PROTOTYPE DATABASE FOR TSUNAMI EARLY WARNING SYSTEM WITH DATA ASSIMILATION IN MALAYSIA

CHAI Mui Fatt* **Supervisor : Yushiro Fujii****
MEE07171

ABSTRACT

In order to create a prototype of tsunami database for tsunami early warning system with data assimilation in Malaysia, we located 16 source points in total around the Andaman Sea with 4 magnitudes (M_w6.5, 7.0, 7.5 and 8.0) and 4 depths (0, 10, 20 and 30 km). The coastal and forecast points are located along the Malaysian coastal area at 1 m and 30, 40, 50 and 60 m of bathymetric contour depth with random interval distance, respectively. In numerical simulation, TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis, No.2) is used to calculate the tsunami waveforms at the output points. Tsunami arrival times at the coastal points are calculated using inverse tsunami travel time by TTT (Tsunami Travel Time). Tsunami database was constructed by using MySQL database which contains of 256 scenario earthquakes that cover historically most active subduction zone around the Andaman Sea. The nearest surrounding data points of a determined hypocenter can be retrieved from database by interpolation, extrapolation and two maximum risk methods. In tsunami data assimilation, TUNAMI-F1 (Tohoku University's Numerical Analysis Model for Investigation of Far-field tsunamis, No.1) is used to calculate the tsunami waveforms at the buoy station of Malaysia. Green's functions, which are calculated tsunami waveforms from faults assigned 1.0 m of slip, are prepared for 16 model sources. In two inversion tests, the initial conditions are precisely resolved by non-negative least squares method. For inversions of two real cases, the slip is almost resolved at the nearest fault and has shown instability in slip distributions for whose epicenter is located closer and slightly out from model sources, respectively.

Keywords: Numerical Simulation, Tsunami Database, Tsunami Data Assimilation.

INTRODUCTION

The Sumatran mega-thrust earthquake that occurred on 26 December 2004 in Indian Ocean has triggered massive tsunami which devastated along the northwest coastal areas of Peninsula Malaysia. In response to this event, Malaysian government has decided to set up the Malaysian National Tsunami Early Warning System in 2005. The purpose of this study is to create a prototype of tsunami database for tsunami early warning system with data assimilation in Malaysia.

THEORY AND METHODOLOGY

Bathymetry Data

In this study, we used GEBCO (The General Bathymetric Chart of the Oceans) with spatial grid size of one arc-minute (~1850 m) to calculate the tsunami travel times and waveforms. The map of bathymetric data in the region of study area is shown in Figure 1.

---

*Malaysian Meteorological Department (MMD), Malaysia
**International Institute of Seismology and Earthquake Engineering (IISEE), Building Research Institute (BRI), Tsukuba, Japan

Tsunamigenic Earthquake Locations

The tsunamigenic earthquake events were searched through Global Centriod Moment Tensor (CMT) Project catalog search from the year 1976 until 2007 (http://www.globalcmt.org/CMTsearch.html). The magnitude and depth range between 6.3 to 10 and 0 to 100 km, respectively. Epicenters chosen lie within 3^0N to 12^0N and 90^0E to 103^0E in latitude and longitude, respectively. Comparison is made with other searcher tsunami databases from Integrated Tsunami Database for the World Ocean (WinITDB) and National Geophysical Data Center (NGDC) Tsunami Event Database (http://www.ngdc.noaa.gov) which covers wider data for a year -2000 to 2007. The comparison has shown that the locations of the tsunamigenic earthquake were located along the subduction zone and Sumatra Fault line (Figure 1).

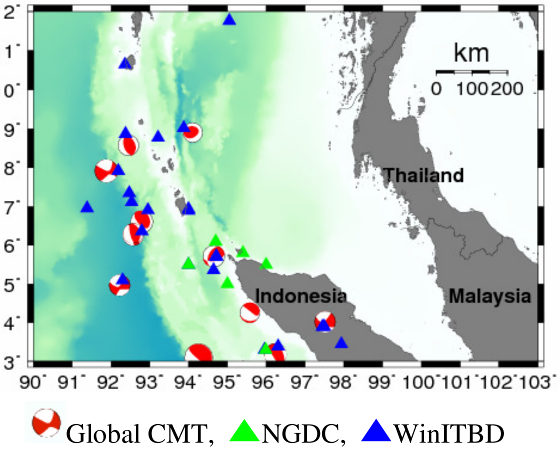

Figure 1. Locations of the tsunamigenic earthquakes with bathymetry data (GEBCO, one arc-minute) in this study area.

Magnitude and Depth

We chosen 4 magnitudes (M$_w$6.5, 7.0, 7.5 and 8.0) and 4 depths (0, 10, 20 and 30 km), based on the historical earthquake events from WinITDB and Global CMT Project catalog search at study source area. The minimum magnitude of M$_w$6.5 was chosen based on the tsunami warning criteria of Malaysian Meteorological Department when distant tsunami more than 200 km from Malaysian coastline exists (e.g. Saw, 2007).

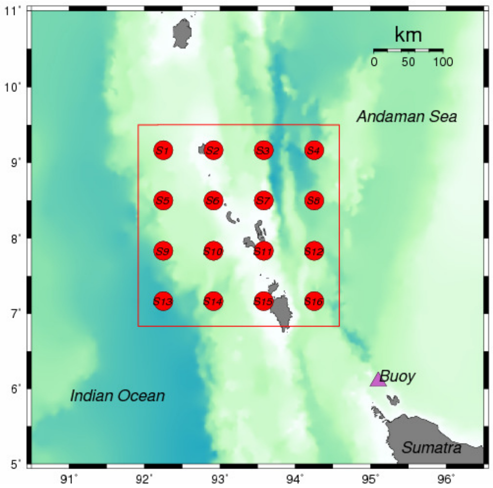

Figure 2. Locations of the 16 source points at Andaman Sea (red circles). The purple triangle shows the location of Malaysian deep ocean buoy.

Source Points

We located 16 source points in total at Andaman Sea northern part of Sumatra which covers the region from 6.83^0N to 9.50^0N and 91.92^0E to 94.58^0E in latitude and longitude, respectively (red line in Figure 2). Each source point is located on the grid with distance interval of 40 arc-minute (~74 km).

Forecast and Coastal Points

17 coastal points and 44 forecast points in total are located along the bathymetric contour depths of 1 m and 30, 40, 50 and 60 m, respectively, with random interval distance. Each bathymetric contour depth of the forecast points is consists of 11 points (Figure 3). The location of the coastal points are placed and searched through Google Earth (2008) considering the most valuable areas for tsunami impacts, denser population areas and tourism attractions. The tsunami heights at the coastal points are estimated by Green's Law.

Green's Law

The Green's Law, conservation of potential energy along the rays (e.g. Satake, 2008), is applied to estimate reliable tsunami heights for coastal points from the forecast points at different bathymetric contour depths. This law is only applicable to direct waves and is not taken account for the reflected waves or edge waves. The tsunami wave front at a forecast point is assumed to be parallel with the one at a coastal point. The tsunami height at a coastal point is calculated by the following equation:

$$h_0 = \left(\frac{d_1}{d_0}\right)^{\frac{1}{4}} h_1$$

Here, h_0 and h_1 are tsunami height at the coastal and forecast point and d_0 and d_1 are water depth at the coastal and forecast point, respectively.

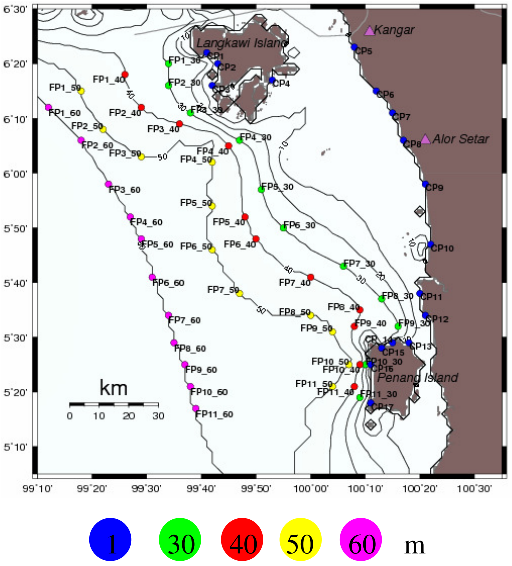

Figure 3. Bathymetry contour map of coastal points (blue dots) and forecast points (green, red, yellow and purple dots).

Initial Condition

An initial profile of tsunami source is assumed to be the same as a deformation of ocean bottom due to earthquake when the wavelength of the ocean bottom is much larger than the water depth (Kajiura, 1963). We used the elastic theory of Okada (1985) to calculate the crustal deformation at the ocean bottom due to a fault motion. In this study, a single segment is applied to all 16 source points. For each source point, we assume that the fault model has the same angle of strike (ϕ) as 340^0 (Fujii and Satake, 2007) which is parallel to the trench axis, dip angle (δ) is 45^0 and rake angle (λ) is 90^0. Other parameters such as slip amount (U) in cm, length (L) and width (W) in km which are controlled by moment magnitude (M_w), are determined by Scaling Law (Tatehata, 1997). The equations of Scaling Law are expressed as follows:

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

Tsunami Travel Time (TTT)

TTT can calculate tsunami travel times on all of the grid points from a supplied bathymetric data using Huygen's principle (e.g. Fujii, 2008). In this study, tsunami travel times were inversely calculated from the coastal points to the source points. The minimum value of tsunami travel time from a coastal point to the grid points of a deformation source area which has absolute value more than 0.04 m is selected as the tsunami arrival time.

Numerical Simulation by Using TUNAMI-N2

TUNAMI-N2 is applied to shallow water theory in shallow and deep seas. The propagation of tsunami which initiated at each fault is numerically solved by using the finite-difference method (Imamura, 1995). The procedures to run the tsunami numerical simulation are described by Fujii (2008). The dimension of calculation area is 781 and 541 grid points for longitude and latitude, respectively, which covers the region from 90^0E to 103^0E in longitude and from 3^0N to 12^0N in latitude. The temporal interval (Δt) is 3 s to satisfy the CFL (Courant Friedrics Lewy) stability condition. The calculation time was set to 12 hours. The total number of computations is 256 cases for the source points.

Tsunami Database

Tsunami database was constructed by using MySQL database which consists of 258 tables, out of which one table for "FP" and "HYP" each, and 256 tables for simulation results. FP table contains the number, longitude, latitude, depth, name and block of the coastal points. HYP table contains the case name, longitude, latitude, magnitude, depth, strike, dip, rake, length, width and slip of the source points. Each table in simulation result contains the number of the coastal points, case name of source point, arrival time of tsunami, maximum tsunami height and its time at coastal points.

Retrieving from Tsunami Database

Input data to retrieve results from the tsunami database are recently determined hypocenter parameters such as longitude, latitude, depth and magnitude. Four corners surrounding the input data point are contained values of longitude, latitude, depths and magnitudes. The tsunami heights at each nearest corner with a determined hypocenter are retrieved from the database. The tsunami heights according the determined hypocenter are retrieved by using epicenter location, magnitude and depth interpolation methods. Otherwise, the extrapolation method is performed when no surroundings data point is available. In maximum risk method 1 or 2, data point which gave the maximum tsunami height at each coastal point among the source points within the circle area with a half of fault length or the rectangular fault area, respectively, is selected as the database output. We assumed that the recently determined hypocenter is located at 93.250^0E and 8.167^0N in longitude and latitude with $M_w8.5$ and 12 km depth, respectively.

Tsunami Data Assimilation

Initial Condition

The deformation on the ocean bottom is computed for each fault with 1.0 m of slip by the equations of Okada (1985). This displacement is used as an initial condition for the synthetic waveform or Green's function from each fault.

Numerical Simulation by using TUNAMI-F1

TUNAMI-F1 is applied to linear theory for tsunami propagation over the ocean in the spherical coordinates system and numerically solves the governing equations by using finite-difference method (e.g. Nagano, 1991). The area of the numerical calculations covers the region from 90^0E to 103^0E in longitude and from 1^0N to 14^0N in latitude. The dimension of calculation area is 781 and 781 grid points for longitude and latitude, respectively. A temporal interval of 3 s was used to satisfy the CFL stability condition. The computation time of numerical simulation was set to 12 hours.

Tsunami Waveform Inversion

The observed tsunami waveform at the buoy station is expressed as a linear superposition of the computed waveforms from all the faults. The slip amount on each fault can be estimated by using the inversion of non-negative least squares method (Lawson and Hanson, 1974). In numerical simulation, 16 single faults are selected with $M_w7.5$ and 20 km depth for each source point. The initial conditions of the Green's functions are tested by two cases in which the slips of 1.0 or 2.0 m of are assigned to a faults. For real case inversions, two cases with $M_w7.5$ and 20 km depth for each were selected as tsunami generation. The locations of the epicenters are closer or slightly out from model sources.

RESULT AND DISCUSSION

Based on the numerical simulation and TTT results, the tsunami heights and arrival times depend on the magnitude and depth of the source. The tsunami heights and arrival times at coastal points are increased and become faster as the magnitude getting higher. As the source depth is getting deeper, the tsunami heights and arrival times at the coastal points are slightly higher and faster, respectively than a shallower source.

The comparison of results shows that tsunami heights at coastal points obtained directly from numerical simulations (CP) have lower values than the ones at forecast points by the application of the Green's Law (GL) calculations for most cases (Figure 4). Therefore, the tsunami heights calculated with Green's Law are more appropriate and applicable for tsunami warning.

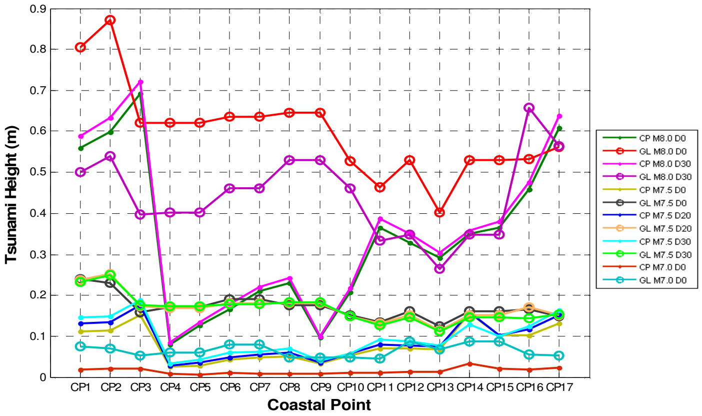

Figure 4. Tsunami heights at the coastal points by different magnitudes and depths.

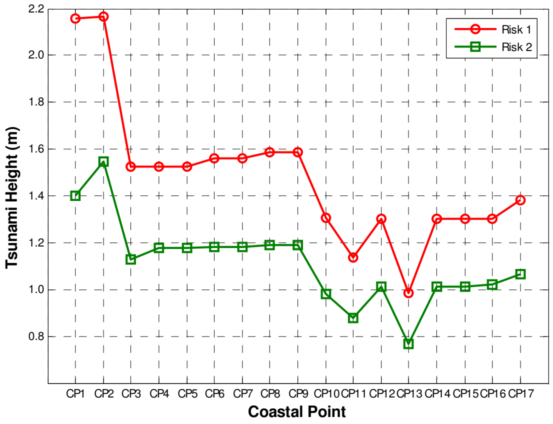

Figure 5. Maximum tsunami heights at the coastal points obtained by the maximum risk method 1 (red line) and 2 (green line).

The database output of maximum risk method 1 has shown that the maximum tsunami height at each coastal point is a combination data from source points of S12 and S8 (red line in Figure 5). For the maximum risk method 2, the source point of S11 has shown the maximum tsunami height at each coastal point and was selected as the database output (green line in Figure 5).

The initial conditions of Test Case 1 and 2 were precisely resolved by the inversion methods and each synthetic waveform is completely agreed with the observed one at the buoy station (Figure 6A and 6B).

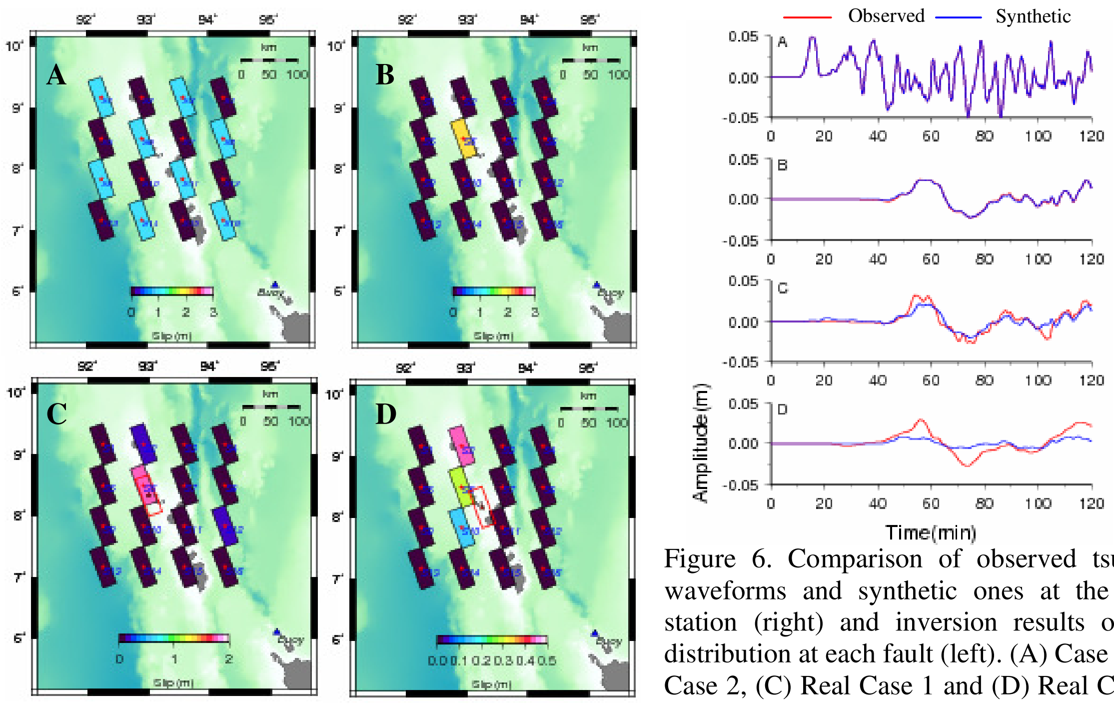

Figure 6. Comparison of observed tsunami waveforms and synthetic ones at the buoy station (right) and inversion results of slip distribution at each fault (left). (A) Case 1, (B) Case 2, (C) Real Case 1 and (D) Real Case 2. The red rectangle is the fault of each real case.

For Real Case 1 (Figure 6C), the largest slip was resolved at fault S6 (1.711 m) which is the vicinity to the epicenter than other faults and the synthetic waveform generally agrees with the observed waveform at the buoy station. However, for the Real Case 2 (Figure 6D) has shown an instability in slip distribution as the largest slip was estimated at fault S2 (0.436 m) and the synthetic waveform is not well reproduced.

CONCLUSIONS

A prototype of tsunami database for tsunami early warning system with data assimilation was successfully constructed. In tsunami database, the nearest data points of a determined hypocenter are retrieved from database by interpolation method. Otherwise, extrapolation method is performed when no surrounding data is available. To optimize the most severe case of tsunami event at each coastal point, two maximum risk methods can be applied.

According to the result of analysis, variation of tsunami heights and tsunami arrival times at coastal points depend on magnitude and depth of the source. The tsunami heights and travel times at coastal points are increased and faster, respectively, as the magnitude becomes larger. On the other hand, the tsunami heights and travel times at the coastal points are slightly higher and faster as the source depth is deeper.

For tsunami data assimilations, the slip amount distributions were determined by using the inversion of non-negative least squares method. The initial conditions of the Green's functions were tested by Case 1 and 2. They were precisely resolved and the synthetic waveform completely agreed with the observed one at the buoy station. For the Real Case 1, the slip distributions are almost resolved at the nearest fault and the synthetic waveform generally agreed with the observed one at the buoy station. However, the Real Case 2 has shown the instability in slip distribution and the synthetic waveform were not well reproduced to match with the observed one at the buoy station.

Combination of the tsunami database by pre-computed scenario earthquakes and the tsunami data assimilation for source estimation will be the useful tool for tsunami forecasting.

AKNOWLEDGEMENT

I would like to express my gratitude to Dr. Bunichiro Shibazaki (IISEE, BRI) for their helpful discussions, valuable comments and guidance during my study in IISEE.

REFERENCES

Fujii, Y., and Satake, K., 2007, Bulletin of the Seismological Society of America, 97, pp. S192-S207.
Fujii, Y., 2008, IISEE Lecture Note 2007-2008, IISEE, BRI.
Imamura, F., 1995, manuscript for TUNAMI code, School of Civil Engineering, Asian, 1-45.
Kajiura, K., 1963, Bulletin Earthquake Research Inst, 41, 535-571.
Lawson, C. L., and R. J. Hanson, 1974, Prentice Hall, Inc., Englewood Cliffs, New Jersey, 340 pp.
Nagano, O., Imamura, F. and Shuto, N., 1991, Natural Hazards 4, 235-255.
Okada, 1985, Bulletin of the Seismological Society of America, 75, 1135-1154.
Satake, K., 2008, IISEE Lecture Note 2007-2008, IISEE, BRI.
Saw, B. L., 2007, IOC, Doc. No. IOC/PTWS-XXII/14.16.
Tatehata, H., 1997, Perspectives on Tsunami Hazard Reduction, 175-188.