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ADAPTIVE MESH REFINEMENT APPLIED TO TSUNAMI MODELING: TSUNAFLASH

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ABSTRACT: After the devastating Andaman-Sumatra Tsunami of December 2004, the international community has strived to introduce measures to prevent hazards from future tsunamis as much as possible. In this endeavor numerical modeling plays a key role, since forecasts as well as inundation mapping efforts rely on numerical simulation.
In this presentation, we introduce a new triangle-based adaptive mesh finite element numerical model for tsunami propagation (and inundation) simulations. TsunaFLASH combines numerical methods developed in the framework of the unstructured triangular, yet non-adaptive, tsunami model TsunAWI with adaptive mesh refinement capabilities provided by the mesh refinement library amatos. Adaptive methods are well suited for accurate resolution of localized features, maintaining computational efficiency in terms of the number of computations and the required memory.
This presentation will introduce the first developments of TsunaFLASH, which use bathymetry and topography data derived from ETOPO5 and focus on the Indian Ocean region. The finite element based discretization scheme with conforming and non-conforming linear elements will be introduced, as well as the coupling with the software RuptGen (Babeyko, 2007), which generates the initial uplift function.

Keywords: adaptive mesh refinement, tsunami modelling, TsunaFLASH, TsunAWI, AMATOS

1. INTRODUCTION

Numerical modeling has been used as a tool for analyzing and reconstructing tsunamis for 39 years (Aida, 1969). Nowadays many tsunami codes are available open-source/free-ware (such as: COMCOT, 1994; TUNAMI, 1995-2003; MOST, 1996-1998; ANUGA, 2004-2006) and commercial-ware (such as: MIKE21 by DHI and 3DD by ASR). Many numerical methods have been applied and are represented in these codes (Finite Difference, Finite Element, Finite Volume). Gridding methods such as structured and unstructured non-adaptive have been applied.

In the end of this year (2008) **TsunAWI** (Tsunami unstructured mesh finite element model developed at Alfred Wegener Institute) by Behrens *et al.* (2006 - 2008)**,** will be launched as operational model in the German – Indonesian Tsunami Early Warning System (GITEWS) framework. A new development uses adaptive mesh refinement to improve computational efficiency and accuracy. This new approach is called **TsunaFLASH**. To our knowledge this is the only approach to adaptive mesh refinement tsunami modeling besides the block-structured adaptive finite volume code TsunaCLAW by LeVeque and George (2006).

2. SHALLOW WATER EQUATIONS

Two dimension of shallow water equations, adopted from TsunAWI (Behrens *et al.*, 2007; Behrens, 2008), are used in TsunaFLASH:

$$\frac{\partial \vec{\upsilon}}{\partial t} + (\vec{\upsilon}\cdot\nabla)\vec{\upsilon} + f\times\vec{\upsilon} + g\nabla h + \frac{C_d\,\vec{\upsilon}\,|\vec{\upsilon}|}{\rho(h+H)} - \nabla\cdot(A_h\nabla\vec{\upsilon}) = 0 \qquad (1)$$

$$\frac{\partial h}{\partial t} + \nabla\cdot(\vec{\upsilon}\quad(h+H)) = 0 \qquad (2)$$

$$\vec{\upsilon} \cdot \vec{n} = \sqrt{\frac{g}{h+H}} h \quad (3)$$

$$\vec{\upsilon} \cdot \vec{n} = 0 \quad (4)$$

Equations (1) and (2) are the momentum and continuity equations resp., where $(\vec{\upsilon} \cdot \nabla)\vec{\upsilon}$ is the advection term, $f \times \vec{\upsilon}$ the Coriolis term, $g\nabla h$ the pressure gradient, $\frac{C_d \vec{\upsilon}|\vec{\upsilon}|}{\rho(h+H)}$ the bottom friction, $\nabla \cdot (A_h \nabla \vec{\upsilon})$ the viscosity term, g gravitational force, h the elevation above mean sea level, and H the water depth.

Equations (3) and (4) represent radiation condition for open boundary and no-slip condition for land boundary resp., where $\vec{n}$ is the normal outward vector.

3. UNSTRUCTURED FINITE ELEMENT

Equations (1) and (2) are space-discretized by finite elements with a conforming and non-conforming linear scheme (denoted P^1-P^1_{nc}) based on Hanert *et al.* (2005). Time-discretization is achieved by applying an explicit leap frog scheme as in Imamura *et al*. (2006). Time-step size is controlled dynamically in order to adhere to the Corant-Friedrichs-Levy (CFL) condition for stability of the explicit time scheme.

4. ADAPTIVE MESH REFINEMENT

We adopt a triangular adaptive mesh refinement technique as a new approach for tsunami modeling. AMATOS (Adaptive Mesh generator for ATmosphere and Ocean Simulation) by Behrens (1996, 1998, 2003, 2006) and IGG (The Initial Grid Generator) are employed for generating adaptive triangle meshes. The refinement strategy used is bisection of triangle's marked edge (Behrens *et al.*, 2005) and grid ordering is based on Sierpinski's space filling curve (Behrens and Zimmermann, 2000).

For conducting numerical experiments, we use two setups with finest refinement level of 17 and 20 (see Table 1).

Table 1. Highest local grid resolution corresponds to adaptive refinement level

Refinement Level	Resolution approx. (km^2)
17	177
20	22

5. CODES AND DATA

TsunaFLASH and amatos are both written in Fortran90. The experiments are conducted on a SUN FIRE X4600M2 Linux 64-bit machine using Intel's Fortran Compiler *ifort*. General Mesh Viewer (GMV) Ver. 4.5 (from Los Alamos National Laboratory, USA) is used for visualization.

Bathymetry and topography data are derived from ETOPO5 (5 arc-minute resolution) and focus on the Indian Ocean region (20°E – 134°E, 40°S – 26°N).

Details of the discretization can be deduced from Behrens et al. (2007). A re-implementation of the TsunAWI code has been performed, though.

6. NUMERICAL EXPERIMENTS AND PRELIMINARY RESULTS

Some preliminary tests have been performed with TsunaFLASH, varying the initial conditions: a cosine bell test case, an elliptic source, and a sophisticated realistic source using rupture generator (RuptGen).

The grid refinement during theses tests is controlled by a simple gradient-based refinement criterion: for steep sea surface elevation (ssh) the grid is refined, while a low gradient in ssh leads to grid coarsening. Typical evolutions of the number of nodes, edges and elements are depicted in figure 4.

6.1 COSINE BELL INITIAL CONDITIONS

For our first numerical experiment, we use the cosine bell as initial condition. We deploy it in Sunda Strait approximately at Krakatoa (bahasa: Krakatau) coordinate (105.5°E, 6.20°S or 105.7°E, 6.9°S), since we want to explore the behavior of adaptive grids in the presence of reflected boundary waves and complex bathymetry (see figure 1).

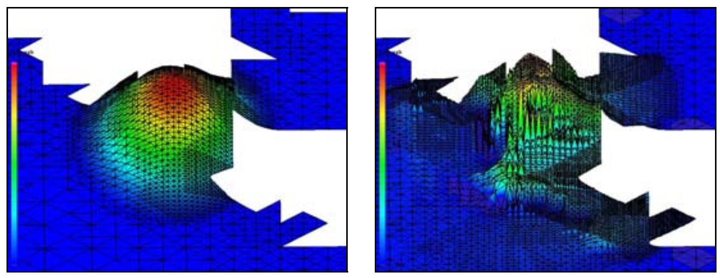


Figure 1. Experiment using cosine bell initial conditions in Sunda Strait

6.2 ELLIPTIC SOURCE INITIAL CONDITIONS

Using an elliptic function to mimic the initial uplift, neglecting the fault mechanism parameters, we reconstructs more or less the common excitation shape of single Okada's plate (Okada, 1985; Okada, 1992). This elliptic source contains uplift and depression (see Figure 2 and Figure 3). A formula for this initial condition is given by:

$$I(x,y) = \sin(x) * \sin(y), \quad (x,y) \in [0,2\pi] \times [0,\pi]. \tag{5}$$

Elliptic sources are also used in the Integrated Tsunami Data Base (ITDB) by Gusiakov (2007), however, only with single uplift or depression shape. The construction of such a source is demonstrated in figure 2. With this source preliminary test runs have been performed in the area of northern Sumatra (see figure 3).

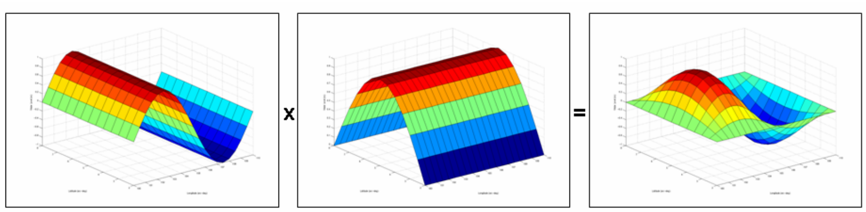
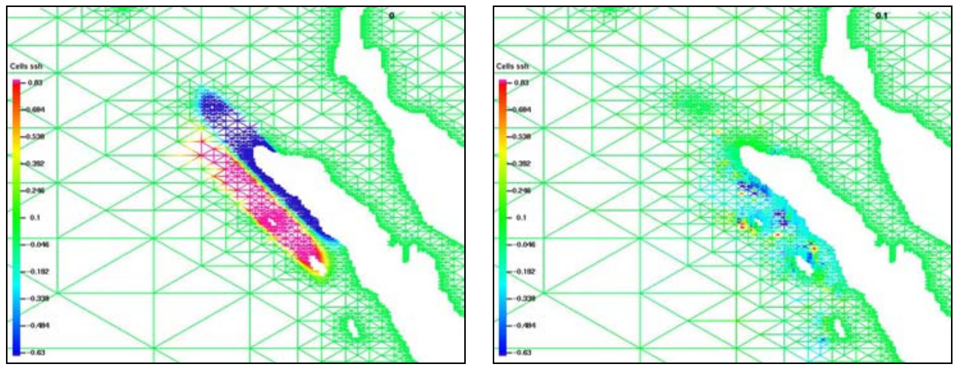


Figure 2. Construction of elliptic source from two sine functions.



timestep no. 0000 timestep no. 9950

Figure 3. Elliptic source applied in TsunaFLASH

6.3 INITIALIZE USING RUPTGEN

While George and LeVeque (2006) employ dynamic motion of the seafloor bottom based on Ammon *et al.* (2005) for generating the initial condition related to the Andaman-Sumatra tsunami of 2004, we use RuptGen by Babeyko (2007) which published in Babeyko *et al.* (2008).

Our slip distribution follows that of Geist *et al*. (2007) which based on Banerjee *et al*. (2007). The corresponding coseismic slip distribution serves as complex input to RuptGen and results in a total seismic moment Mo. 7.19178e+22 Nm, corresponding to a moment magnitude Mw 9.17, which compare well with the Mw. 9.2 used in Titov *et al*. (2005), Mw. 9.15 from Chlieh *et al*. (2007) and Mw. 9.14 as in Geist *et al*. (2007).

The excitation has maximal uplift of 5.87 meters and maximal depression -2.16 meters distributed along the Sumatra-Andaman trench (see Figure 5). This excitation shape more or less corresponds to the shape in Geist *et al.* (2007).

Typical evolution of the number of nodes, elements and edges is shown in figure 4. Figure 5 gives two snapshots of the simulation with some emphasis on the grid refinement. Obviously, the refinement criterion is not capable of capturing the wave front, once it becomes small or shallow. Therefore, the wave propagation into the deep ocean is not accurately captured. Further development is needed to develop better refinement criteria.

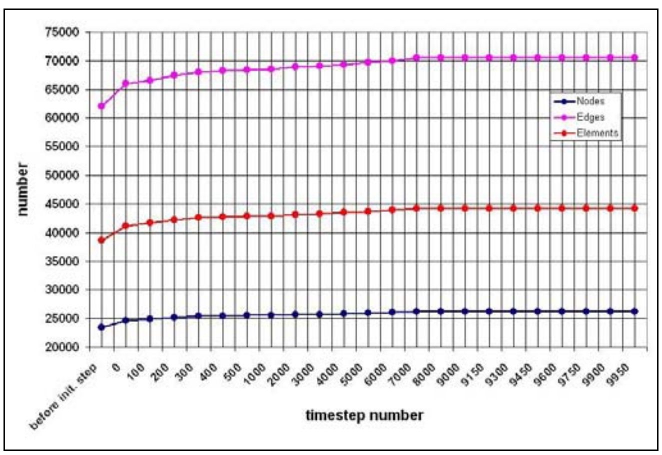


Figure 4. Number of nodes, edges, and elements during the simulations of Aceh tsunami 2004 event

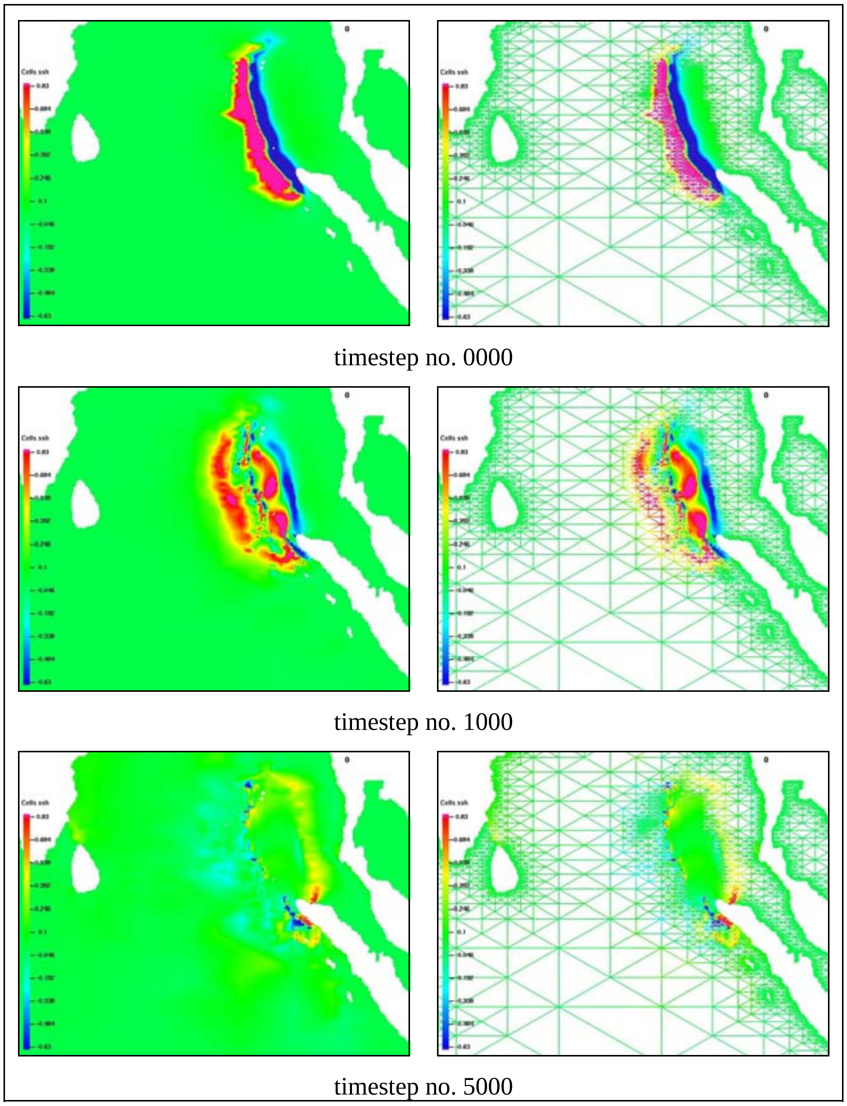


Figure 5. Experiment results using adaptive mesh refinement for Aceh 2004 event. Left: face; Right: grid appearences. The sea level color scale used is for better visualization, where actual max. uplift is 5.86589 meters and maximal depression is -2.15582 meters

7. SUMMARY AND FUTURE DEVELOPMENT

The results of numerical experiments using diverse initial conditions for TsunaFLASH are promising. However, the numerical scheme needs to be stabilized, wave propagation properties need to be analysed, and the refinement criterion needs to be enhanced.

Future developments will concern inundation boundary conditions alternative numerical schemes, and improvements to the friction and viscosity representations.

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