

## **Large scale tsunami simulation for 2004 Indian Ocean tsunami using parallel GPU computing**

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### **ABSTRACT**

This study couples two different numerical schemes, finite different method and smoothed particle hydrodynamic (SPH) method to more accurately assess the impact of tsunami over a coastline. The model performs large scale tsunami simulation of 2004 Indian Ocean earthquake and tsunami. To handle the SPH model general-purpose computing on graphics processing units manage the computation. The result of the simulation is validated against the observation data of the tsunami. In this research, Banda Aceh city, in Indonesia is chosen as the observation location. COMCOT, a tsunami wave simulation engine, simulates the wave generation and propagation on the open ocean. Instead, DualSPHysics, a SPH solver, simulates the near coast wave propagation and the tsunami wave inundation. The 2004 Indian Ocean earthquake and tsunami resulted in a catastrophic event in the Southeast Asian region. The simulation performed in this study provides information about tsunami propagation and tsunami inundation on the coastline with an accuracy greater than available by the current state of the art. This information is important for damage mitigation as well as comprehensive resilient disaster management planning. This work can be expanded to perform probabilistic tsunami hazard analysis. Challenges arose in several areas, such as: the handling of the complex bathymetry and topography, and the computational cost of tsunami simulation. Recent advances of numerical methods as well as computational tools encouraged further improvements on tsunami simulation research.

### **1. INTRODUCTION**

Tsunami is a series of wave generated due to disturbance occurs on the sea. The source of disturbance can be submarine earthquake, submarine landslide, extreme weather, or asteroid impact. Recent records shows, tsunami is dangerous and its impact is catastrophic. The magnitude of destruction caused by tsunami can be as similar as earthquake. Some examples of tsunami event are: 2004 Indian Ocean earthquake and tsunami and 2011 Tohoku earthquake and tsunami.

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In tsunami generation, the disturbance results on displacement of a body of water in large volume instantaneously and generate series of wave in the sea surface. These waves, although looks like normal wave but it is different compared with the wind-generated wave. The normal wind-generated wave will have period around 10 seconds with the wave length of 150 m, while the tsunami wave will have period of one hour and wave length as far as 100 km. However, it is difficult to detect tsunami wave in the vast area of the ocean, as the appearance is not significantly different with wind-generated wave.

To have comprehensive knowledge of tsunami hazard is important matter for city planner and disaster manager, especially in the tsunami-prone area. Moreover, for the development planning located near the coastline should be aware of the occurrence of tsunami event, especially if submarine active fault existed near coastline. The building code should consider the tsunami loading. Some of the building codes already consider the tsunami loading on their calculation such as Coastal Construction Manual by FEMA, City and County of Honolulu Building Code by the Department of Planning and Permitting of Honolulu, Hawaii.

In this study we couples two different numerical schemes, finite different method and smoothed particle hydrodynamic (SPH) method to assess the impact of tsunami over a coastline. The generation and propagation of tsunami wave will be simulated using COMCOT (Wang, 2009) and the near coast wave propagation and the tsunami wave inundation is estimated using smooth particle hydrodynamic (SPH) model (Crespo et al. 2015). The model performs large scale tsunami simulation of 2004 Indian Ocean earthquake and tsunami and Banda Aceh city, in Indonesia is chosen as the observation location.

## **2. METHOD**

### **2.1. 2004 Earthquake and Tsunami**

The 2004 Indian Ocean earthquake occurred at 00:58:53 UTC on 26 December 2004. The epicenter is estimated on the west coast of Sumatra, Indonesia, with moment magnitude of 9.1–9.3. The tsunami wave generated break at the west and north coasts of northern Sumatra, Indonesia particularly in Aceh province, early in the morning. From the post-tsunami survey, tsunami subsidences were 0.2–0.6 m (0.7–2 ft) at Banda Aceh, more than 0.2 m (0.7 ft) at Peukan Bada, and more than 1.5 m (5 ft) at Lhoknga and Leupung (Kawata et al. 2005)

### **2.2. Observation Point**

Lhoknga is a town within the district of the same name, in Aceh Besar Regency, Aceh Special Region, Indonesia, located on the western side of the island of Sumatra, 13 km southwest of Banda Aceh the capital of Aceh Special Region. This area affected severely in 2004 earthquake and tsunami event, mostly due to inundation of tsunami wave. Available data from post-tsunami survey in Lhoknga will be used in this research as validation for our tsunami model.

### 2.3. COMCOT Tsunami Model

Cornell Multi-grid Coupled Tsunami Model (COMCOT) is a finite difference scheme solves the generation and propagation of tsunami on the open ocean. COMCOT was developed by Yongsik Cho and S.N. Seo, they were incorporating tsunami model from Shuto (1991) and Imamura et al. (1988). The improvement of COMCOT since its inception include, 1) introduction of moving boundary, 2) user interface of COMCOT, and 3) implementation the scheme for general grid matching.

COMCOT uses explicit staggered leap-frog concept to solve shallow water equations. COMCOT solves the numerical scheme in both spherical and Cartesian coordinates. The numerical estimation of tsunami wave propagation performed in the nested grid system. This means that inside certain area of estimation, there is smaller region of estimation area, and so on. Numerical scheme of COMCOT is performed inside the grid system. The benefit of nested grid system is its efficiency when numerically estimates the wave propagation near coastline where the topography start to vary and depth of the sea decreases.

Another feature of COMCOT include its capability to reproduce the whole phase of tsunami event, from tsunami generation, propagation over the open sea, and tsunami inundation over the coastline. COMCOT also capable to estimate tsunami generation considers multiple source of tsunami. In this study, COMCOT is used to simulate the generation and propagation of the tsunami waves in the open ocean area. We use the COMCOT model that is available on internet portal and open to use by registered user. The tsunami computational portal is shown in Fig. 1

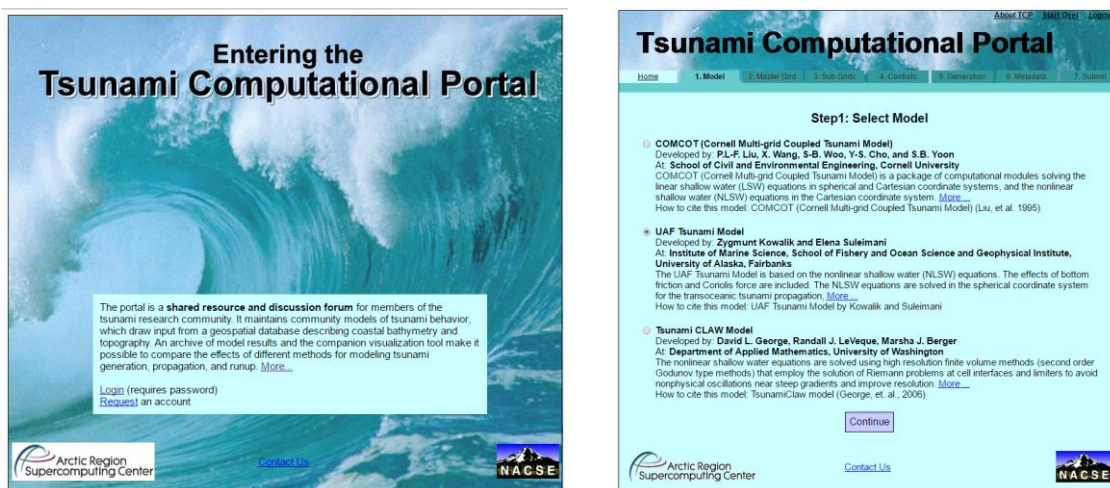


Figure 1. Tsunami Computational Portal Website

## 2.4.SPH Model

Smoothed particle hydrodynamics (SPH) is a numerical scheme using particle method for the estimation method (Monaghan, 1992). The particle method is a numerical method which does not the grid for its numerical operations (mesh-less method). Initially the SPH method originated to account the phenomena of astrophysics, however the method can be extended to solve the fluid dynamics problems (Monaghan, 1992). The SPH method found successfully simulate the breaking dam problem, waterfalls, flood inundation, and multiphase fluid flow.

The SPH method solve the conservation laws of continuum fluid by introducing the concept of kernel function. The kernel function serves as the interpolation function that provides values of specific particle points given its weighting property due to interactions with other particles. The common kernel function that used in the SPH method is cubic spline and Gaussian function. The integral formulation for SPH method is

$$F(x) = \int F(x')W(x-x', y) dx' \quad (1)$$

where  $W$  is the smoothing kernel, and the integration is over the entire interest domain of  $x$  and  $x'$ . Some other important aspects of SPH method beside the smoothing kernel are; the derivation of motions, fluid viscosity, and boundary condition.

One of the challenge of using SPH is computationally more expensive than mesh based FEM and up to now it required large scale supercomputers and was limited to small scale problem. The advent of general purpose graphic processing unit (GPGPU) allowed the use of SPH for the large scale simulation on desktop computers and workstations equipped with GPUs.

The simulation of the tsunami waves is done using DualSPHysics (Crespo et al. 2015). DualSPHysics was developed on C++, CUDA, and Java codes and it was used to understand the behavior of fluid particle especially on the free-surface flow phenomena. In this study DualSPHysics is used to simulate the propagation and inundation of tsunami waves on the coastline.

## 3. RESULT

Topography of Lhoknga coastline is modeled using opensource 3D graphic software called Blender (Hess, 2007), the model is shown in Fig. 2. The raw data is obtained from Google Maps and modified using Sketchup. We reduced the observation area due to limited computational power on modeling the topography, due to problem with detail of minor coastal infrastructures. Final model is shown in Fig. 3.

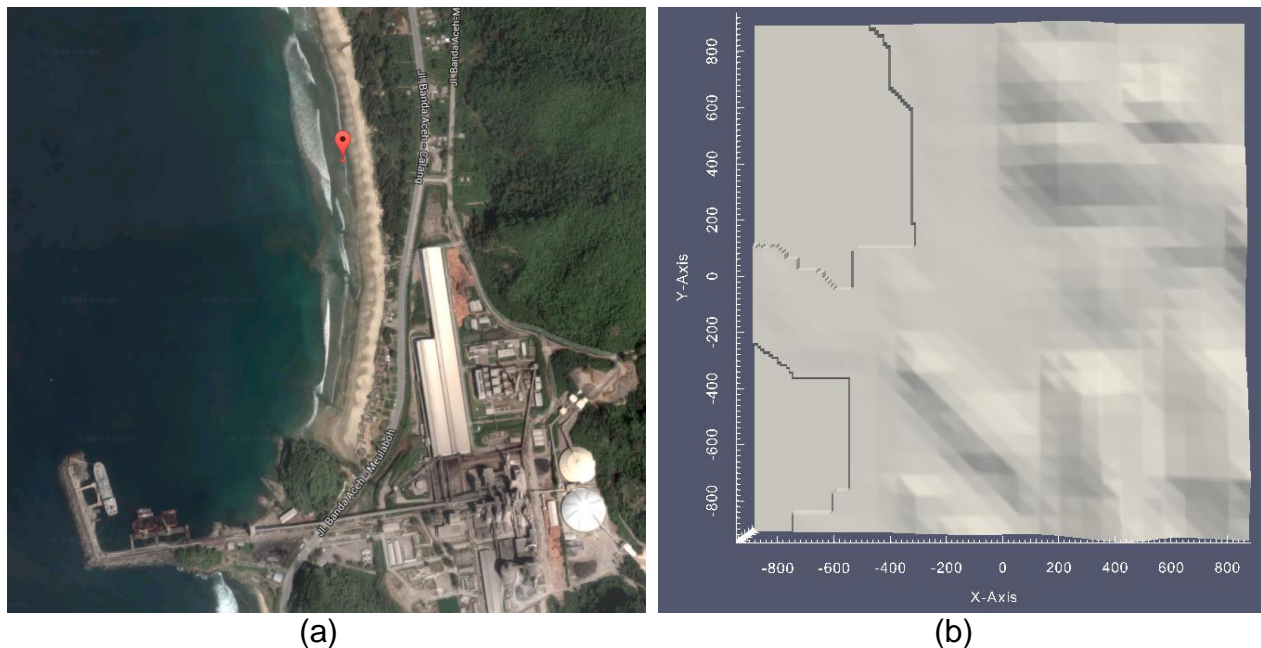
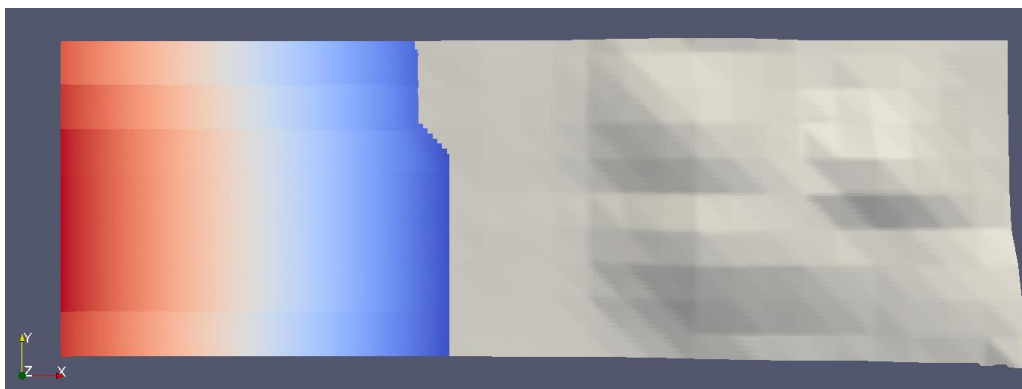


Figure 2. (a). Aerial map of Lhoknga town taken with Google Maps. (b) 3D model of Lhoknga created with Blender

The tsunami simulation performed in two steps, first step is tsunami generation and propagation using COMCOT. The second step is propagation and inundation in Lhoknga coastline using DualSPHysics. The tsunami generation of 2004 tsunami modeled using fault properties from Wang and Liu (2006). The propagation data from COMCOT is reproduced in DualSPHysics. The height evolution in the coastline is recorded from the DualSPHysics output.



(a)

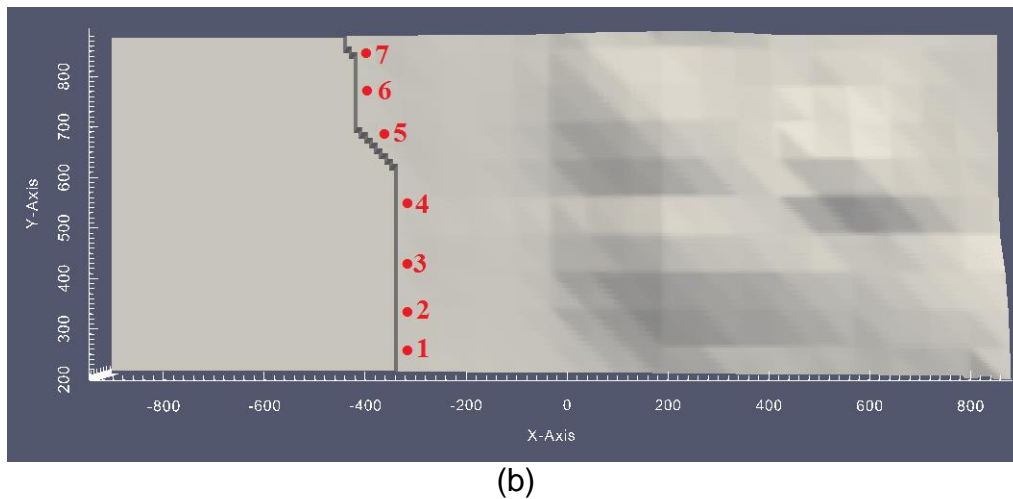


Figure 3.(a) Final 3D model for the simulation. (b) Seven points of observation location.

The setup for propagation and inundation is shown in Table 1. During the simulation, evolution of wave height is recorded. There are 7 different places of wave observation as shown in Fig. 3b. The record of tsunami inundation height from the tsunami simulation is shown in Fig. 4 & 5.

Table 1. Properties at the boundary of the SPH model

Number of particles	Total simulation step	$\Delta t$	Distance between particles
44,100,000	440	0.1	1

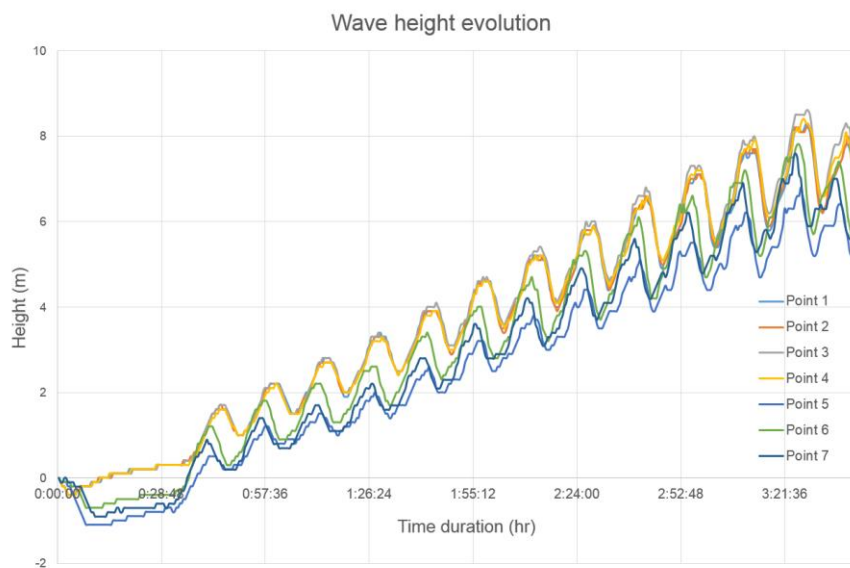


Figure 4. Wave height evolution at the observation points

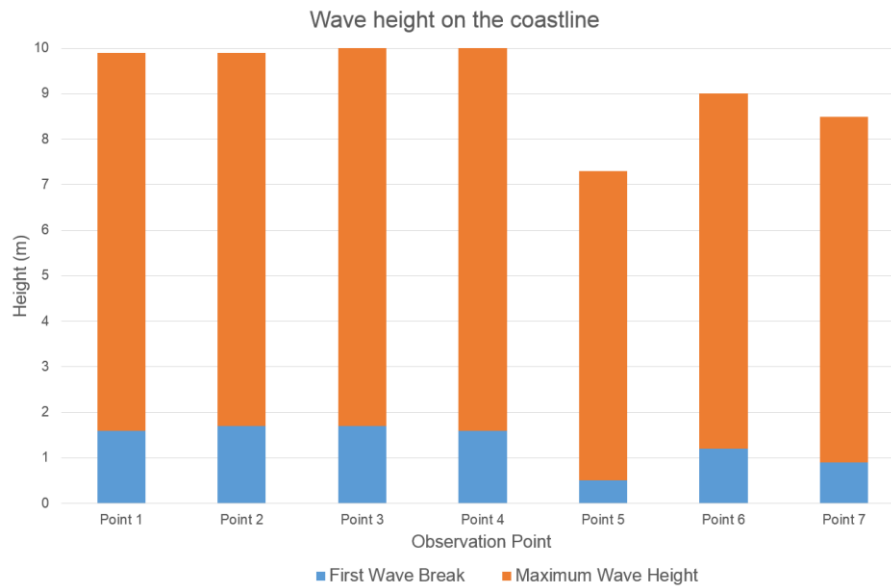


Figure 5. Height of first wave break and maximum inundation at every observation points

## CONCLUSION

In this study, mesh-based and mesh-less numerical method are coupled to simulate tsunami event. We modeled 2004 Indian Ocean tsunami and observed the wave inundation on the coastline. We also observed the evolution of tsunami wave in seven observation points along the coastline. This new method provide improved knowledge of tsunami generation, propagation, and inundation. The knowledge that will be helpful for city planner and disaster mitigation manager, especially in the tsunami prone area.

SPH model itself is developed around 30 years ago, the limitation of computational power hinder its development and application in engineering fields. Recent progress on parallel GPGPU computing provides opportunity to implement large scale SPH models with up to millions of particle in a reasonable time at a reasonable cost. The results shows how this advance in technology can be used for the risk assessment of civil infrastructure systems.

Improvement of SPH model and GPGPU processing should be significant benefit for tsunami research. Large urban area will be analyzed in a greater detail and a full probabilistic approach can be incorporated in the assessment. This will increase the accuracy of tsunami risk assessment on every possible infrastructure networks located in the observation area (i.e., highways, power grid, and emergency routes).

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