A Research Report

On

Computer Simulation of 2011 East Japan Earthquake and Tsunami

SCHOOL OF SCIENCE
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Acknowledgement

It was a great experience for me to be part of University of Tokyo Research Internship Program (UTRIP). A summer project is a golden opportunity to learn the things from experienced people and to use the theoretical knowledge to solve a real life problem. I had always been attracted towards research for the sheer proposition of having the freedom to explore new uncharted territories, of having the possibility to learn concepts which don't exist in regular books. I consider myself very fortunate and honoured to work with so many wonderful people who helped me to complete the project and enhance my skills.

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Computer Simulation of 2011 Tohoku Tsunami

1. Introduction

A giant earthquake of Mw 9.0 (according USGS) occurred near the east coast of Honshu, Japan, on 11th March 2011. This earthquake was fourth largest of the world and largest in Japan's history. It produced devastating tsunami disaster causing around 20,000 casualties and severe damage to Fukushima Nuclear Power Plant.

Through this project an attempt has been made to model the 2011 Tohoku tsunami numerically to see the coastal behavior of tsunami wave in coastal region if any similar tsunami recurs. Also this model can be used for preparing database for tsunami early warning systems.

2. Area of Study

The 2011 Tohoku earthquake was result of continuous subduction of Pacific plate beneath north Honshu continental plate at a rate of about 83 mm per year (USGS). In this area other major earthquakes with tsunami had occurred in 1896 and 1933. The study area is shown in figure with epicenter for 2011 Tohoku earthquake.

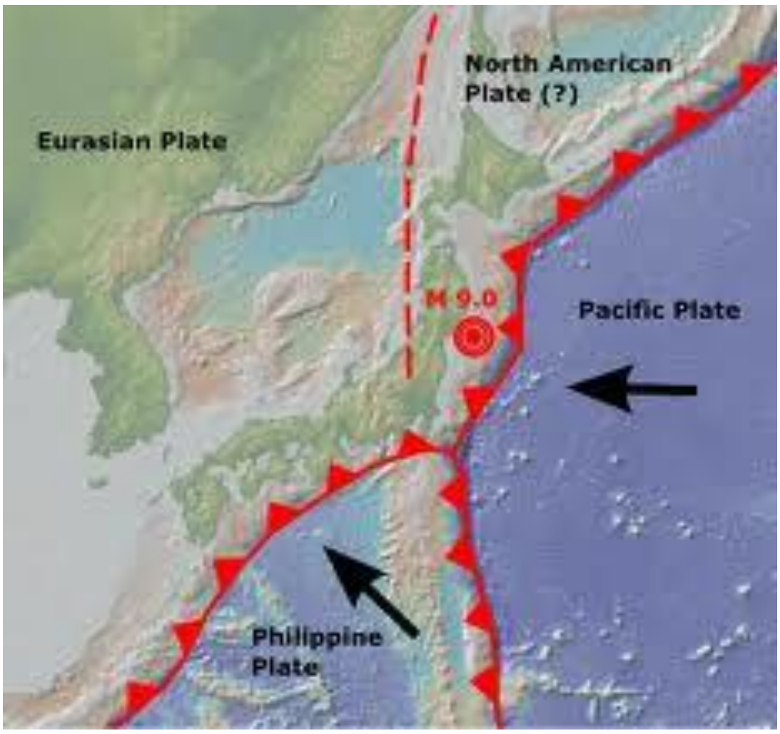


Figure 1: Study area for 2011 Tohoku tsunami where arrows are showing direction of movement of tectonic plates.

3. Tsunami Modeling

The objective of tsunami modeling research is to develop numerical models for faster and more reliable forecasts of tsunamis propagating through the ocean and striking coastal regions.

3.1 Modeling Approaches

3.1.1 Forward Modeling: From given initial condition, it computes the propagation of tsunami waves in the ocean and calculates the tsunami arrival times and run up heights along the coasts. For this detailed topographic and bathymetric data is required.

3.1.2 Inverse Modeling: In this approach tsunami sources are quantified based on observations. Tsunami observations including instrumental sea level data and run up heights are used for modeling and quantifying tsunami sources. Also earthquake fault parameters are obtained by waveform inversion of tsunami data.

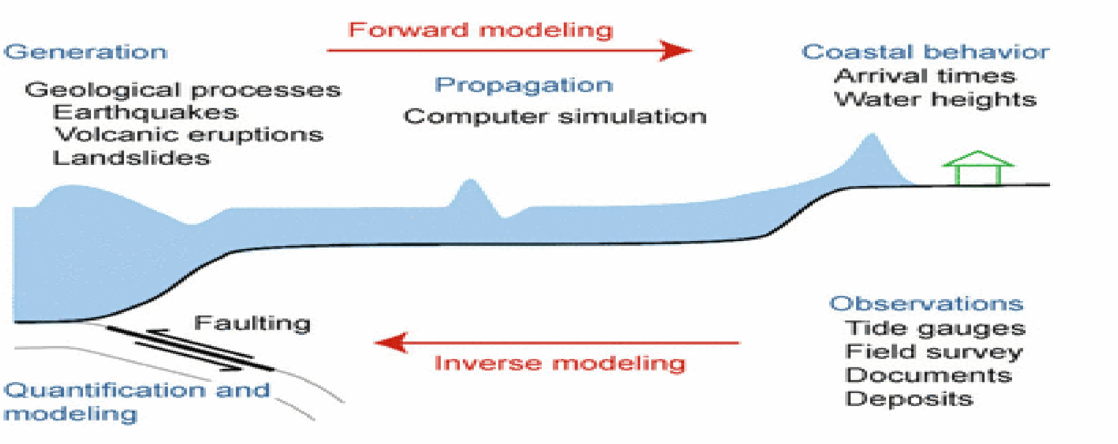


Figure 2: Tsunami modeling and its approaches. Courtesy: Tsunamis, Inverse Problem of [2], Satake, 2011, Extreme Environmental Events.

3.2 Forward Modeling

It consists of three stages:
i) Generation
ii) Propagation
iii) Coastal behavior

3.2.1 Generation

It includes estimation of initial disturbance at the ocean surface due to the earthquake triggered deformation at the sea floor.

Once the initial conditions are provided, propagation and coastal behavior can be numerically computed for an actual bathymetric and topographic data. Since initial conditions associated with tsunami generation process is not well known, tsunami source is estimated indirectly on the basis of seismological analysis.

Here, Okada's model [1] has been used to calculate the sea floor deformation and thus provides initial condition required for tsunami propagation. Basic parameters required as input for Okada's model are nine components of fault plane.

Nine components of fault plane:-

- Latitude, longitude and top depth (d) of edge
- Strike (θ), dip (δ) and rake angle(λ)
- Fault length (L), width (W) and net slip (U)

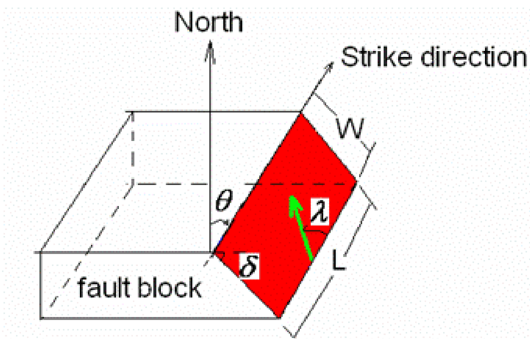


Figure 3: Different components of a fault plane.

Okada model is derived from a Green's function solution to the elastic half space problem. Uniform displacement of the solid over a finite rectangular patch specified using the parameters described above, when inserted in a homogeneous elastic half space at a distance 'd' below the free surface, leads to a steady state solution in which the free surface is deformed. This deformation is used as the seafloor deformation. Of course this is only an approximation since the actual seafloor in rarely flat, and the actual earth is not a homogeneous isotropic elastic material as assumed in this model. However, it is often assumed to be a reasonable approximation for tsunami modelling, particularly since the fault parameters are generally not known very well even for historical earthquakes.

3.2.1.1 Calculation of fault parameters

When an earthquake occurs, seismic waves propagate and are observed by seismometers installed on the land and ocean. Based on the observation seismic moment is computed by instrument. Based on the arrival of P and S waves it computes source location. Further rupture length, width and net slip is calculated as follows:

$$M_w = \frac{2}{3} \log M_0 - 10.7$$

Moment magnitude,

Rupture Area, A = 10^ (-3.49+0.91*M_w) where, 'L' length in km

Rupture length, L = 10^ (-3.22+0.69*M_w) (Wells and Coppersmith [3], 1994)

Rupture width, W = Area/length

Net slip, U = M_o / μLW where, μ is elastic modulus of crust

Alternatively, above parameters can also be calculated from aftershocks distributions as shown in figure 4.

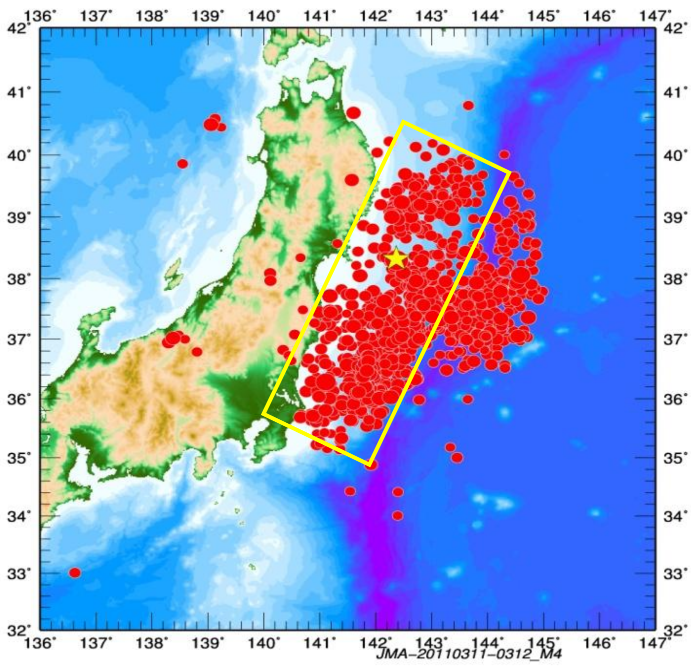


Figure 4: Aftershocks of 2011 Tohoku earthquake. (Based on 2011_03_11 – 2011_03_12 JMA data)

Fault parameters for 2011 Tohoku earthquake are following:-

Strike = 203°, Dip = 10°, Rake = 88°

Epicenter: 38.297° N, 142.372°E (From USGS Earthquake data)

M_o = 5.31 x 10^29 dyne-cm (Global CMT Project Moment Tensor solution)

L = 383 km, W = 146 km, d = 5 km

Slip = 21.45 m,

Edge location:- Lat: 38.6° N

Lon: 143.6° E (Obtained from aftershocks distributions, Fig.4)

Contour interval: 0.35 m

3.2.1.2 Surface displacement

Initial waveform obtained from Okada's model varies with fault parameters. Also surface deformation due to 2011 Tohoku earthquake has been calculated using obtained fault parameters and are shown in figure 5.

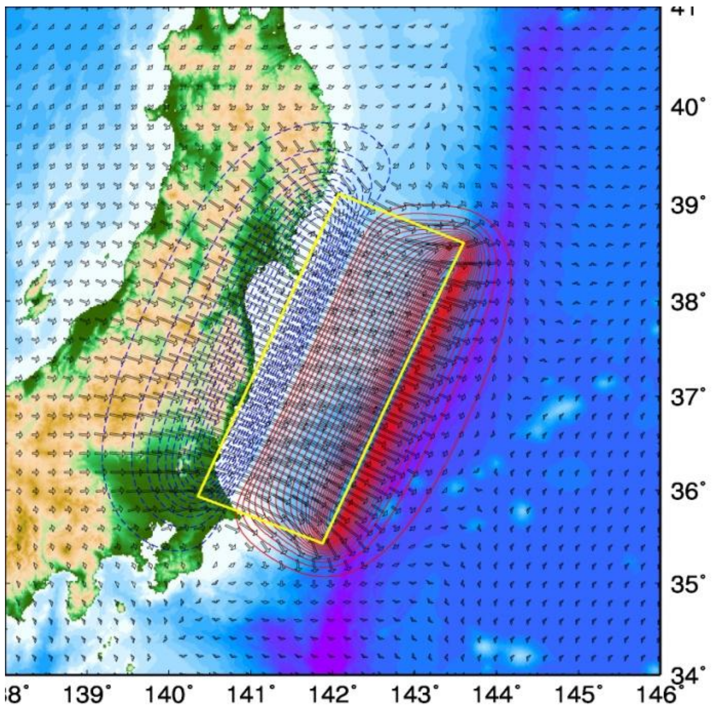


Figure 5: Surface displacement due to 2011 Tohoku earthquake based on Okada's Model.

In Figure 5 vertical displacements are shown by contour lines where red and blue lines represent upliftment and subsidence respectively. Arrow represents horizontal movement of surface. There was maximum upliftment and subsidence of 8.42 m and 4.52 m respectively while maximum horizontal movement of 15.21 m was estimated.

3.2.2 Propagation

Assuming long waves and including the bottom friction and the Coriolis force, equations for tsunami propagation in two dimensions are following:

Equation of motion based on momentum conservation:-

$$\frac{\partial V_x}{\partial t} = -V_x \frac{\partial V_x}{\partial x} - V_y \frac{\partial V_x}{\partial y} - fV_y - g\frac{\partial h}{\partial x} - C_f \frac{V_x\sqrt{V_x^2 + V_y^2}}{d+h}$$

$$\frac{\partial V_y}{\partial t} = -V_x \frac{\partial V_y}{\partial x} - V_y \frac{\partial V_y}{\partial y} - fV_x - g\frac{\partial h}{\partial y} - C_f \frac{V_y\sqrt{V_x^2 + V_y^2}}{d+h}$$

Equation of continuity based on mass conservation:-

$$\frac{\partial h}{\partial t} = -\frac{\partial}{\partial x}\{V_x(h+d)\} - \frac{\partial}{\partial y}\{V_y(h+d)\}$$

Where f is Coriolis parameter
C_f is dimensionless bottom frictional coefficient
V_x , V_y are depth- averaged velocity in X and Y directions.

Here positive X direction is considered as east and positive Y direction is considered as south. Computation has been done using finite differences approach with staggered grid (Leap-frog) scheme. The Courant-Friedrichs-Lewy (CFL) stability condition used is following:

$$\Delta t \leq \frac{\Delta x}{\sqrt{2gd}}$$

Physically, it means that time step Δt must be equal or smaller than the time required for the disturbance to travel the spatial grid size. These are boundary conditions provided for computation:

i) $V = 0$ at land ocean boundary with assumption of total reflection of energy on the coast.

ii) Radiation condition at open boundary to outside of computational region i.e. waves go out of computational region keeping their slopes same.

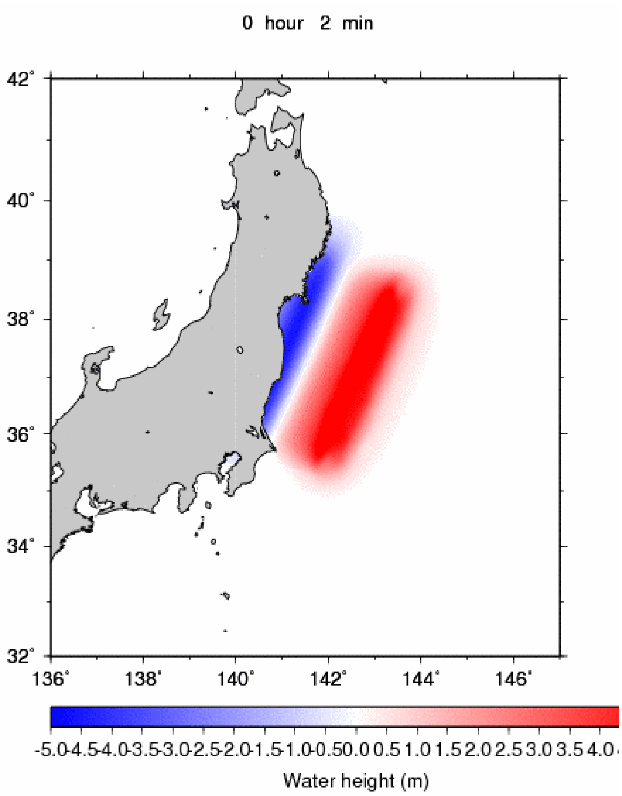
All these input conditions, tsunami propagation formula and boundary conditions are incorporated in a program written in FORTRAN 77 language which includes subroutine files for Okada's model.

3.2.3 Coastal behavior

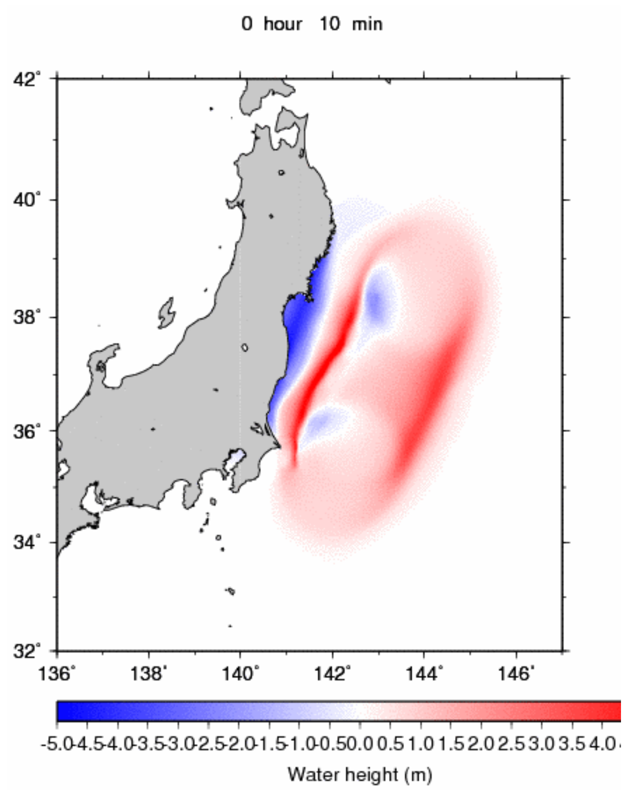
Run up height and arrival time at any point of land ocean boundary can be observed from output file of program. For 2011 Tohoku tsunami, tsunami waves struck Sanriku coast near Miyako city after 28 minutes of and Sendai coast after 65 minutes of earthquake.

4. Results

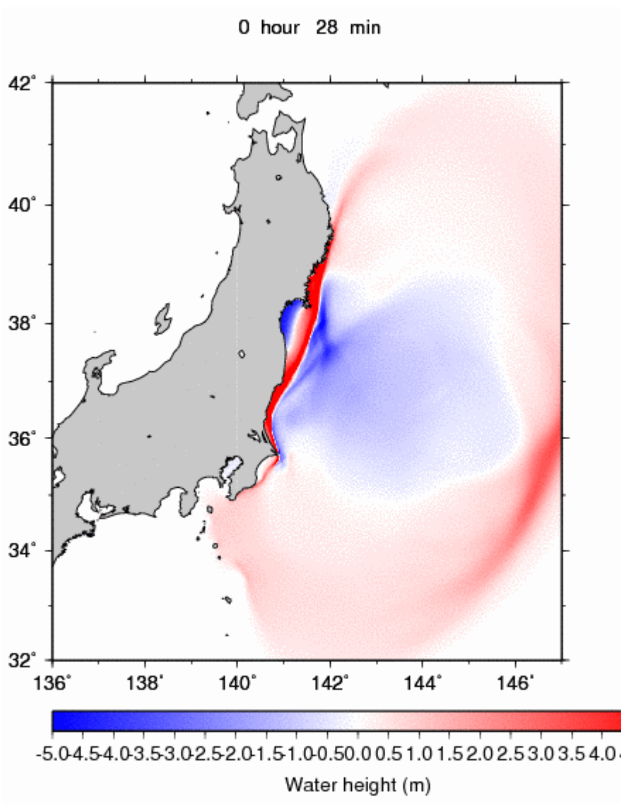
The results of simulation of 2011 Tohoku tsunami are shown in figure. Run up height and arrival time at coast can be computed from these figures.



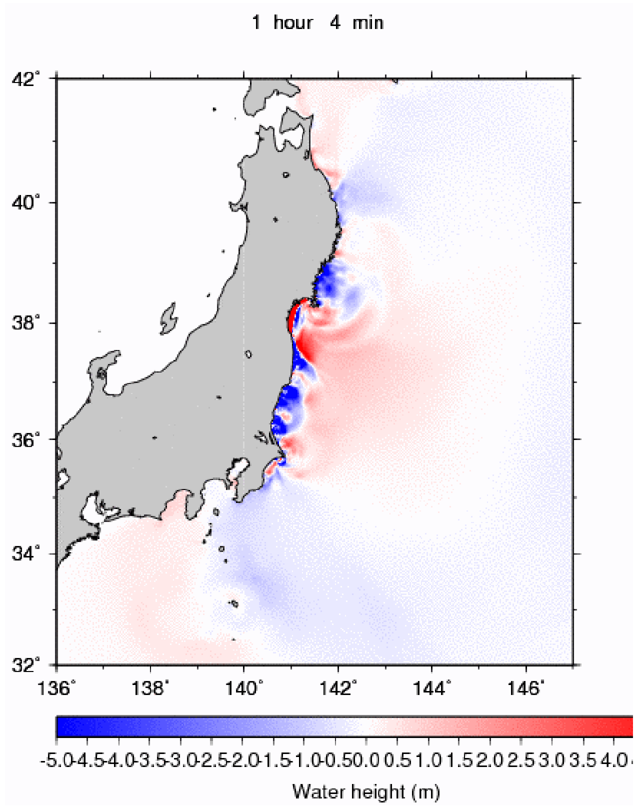
6(a)



6(b)



6(c)



6(d)

Figure 6: Tsunami waves after 2 minutes Fig. 6(a) and 10 minutes Fig. 6 (b). Tsunami waves struck Sanriku coast and Sendai coast in 28 minutes. Fig. 6(c) and 65 minutes Fig. 6(d) respectively.

5. Scope for Improvement

Like every simulation it is also based on certain assumptions, mathematical approximations and input and boundary conditions. Since tsunami generation in ocean is not directly observable, input condition is provided on the basis of indirect seismological analysis using Okada's model. In Okada's model it has been assumed that earth is a homogeneous isotropic elastic material which is not true in real case.

In boundary condition it has been assumed that total energy is reflected at land ocean boundary which is not true in real case. Therefore if there will be improvement in input and boundary conditions, result will be more accurate.

References

[1] Okada Y (1985) Surface deformation due to shear and tensile faults in a half space. *Bulletin of the Seismological Society of America* 75: 1135 - 1154

[2] Satake, K. Tsunamis, Inverse problem of, in W.H.K. Lee (ed.) Complexity in Earthquakes, Tsunamis, and Volcanoes, Encyclopedia of Complexity and System Science, Springer, 2009

[3] Wells D L and Coppersmith K J (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement. *Bulletin of the Seismological Society of America* 75: 974 - 1002