TSUNAMI SIMULATIONS FOR A PROTOTYPE OF TSUNAMI DATABASE IN SOUTHWESTERN SUMATRA

Sugeng Pribadi [*]
MEE06016

Supervisor : **Yushiro Fujii** [**]
Yohei Hasegawa [***]
Yosuke Igarashi [***]

ABSTRACT

The purpose of this study is to create a prototype of tsunami database for tsunami warning system. Firstly we fix the locations of forecast and coastal points along the coast of Padang, Muarabunga and Bengkulu. We also set the source points covering the deformation area of the 1833 Bengkulu, Sumatra earthquake (M_w 8.9) as the real case. The number of source points is 33 with 4 magnitudes (M_w 8.5, 8.0, 7.5 and 7.0) and 2 depths (0 and 10 km) for each source point. The total number of computation is 231 for the source points and 1 for the real case. We calculate a seafloor deformation due to the fault, which is assumed as initial condition of tsunami source. For tsunami simulation, TUNAMI-N2 (Tohuku University's Numerical Analysis Model for Investigation of Near-field Tsunami, No-2) and TTT (Tsunami Travel Time) are used to obtain the estimation of tsunami heights and arrival times, respectively for quantitative tsunami forecasting. The calculated tsunami heights by using Green's Law show higher pattern than those at some coastal points and may give more realistic values for tsunami estimation. The computed results are stored in appropriate file system for tsunami database. When an earthquake occurs, the values will be retrieved by the interpolation of the data from the database for the information of tsunami warning. We have also made the message format which contains information of vulnerable coastal areas, predicted tsunami arrival times and tsunami heights.

Keywords: Tsunami Heights and Travel Times, Tsunami Simulation and Database, Tsunami Warning.

INTRODUCTION

Indonesia is one of the most seismically active countries. Some large earthquakes have generated tsunamis. The huge tsunami generated by the 2004 Sumatra earthquake, caused more than 200,000 deaths. Since 2005, Indonesia Meteorological and Geophysical Agency (BMG) has been establishing Tsunami Early Warning System (TEWS) for giving fast warning by seismic auto-detection analysis. The system is still under developing to reduce the false alarm. We refer to tsunami database by Japan Meteorological Agency (JMA) which contains tsunami simulation results to be used for tsunami warning system by calculating tsunami heights and tsunami travel times from determined hypocenter.

Tsunami Simulation and Database

[*] Meteorological and Geophysical Agency (BMG), Jakarta, Indonesia
[**] International Institute of Seismology and Earthquake Engineering (IISEE), BRI, Tsukuba, Japan
[***] Japan Meteorological Agency (JMA), Tokyo, Japan

The purpose of this study is to create a prototype of tsunami database. We select forecast and coastal points as the output points along the coastal area, and then calculate a seafloor deformation due to fault, which is assumed as initial condition (tsunami source). The tsunami simulation softwares of TUNAMI-N2 and TTT provide the estimation data of the tsunami heights and tsunami arrival times in those areas. Then the results are stored in tsunami database to be retrieved by interpolation method for tsunami warning information.

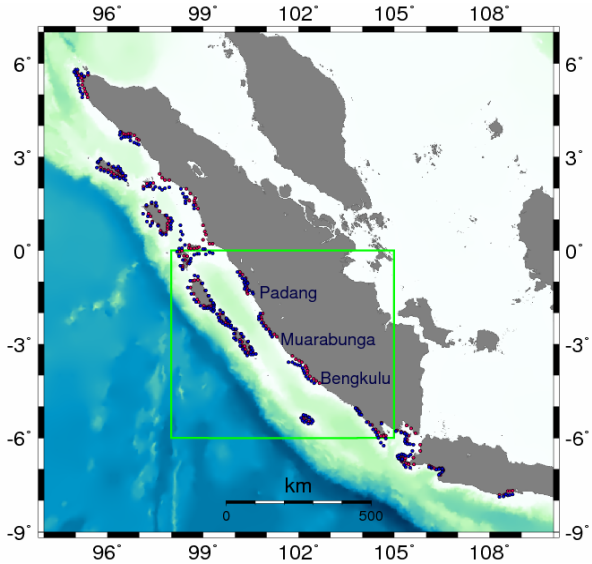

Figure 1 Location of 526 output points along the coast of Sumatra and Java Islands with the bathymetry grid contour of each city. Red dots are coastal points. Blue dots are forecast points. Green lines box shows the site study.

Scope of Study Area

The scope of this study is coastal area of southwestern part of Sumatra which covers the coordinates latitude 0° - 6° S, longitude 98° - 105° E (Figure 1). We concern the big cities of Padang, Muarabunga and Bengkulu on southwestern coast of Sumatra, which are very close to the 1833 Sumatra earthquake (M_w 8.9) source as the evidence of large tsunami may indicate high probability of tsunami in the future (Siripong, 2007).

METHOD OF ANALYSIS

Bathymetry Data

The accurate bathymetric data is essential for tsunami numerical simulation because the phase velocity of tsunami or long wave depends on the water depth. The General Bathymetric Chart of the Oceans (GEBCO) is available for global area and can provide the bathymetry data for calculating tsunami travel times and waveforms. The computation area is shown in Figure 1. The interval of grid space is 1 arc-minute (~1850 m).

Output points for Tsunami Simulation and Green's Law

We fix the forecast points offshore along 50 m depth contour and coastal points near the land with random interval distances. The total number of forecast and coastal points is 526 in 20 cities along west coast of Sumatra and south coast of Java. The output point parameters include station name, latitude, longitude on grid space. We concern only three vulnerable cities of Padang, Muarabunga and Bengkulu. The number of output points is 33 for coastal points and 33 for forecast points.

We use the Green's Law calculation to avoid the longer computational time with finer grid system. The Green's Law is needed to obtain the reliable tsunami heights for coastal point from that of forecast point at the sea using energy conservation law along the ray (JMA, 2007). Tsunami height in the coast is defined as,

$$H = \sqrt[4]{\frac{h_1}{h} H_1}$$

, where H_1 and h_1 are tsunami height and sea water depth in the forecast point, H and h are tsunami height and sea water depth in the coastal point.

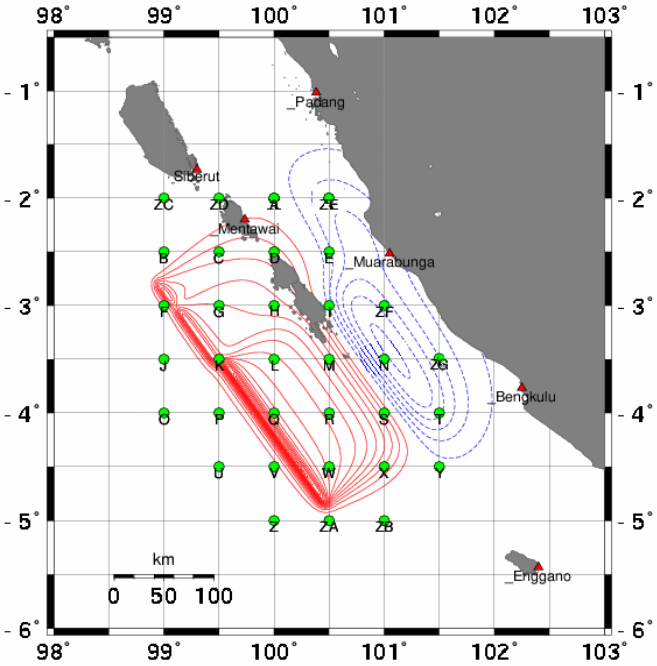

Figure 2 Source points (green dots) location covering the crustal deformation area of the 1833 Bengkulu, Sumatra earthquake (Borero, 2006). Red triangles denote cities. Contour interval is 0.2 m. Red contour is uplift area. Blue contour is subsidence area.

Source Points

We fix the source point which is located in the center of tsunami source area (fault). In this study, we define the source points covering seafloor deformation caused by the 1833 Sumatra earthquake as the real case. The number of source points is 33 with 4 magnitudes (M_w 8.5, 8.0, 7.5 and 7.0) and 2 depths (0 and 10 km) for each source point. The total number of computation is 231 for the source points and 1 for the real case (Figure 2).

Initial Condition

An initial profile of tsunami source can be considered to be the same as a deformation of sea bottom (Okada, 1985) due to earthquake. We refer the source model by Borero (2006), and Natawidjaja (2006) to determine the real case fault parameters such as coordinate of the tsunami source point, depth and angle of strike, dip and slip. For the real case, Natawidjaja (2006) mentioned that the 1833 Sumatra earthquake (M_w 8.9) had 3 subfaults with different rupture sizes. For the other 33 source points, we used single segment. For the real case, all of the strike angles are parallel to the direction of Sunda trench axis that is assumed as 325 degree from the north clockwise. All of the dip and slip angles are assumed as 10 and 90 degree, respectively. The depth of top left corner is 5 km. For each source point, we assume the same strike angle of 325 degree, dip angle of 45 degree, slip angle of 90 degree, and two depths of 0 and 10 km for top left corner.

For each source point to calculate fault parameter, we use Scaling Law is controlled by magnitude (Tatehata, 1997). The formulas are:

$$\log L = 0.5M_w - 1.9 \ , \quad W = \frac{L}{2} \ , \quad \log U = 0.5M_w - 1.4$$

, where L is length (km), W is width (km), U is slip (m), M_w is moment magnitude.

For calculation of depth of fault center (*DFC*), we use depth of top left corner (*TLC*) of fault, which is input of tsunami simulation. Here, δ is dip angle which is assumed as 45 degree. The equation is defined as:

$$DFC = \cos\delta \cdot \frac{W}{2} + TLC \ .$$

Basic Equations

We use near field tsunami propagation theory in shallow sea (non-linear) with constant grids of Cartesian coordinates. The governing equations of 2-D shallow water theory are denoted by two basic equations of continuity and momentum equations (Koshimura, 2007) as follows.

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)=-gD\frac{\partial \eta}{\partial x}-\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)=-gD\frac{\partial \eta}{\partial y}-\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}$$

$$M=\int_{-h}^{\eta} u dz=\bar{u}(\eta+h)\ ,\quad N=\int_{-h}^{\eta} v dz=\bar{v}(\eta+h)\ ,\quad D=h+\eta$$

, where u and v are water particle velocities in the x and y directions, $\bar{u}$ and $\bar{v}$ are average velocities, D is total water depth, h is water depth, η is water elevation, M and N are discharge fluxes in x and y directions, g is gravitational acceleration, n is Manning roughness coefficient, t is time.

TUNAMI-N2 and TTT

TUNAMI-N2 developed at DCRC (Disaster Control Research Center, e.g. Imamura et al., 2006), is the numerical analysis model for investigating near field tsunami. In this study, we use grid interval (Δx, Δy) of 1850 m, gravity acceleration (g) of 9.8 m/s^2, and maximum bathymetry depth (h_{max}) of 7,271 meter. We set the time temporal interval (Δt) as 2 seconds which is less than CFL condition. This temporal interval is used to define sampling time of waveforms and snapshot time for tsunami movie files. We can calculate maximum heights of tsunami at the output points.

TTT developed by Paul Wessel, Geoware, can calculate tsunami travel times using Huygen's principle on a geographic latitude and longitude grid of each output point derived from a supplied bathymetric data such as GEBCO. By using TTT software, we can prepare the inverse refraction diagram to calculate inverse travel time of tsunami from the coastal point to the source. It is useful to determine the exact and minimum value of tsunami travel times from each output point into the outermost part of deformation area. We only take the minimum value as the fastest travel time to the coastal point by "min-max" commands of GMT. We extract all tsunami travel times from whole inverse refraction diagrams of all output points.

RESULT AND DISCUSSION

From all of the tsunami simulation results, we chose several cases as the samples. We choose the variation data of tsunami heights and tsunami travel times in each coastal point depending on different source points, then compare with the Green's Law calculation.

For tsunami heights (Figure 3A), tsunami sources closer to the coastal area cause higher tsunami heights. The source of ZE (2.0° S, 100.5° E) makes tsunami amplitude higher in Padang and some part of Muarabunga coastal points. The real case source and ZG source (3.5° S, 101.5° E) cause high tsunami amplitudes half of the coastal points in Bengkulu city. For tsunami travel times (Figure 3B), the most of far source points into the coastal point give longer times of tsunami travel. The source ZE and E (2.5° S, 100.5° E) cause longer tsunami travel time into almost Bengkulu city coastal points and real case make longer tsunami travel time into almost Padang city coastal points.

For tsunami heights of Green's Law calculation, more closed coastal point to the source give higher value, like as Bengkulu coastal point. For the real case (M_w 8.9), the Green's Law heights (green line) is more stable by giving higher tsunami heights. However, the coastal calculation of Muarabunga city and some part Bengkulu city, show the deviation (Figure 3C). This data indicate that we could not use the Green's Law at some forecast points for tsunami warning issue.

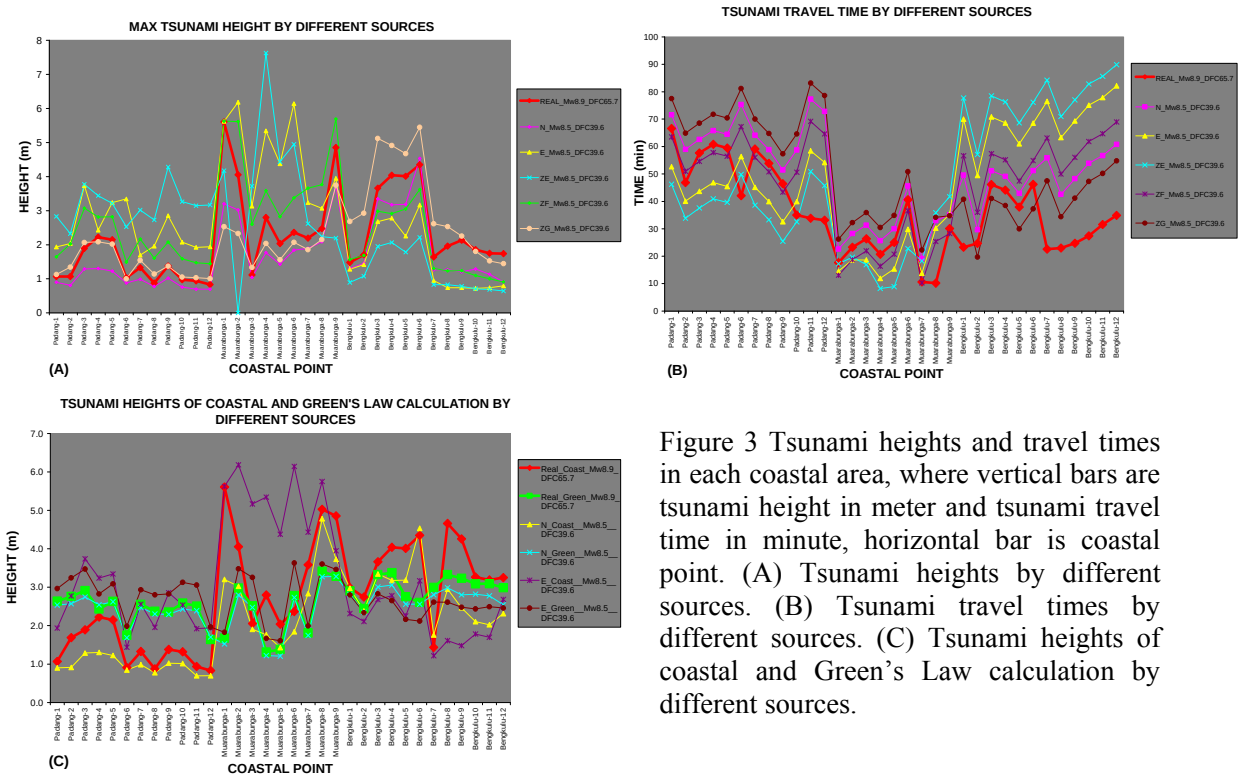

Figure 3 Tsunami heights and travel times in each coastal area, where vertical bars are tsunami height in meter and tsunami travel time in minute, horizontal bar is coastal point. (A) Tsunami heights by different sources. (B) Tsunami travel times by different sources. (C) Tsunami heights of coastal and Green's Law calculation by different sources.

TSUNAMI DATA BASE

Database Storing and Interpolation Method

Originally data format of simulation results are in the text format. Then, we put the data in Excel file format as the first database storing system. We have to change the data into MySQL format referring to JMA's tsunami data base. Then, the data should be put in hypocenter table. Each hypocenter data (hyp point) has some values of latitude and longitude coordinate, focal mechanism, magnitudes, depths, and simulation results. Each simulation result contains the estimation values of tsunami heights and tsunami travel times for all coastal points. We can retrieve the interpolated result by searching four closest hyp points surrounding a present determined hypocenter. The interpolation method consists of epicenter location interpolation, magnitude-depth interpolation, maximum risk interpolation, and magnitude-depth extrapolation (Kiyomoto, 2007).

Tsunami Warning Information

We made a message format for tsunami warning information, which contains tsunami arrival times, and tsunami heights for all vulnerable coastal areas. Tsunami arrival time is used to know when tsunami will reach to the coastal area in the exact local time after present origin time of earthquake. Arrival time is summation of tsunami travel time estimation and origin time, which is shown as hours, minutes and seconds unit. The tsunami warning message contains several types of tsunami warning information which based on tsunami height (H) criteria. Those information are major tsunami warning ($H \geq 2$ m), tsunami warning ($1 \leq H < 2$ m), and tsunami warning advisory ($H < 1$ m).

CONCLUSION

In this study we have created a prototype of tsunami database. We chose the 1833 Bengkulu earthquake as the evidence of large tsunami that occurred in southwestern coast of Sumatra. The study started from fixing a mount location of forecast points and coastal points as the output points along the coast of Padang, Muarabunga and Bengkulu, then calculating a seafloor deformation due to fault that is assumed for initial condition of tsunami source. Tsunami simulation using the tsunami softwares TUNAMI-N2 and TTT provided the estimation data of tsunami heights and tsunami arrival times in those areas for tsunami forecasting.

According to the result of analysis, we found that the coastal points which are far from the source have the smallest tsunami height and the longest tsunami travel time. On the other hand, most of the tsunami sources close to the coastal area cause higher tsunami height. Tsunami travel times almost have the similar values between different magnitudes and depths at the same source points. The calculated tsunami heights by using Green's Law show higher pattern than those at some coastal points and may give more realistic approximation for tsunami estimation.

The computed results are stored in appropriate file system for tsunami database. When an earthquake occurs, the values will be retrieved by the interpolation of the data from the database for the information of tsunami warning. We have also made the message format which contains information of vulnerable coastal areas, predicted tsunami arrival times and tsunami heights. The tsunami warning information gives early warning for evacuation and precaution.

ACKNOWLEDGEMENT

We thank to Dr. B. Shibazaki (IISEE), Dr. T. Hara (IISEE), Mr. M. Kiyomoto (JMA), and all lecturers for their guidance to complete this study.

REFERENCES

Borrero, J.C., et al., 2006, PNAS, U.S.A., 103, 52, 19673-19677.
Imamura, F., et al., 2006, TSUNAMI MODELLING MANUAL, DCRC, Tohuku University, Japan, 72pp.
Japan Meteorological Agency (JMA), 2007, Lecture Note of JMA, Tokyo, Japan.
Koshimura, T., 2007, Lecture Note of IISEE, Tsukuba, Japan, 19pp.
Kiyomoto, 2007, Lecture Note of JMA, Tokyo, Japan.
Okada Y., 1985, Bulletin Seismological Society of America, 75, 1135-1154.
Natawidjaja, D.H., et. al., 2006, Journal of Geophysical Research, 111, B06403, 37pp.
Siripong, A., 2007, ICUS Newsletter, The Univ. of Tokyo, Japan, 6, 4, 1-3.
Tatehata, 1997, Perspectives on Tsunami Hazard Reduction, 175-188.