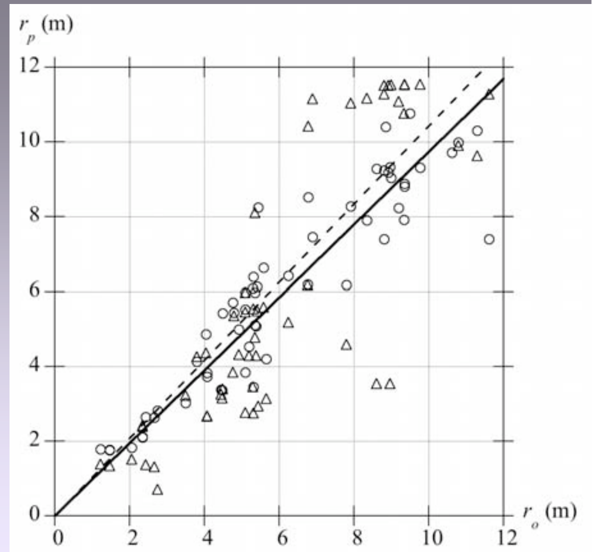


Tsunami impact in Thailand: runup obs./pred.

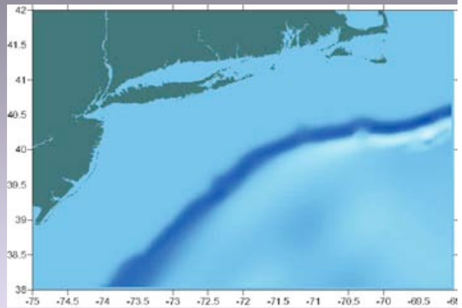
o : 0.25′ ; Δ : 1′

0.25′ Model skill:

R^2 = 0.87

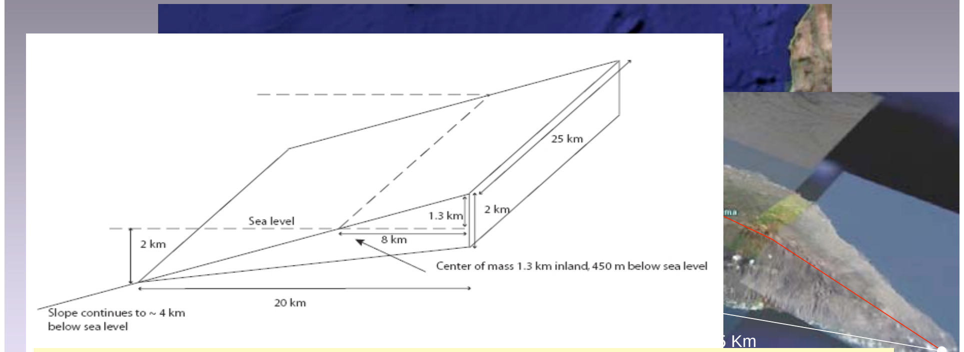


Landslide Tsunami Modeling : Cumbre Vieja



Initial modeling for approximate source :
-> 2′ ocean grid (left)
-> 0.25′ nested coastal grid (right)

Cumbre Vieja volcano collapse : Subaerial landslide source

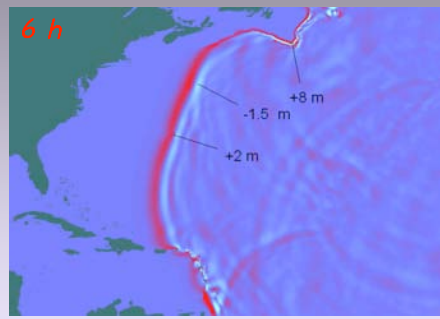


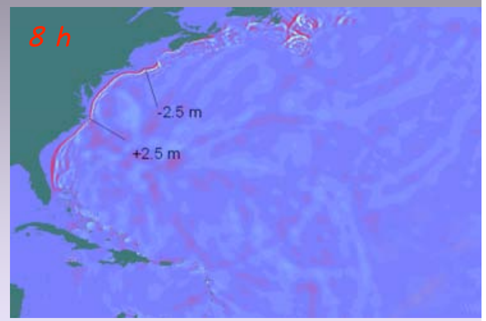
[Sketch of estimated mass failure size and geometry, 200 km^3, 50 m/s; Day, personal communication, 2006]

Conclusions

- Sciences issues: (i) source timing/3D effects for co-seismic tsunamis (beyond Okada, 1985)
  (ii) triggering of landslide tsunamis (current NSF project
  (iii) systematic study of dispersion in tsunami trains
  (iv) spherical Boussinesq model for basin scale propagation -> has been implemented
  (v) predicting details of runup, flooding, structural effects due to tsunamis -> boundary fitted irregular curvilinear grids has been implemented
- See : webpage for publications (http://www.oce.uri.edu/~grilli)

Landslide Tsunami Modeling : Cumbre Vieja





[Initial modeling for approximate source]

Thank you !