VALIDATION OF TSUNAMI INUNDATION MODELING FOR THE 2004 SUMATRA-ANDAMAN EARTHQUAKE FOR MAKING HAZARD MAPS IN PENANG AND LANGKAWI, MALAYSIA

Noor Azam Shaari* **Supervisor: Yushiro FUJII****
MEE11622 **Hideaki YANAGISAWA*****

ABSTRACT

We adopted three heterogeneous slip models estimated by inversion method from satellite altimetry data, tsunami waveform data at tide gauges and the joint data as tsunami source models. Non-Linear Shallow Water Equations (NSWE) by considering the effects of the earth's curvature were applied in the numerical simulation to evaluate the tsunami propagation and runup at the target areas in Penang and Langkawi, Malaysia. We applied a nesting grid system with four layers in the numerical modeling.

The result shows that the locations in the study region, Pantai Acheh, Pantai Tengah, Pantai Chenang, Kuala Triang and Pantai Kok, are prone to the tsunamis, where the tsunami heights of about 2.5 m were calculated. The calculated tsunami waves from the all source models almost reproduce the observed ones at two tide gauges. Tsunami source models with larger slip amount over Nicobar and Andaman Islands contribute to the maximum tsunami runup as high as 4.0 m in Pantai Tengah and Pantai Chenang. These results are almost agreeable to the runup-height data by the field survey.

Keywords: 2004 Sumatra-Andaman earthquake, Tsunami Propagation, Runup, Inundation, Langkawi, Penang.

1. INTRODUCTION

An earthquake that occurred at 00:58:49 (UTC) on December 26, 2004 along the Sumatra Island and Andaman Islands has created a big impact after the giant tsunami waves and struck the world and Malaysia especially in the coastal areas. The 2004 Sumatra-Andaman earthquake with a magnitude of M9.1 at epicenter 3.316 ^{0}N/ 95.854^{0}E (USGS) has generated the giant tsunami waves propagated to few states in the northwest of Peninsular Malaysia. It is recorded that about 68 people died, left 6 missing and 300 injured. The Northern States of the west coast of Peninsular Malaysia have been badly affected by tsunami. Among the state affected were Kedah, Penang, Perlis, Perak and Selangor.

Tsunami simulations from three source models will be used to validate the tsunami propagation in whole inundated areas in Langkawi, Penang and Kedah. This study is also aimed to analyze the tsunami inundation to the target locations in Batu Feringghi (P1), Pantai Chenang (K2) and Kuala Triang (K3). Neighboring location such as P2, P4, K1 and K4 will also be analyzed as they are located inside the same computational domain.

*Malaysian Meteorological Department.
** International Institute of Seismology and Earthquake Engineering (IISEE), Building Research Institute (BRI), Japan.
*** Tohoku-Gakuin University, Japan.

2. DATA

2.1 Bathymetry and topography data

We used the bathymetry data from General Bathymetric Chart of the Ocean (GEBCO) with spatial grid size at 30 arc-sec. Generic Mapping Tools (Wessel and Smith, 2007) is used to process and draw the bathymetry data in the target area lies within 0°N to 15°N and 90°E to 105°E. For the calculation of the inundation, the topography data from Shuttle Radar Topography Mission (SRTM) is applied.

2.2 Computational regions and settings to evaluate tsunami propagations

In order to perform the numerical modeling to evaluate the tsunami wave propagation towards the target area the computational area is divided into three regions (Figure 1). The bathymetry and topography data for all the regions are interpolated from GEBCO 30 arc-sec. The calculation time for the computation is 28,800 s (8 hours) with computation time step (Δt) of 3 s. The Δt is derived from the stability criterion formula $\Delta t \leq \frac{\Delta x}{\sqrt{2gh_{\max}}}$. Maximum sea depth (h_{max}) of the computation region 1 is 5,514 m and gravitational acceleration at 9.81 ms^{-2}. Numerical simulation with the nesting grid system is carried out for the evaluation of the tsunami propagations from source area.

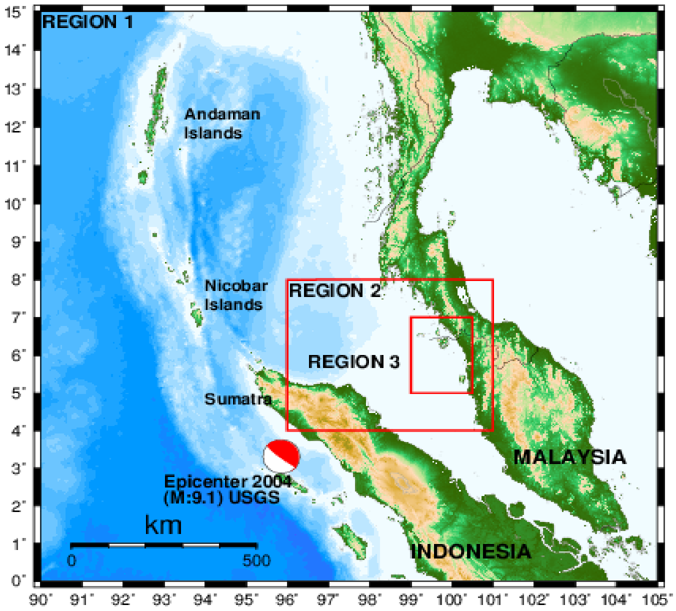

Figure 1. Location and boundary of each computational region.

2.3 Computational regions and settings to evaluate tsunami inundations

In order to evaluate the tsunami inundation at each target locations, the computational area is divided into four regions. The same computational regions as those in *section 2.2* are applied to the regions 1 and 2, but slight changes are made to region 3 to avoid the numerical instability during the computation. The same calculation time for the computation at 28,800 s (8 hours) is used at Δt of 3 s. The computation region 3 at the target area in Penang (Figure 2) and Langkawi (Figure 3) is divided into smaller region 4. Target locations of P1, K2 and K3 are located at their smaller region 4 to analyze the coastal wave amplification.

The bathymetry and topography grids in inundation area are merged for getting finer sea bottom surface and elevation data. The bathymetry for the region 4 is interpolated from GEBCO 30 arc-sec, whereas the topography is from SRTM 3 arc-sec. Three different sets of numerical simulations are performed to analyze the coastal amplification over the respective target locations.

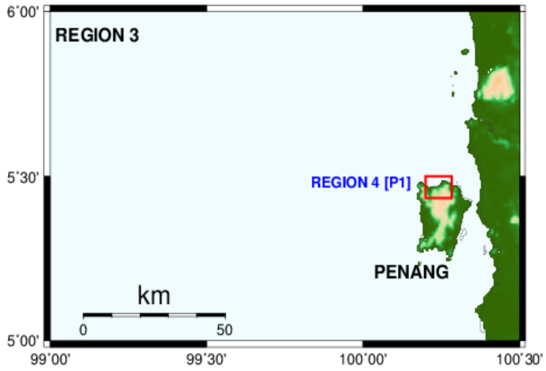

Figure 2. Location and boundary for computational region 3 for Penang.

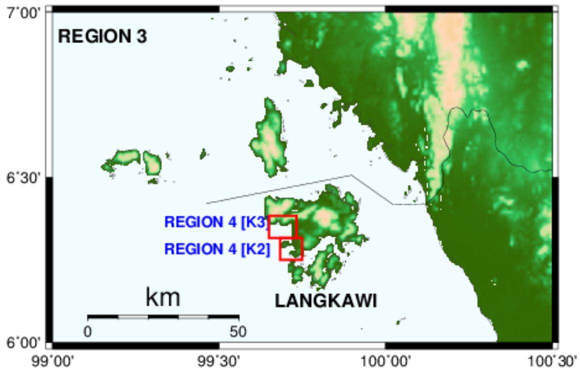

Figure 3. Location and boundary for computational region 3 for Langkawi.

2.4 Tide gauge stations and tsunami waveform data

There are four tide gauge systems that are now operated in the study area. Two of the systems are operated by Department of Survey and Mapping (JUPEM); one located in Penang (5°25’N/100° 21’E) and the other in Langkawi (6° 26’N/ 99° 46’E). The other two operated by Malaysian Meteorological Meteorology (MMD) is located in Penang (5° 27’N/100° 10’E) and Langkawi (6° 15’N/ 99° 44’E). Observed tsunami waveforms by JUPEM at sampling interval of 50 s will be used in the study. Figures 4 and 5 show the locations of the tide gauge stations at Penang and Langkawi.

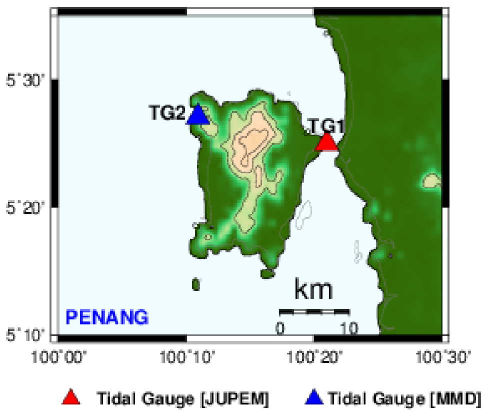

Figure 4. Location of tide gauge station at Penang.

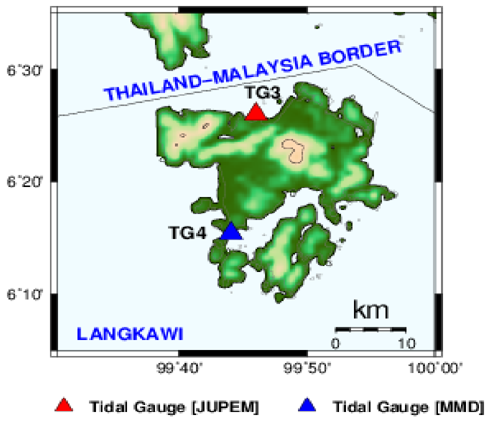

Figure 5. Same as Figure 4, but for Langkawi.

2.5 Tsunami source region and source models

In this study three heterogeneous slip models from Model 1 by Hirata *et al.* (2006), Model 2 by Fujii and Satake (2007), and Model 3 by Tanioka *et al.* (2006) will be used in the validation process. Initial sea surface heights from the slip models shown in Figure 6 are calculated by the Okada formulation (Okada, 1985). The different variation of tsunami propagations is expected to be produced from the different parameters and slip amount used in the simulation.

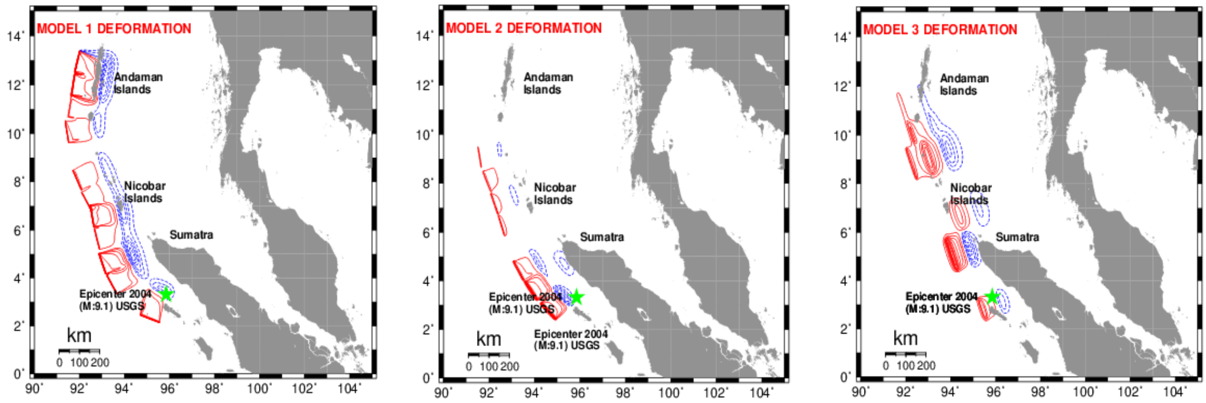

Figure 6. Seafloor deformations by Model 1 (left), Model 2 (center) and Model 3 (right). Red and blue lines indicate the uplift and subsidence area, respectively, with the contour interval of 1.0 m.

3. THEORY AND METHODOLOGY

3.1 Non-linear shallow water and governing equations

The original Tohoku University's Numerical Analysis Model for Investigation (TUNAMI-N2) model neglects the earth's curvature (Dao and Tkalich, 2007). To consider the effects of the earth's curvature, the NSWE model is reformulated in spherical coordinates (Yanagisawa, 2012). The continuity and momentum equations are rewritten as follows;

$$\frac{\partial \eta}{\partial t}+\frac{1}{R\cos\theta}\left[\frac{\partial M}{\partial \lambda}+\frac{\partial}{\partial \theta}N(\cos\theta)\right]=0 \quad (1)$$

$$\frac{\partial M}{\partial t}+\frac{gD}{R\cos\theta}\frac{\partial \eta}{\partial \lambda}+\frac{1}{R\cos\theta}\frac{\partial}{\partial \lambda}\left(\frac{M^2}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial \theta}(\cos\theta\frac{MN}{D})+\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}=0 \quad (2)$$

$$\frac{\partial N}{\partial t}+\frac{gD}{R\cos\theta}\frac{\partial}{\partial \theta}(\cos\theta\eta)+\frac{1}{R\cos\theta}\frac{\partial}{\partial \lambda}\left(\cos\theta\frac{N^2}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial \lambda}(\frac{MN}{D})+\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}=0 \quad (3)$$

Where η is wave amplitude, M is discharge fluxes in the λ (along a parallel of latitude) direction, N is discharge fluxes in the θ (along a circle of longitude) direction, R is radius of the earth at 6378.137 km, t is time and n is manning roughness coefficient (n = 0.025 in this study).

3.2 Runup and inundation height

The main objective of this study is to investigate the onshore effects of a tsunami or runup. Runup and inundation height are referring to the maximum vertical tsunami height onshore and elevation of local watermark measured from the sea level at the time of tsunami attack.

4. RESULTS AND DISCUSSION

4.1 Tsunami wave propagations

The result of Model 1 shows that K1, K2, K3 and K4 are facing large tsunami height from 2.4 m up to 2.9 m but it is slightly lower at P1, P2 and P4. Wave pattern of Model 3 is slightly similar to that of the Model 1 but the tsunami height at K4 is only 1.5 m which is about half of 2.9 m in Model 1. The calculated tsunami height of Model 2 is relatively small compared with Models 1 and 3. The calculated tsunami height at P1, P2 and P4 from Model 1 is almost agreeable to the computation result reported in Koh *et al*. (2009) by using an in-house Tsunami Numerical Simulation Model (TUNA). The pattern of maximum tsunami heights at all coastal points show that P5, K1, K2, K3 and K4 have been hit by the high waves about 2.0 m from Model 1.

Figure 7 shows the calculated tsunami waveforms at four tide gauge stations in Penang and Langkawi and the comparison with the observed waveforms at TG1 and TG3. The calculated waveforms and the observed data generally fit to each other. The waveforms by Model 1 almost reproduce the observed ones.

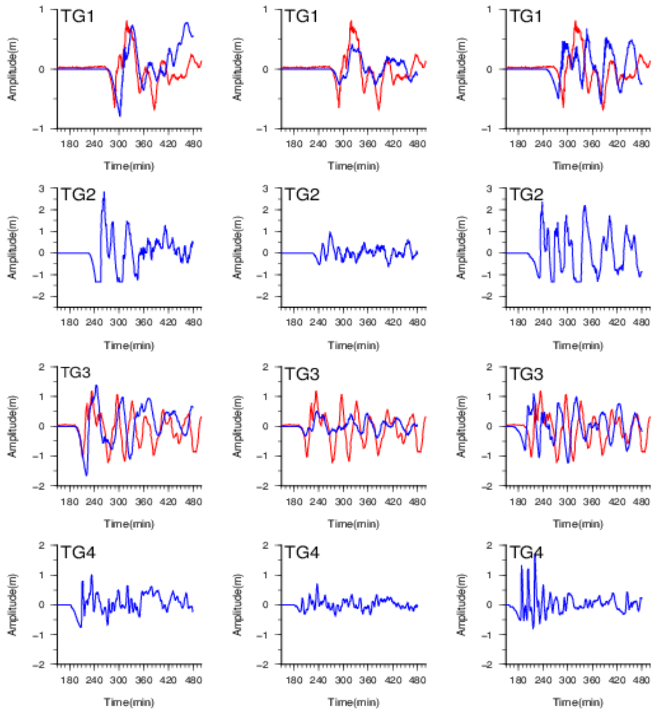

Figure 7. Comparison between the calculated tsunami waveforms (blue lines) and the observe ones (red lines) at tide gauge stations by Model 1(left), Model 2(center) and Model 3(right).

4.2 Tsunami inundation analysis

All the calculated runup heights in Penang are underestimated compared with the observation data. The observed maximum tsunami runup is at as high as 4.0 m at P2 (Figure 8). Maximum tsunami runup estimated at K1 and K2 was between 3.2 and 4.0 m for both Model 1 and 3, respectively (Figure 9). The calculated result is almost agreeable to the observed data which is recorded at the maximum height of 3.75 m at K2. Tsunami runup at the target locations K3 and K4 seem to be overestimated, where the calculated result from Model 1 shows the maximum runup at 5.1 and 5.3 m, respectively (Figure 10). The maximum runup from the observed data is only between 2.25 and 3.09 m. The computed runup at K3 by Model 3 is almost agreeable to the observed data of 3.1 m.

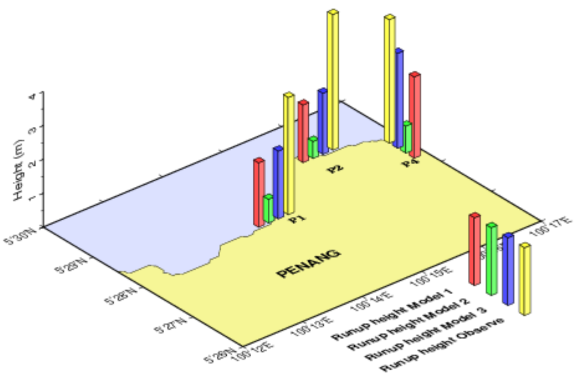

Figure 8. Comparison between the calculated maximum tsunami runup heights and observed ones at the target locations in Penang

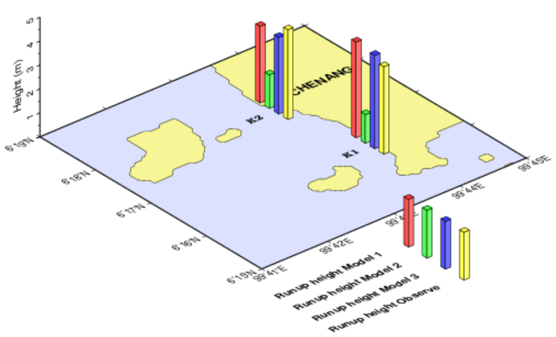

Figure 9. Same as Figure 8, but in Pantai Chenang, Langkawi.

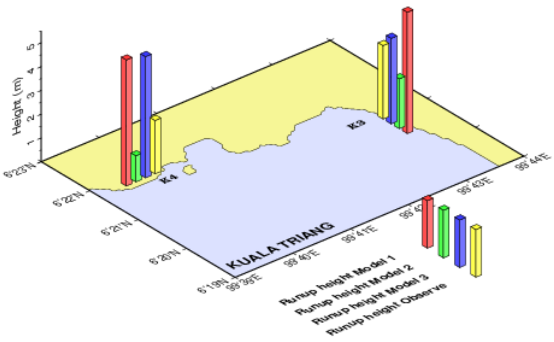

Figure 10. Same as Figure 8, but in Kuala Triang, Langkawi.

5. CONCLUSIONS

The result of the tsunami propagation analysis shows that about 2.5 m of tsunami waves approaching the coastal locations P5, K1, K2, K3 and K4 may severely impact the area if there is no sufficient protection given by the authority. The calculated maximum runup heights at K1 and K2 are as high as 4.0 m which is almost agreeable to the field observation data. The elevation profile also suggests that the location P1, P4 and K2 are exposed to the tsunami threat as they are located at low land. It was also found that the tsunami generated by the source Models 1 and 3 with higher slip distributions in Nicobar and Andaman Islands contributed to the large tsunami heights and runups over the study region. The source parameters from historical earthquakes and tsunamis in the northern Sumatra especially at Nicobar and Andaman islands will be investigated in order to estimate the impact to the northwest Peninsular Malaysia. The inundation results from the numerical simulations will be suggested for making tsunami hazard maps in Penang and Langkawi.

ACKNOWLEDGEMENT

Special thanks to Mohd Yusof Bin Abu Bakar and Zulkifli Bin Mohamad, the officers at the Department of Survey and Mapping Malaysia (JUPEM) and Malaysian Meteorological Department (MMD) for their support to make this study successful.

REFERENCES

Dao, M.H., Tkalich, P., 2007. Natural Hazards and Earth System Sciences, 7, 741-754.
Fujii, Y., Satake, K., 2007. Bull. Seism. Soc. Am., Vol. 97, No. 1A, pp. S192-S207.
Hirata, K., et al., 2006. Earth Planets Space, 58, 195-201.
Koh, H.L., et al., 2009. Journal of Asian Earth Sciences 36(2009) 74-83.
Okada, Y., 1985. B. Seism. Soc. Am. 75 (4), 1135-1154.
Tanioka Y., et al., 2006. Earth Planet Science 58(2006), pp.203-209.
Wessel, P. and W. H. F. Smith, 2007, “The Generic Mapping Tools, version 4.2.0”.
Yanagisawa, H., May 2012, Tsukuba, Lecture Note 2011-2012.