SIMULATION OF TSUNAMI AT EAST COAST OF PENINSULAR MALAYSIA DUE TO THE EARTHQUAKES AT MANILA TRENCH USING TUNA-M2 MODEL

G. Nelvindran*

Civil Engineering Department, Universiti Tenaga Nasional, 43000,
Kajang, Selangor, Malaysia

N.H. Mardi

Civil Engineering Department, Universiti Tenaga Nasional, 43000,
Kajang, Selangor, Malaysia

M.A. Malek

Civil Engineering Department, Universiti Tenaga Nasional, 43000,
Kajang, Selangor, Malaysia
Institute of Power Energy (IPE), Universiti Tenaga Nasional, 43000,
Kajang, Selangor, Malaysia

W.K Tan

School of Mathematical Sciences, Sunway University, Bandar Sunway,
47500 Subang Jaya, Selangor; Malaysia.

S.Y Teh

School of Mathematical Sciences, Universiti Sains Malaysia,
11800 USM, Pulau Pinang, Malaysia
*Corresponding Author

ABSTRACT

This study assessed the impact of tsunami waves simulated to propagate towards South China Sea before reaching the coastlines of east coast Peninsular Malaysia with earthquake source from Manila Trench. The latest set of fault parameters developed in year 2014 incorporating the worst-case scenario of Mw=9.3 were used to generate tsunami from Manila Trench using TUNA-M2. With the study domain set at a rectangle bounded by 100˚E to 125˚E longitude, 0˚N to 25˚N latitude, grid dimensions of 1851×1851 (km) and grid size of 1500 meters, findings from this study showed that the state of Kelantan will experience the highest wave height at 1.96 m followed by Terengganu (1.55m), Pahang (0.65m) and Johor (0.56m). Since Pahang and Johor are expected to experience low wave height, it can be concluded that coast

line of these states is not subjected to critical wave height whereas coastal areas of Kelantan and Terengganu are identified as hazardous areas during the propagation phase of a tsunami event. These waves are expected to reach coastal areas of Pahang at 10hr after the earthquake triggered at Manila Trench. This will then be followed by Johor, Terengganu, and Kelantan at 2 hours later.

1. INTRODUCTION

The active subduction zone stretching between southern Taiwan and the central west coast of Philippines has a length of about 1500 km. It is one of the potential tsunami sources that could devastate communities bordering the South China Sea (SCS). According to Global Positioning System (GPS) geodesy measurements, it is explicitly known that the convergence rate across this megathrust is about 8 cm/year (Galgana *et al.*, 2007).

It is an alarming fact that there are limited studies that were carried out to investigate the potential tsunami threat along the SCS which also contributed to the SCS region being excluded from hazard maps in the past. It is believed that there are potential tsunami sources in the region due to the fault rupture along the Manila Trench. (Liu, Wang and Salisbury, 2009). Among the active tectonic zones in the East Sea, Manila Trench (Figure 1) is identified as the most dangerous. No earthquake larger than Mw = 7.6 has been recorded in the past 100 years in this region which strongly indicates a high probability for larger earthquakes to occur in the future (Bautista *et al.*, 2001). Hence, earthquakes at the fault rupture along Manila Trench is potentially capable of generating tsunamis that may be experienced by Malaysian shores (Mardi, 2014).

This research is extremely significant to Malaysian offshore areas, since there are various power plant and tourist spot along those mentioned states. Research on Malaysian shorelines was previously conducted by Teh and Koh (2010) where an in-house model Tsunami Analysis (TUNA)-M2 was used to simulate the generation and propagation of tsunami based on the Andaman tsunami back in 2004 (Koh *et al.*, 2009). Since then, it was predicted that tsunami from Manila Trench could become a serious risk to Malaysia, especially for Sabah and Sarawak (Terry *et al.*, 2017). This is also supported by the United States Geological Survey (USGS) workshop which identified Manila Trench as a potential tsunami source (Jingming *et al.*, 2016). Therefore, an identical study was conducted using TUNA-M2 to investigate the tsunami propagation at the boundaries of Peninsular Malaysia coastal areas, which includes Sarawak and Sabah with the tsunami induced by earthquake sourcing from the Manila Trench. Based on the simulated results, it was found that the coastline of Sabah will experience higher hazardous tsunami waves followed by Sarawak and Peninsular Malaysia (Mardi, Malek and Liew, 2017).

Therefore, the findings from this study serves as a guideline for the local authorities about the hazard extent of these tsunami waves which may damage and destroy their main properties around the affected boundaries. Local communities could also experience fatalities and injuries once these dangerous waves reach the shorelines, hence findings from this research may help in raising awareness among them regarding the severity of these waves.

The objective of this study is to determine the maximum tsunami wave height and its arrival time to be experienced by the shoreline of east coast Peninsular Malaysia. In this study, simulation of TUNA-M2 model will provide results for states bordering SCS namely Kelantan, Terengganu, Pahang, and Johor located at the east coast of Peninsular Malaysia. This study included tsunami generation and propagation phases where the simulation was conducted at the worst-case scenario of Mw=9.3.

2. METHODOLOGY

TUNA-M2 model is utilized in this study due to its validated capability to simulate tsunami generation and propagation triggered by earthquakes and its computational speed (Mardi et al. 2015). It utilizes shallow water equation (SWE) validated by UNESCO (1997) which uses a staggered-grid scheme as shown Figure 2. TUNA-M2 model is able to simulate two-dimensional (2D) tsunami generation and wave propagation. Equations (1), (2) and (3) are hydrodynamic equations where the conservation of mass and momentum is at average depth since tsunami propagation occurs in the deep ocean (Koh *et al.*, 2009). In equations (1), (2) and (3), the values of M and N are the discharge flux in x and y directions relative to u and v velocities as shown in equations (4) and (5), g is gravitational acceleration, h is sea depth, η is water elevation associated with tsunami and D is total water depth. D value can be expressed as $(h + \eta)$. Bathymetry data used in the simulation are obtained from ETOPO1 using 1 arc-min.

Figure 1 Location of Manila Trench, Philippines (red segment) in the South China Sea
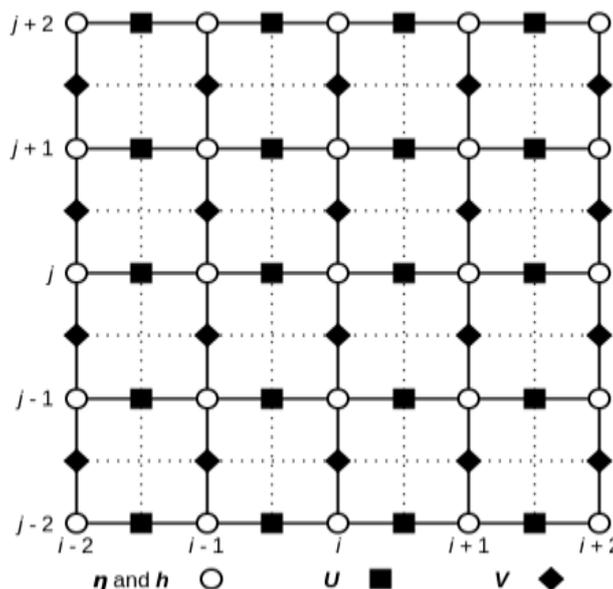
Figure 2 Staggered-grid scheme computational points

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{g^{7/3}}M\sqrt{M^2+N^2} = 0 \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{g^{7/3}}N\sqrt{M^2+N^2} = 0 \tag{3}$$

$$M = u(h+\eta) = uD \tag{4}$$

$$N = v(h+\eta) = vD \tag{5}$$

Equation (6) restricts the time step of the numerical scheme based on the Courant criterion to ensure that it is stable. (Teh *et al.*, 2009)

$$\Delta t \le \frac{\Delta x}{\sqrt{2gh}} \tag{6}$$

2.1. Study Region

The tsunami source considered in this study focuses primarily on tsunami generated by the potential earthquake from the Manila Trench which will then propagate towards the South China Sea and reach the Peninsular Malaysian shorelines. A study boundary was prepared to meet the boundary conditions of the TUNA-M2 model that was used in this research. The boundary for each Peninsular state which includes Kelantan, Terengganu, Pahang, and Johor are included in Figure 4 and labelled as K, T, P and J respectively. Furthermore, the following boundary is chosen due to consideration of the 50m-depth whereby the wave height reaches its peak point before the amplification of waves after the boundary.

2.2. Fault Parameters

In this study, the fault parameters developed by Nguyen et al (2014) will be used as an input for the TUNA-M2 model considering the worst-case scenario of Mw=9.3. The parameters developed by Nguyen et al (2014) is a result of combining the fault parameters proposed by Wu and Huang (2009) and (Megawati *et al.*, 2009). The six fault segments concept was

adopted from Wu and Huang (2009) whereas the parameter values from Megawati et.al (2009).

The incorporation of uniform width of 200 km by Wu and Huang (2009) is considered a poor application for the Manila Trench segments because it is highly unlikely that each segment would fit in the same width size due to topographical and geological factors. Meanwhile, Megawati et.al. (2009) model assigned the width of each segment accordingly with the slip value obtained by the interpolation method which is a better representation of the fault segment. However, Megawati et.al. (2009) divided Manila Trench into 33 segments for the parameters which is not a feasible solution for a numerical simulation. Hence, the fault parameters used in this research (Hong Nguyen *et al.*, 2014) is the most applicable model in tsunami studies due to its improvement on the parameter values that varies in terms of its width which shows a better illustration of the Manila Trench fault segments.

In addition, seismic-reflection profiles traced from profiler records and aligned from north to south along the axis of the Manila Trench illustrated the variation in topography (Ludwig, Hayes and Ewing, 1967) which further denies Wu and Huang assumptions in the parameters. Furthermore, Nguyen's model is the latest source model for tsunami studies generated from the Manila Trench which further justifies the application of the following parameters (Table 1) in the TUNA-M2 model.

The generation from Nguyen source model clearly illustrates a stronger tsunami generation in comparison with Wu and Huang as shown in Figure 5. The wave displacement (m) from Nguyen fault parameters exhibits a larger value than Wu and Huang as well as Megawati. Hence, this worst-case tsunami study based on Nguyen fault parameters is rationalized.

A study domain within a rectangle bounded by 100˚E to 125˚E in longitude and 0˚N to 25˚N in latitude (Figure 4) with grid dimension of 1851×1851 and grid size of 1500 meters is used in this research.
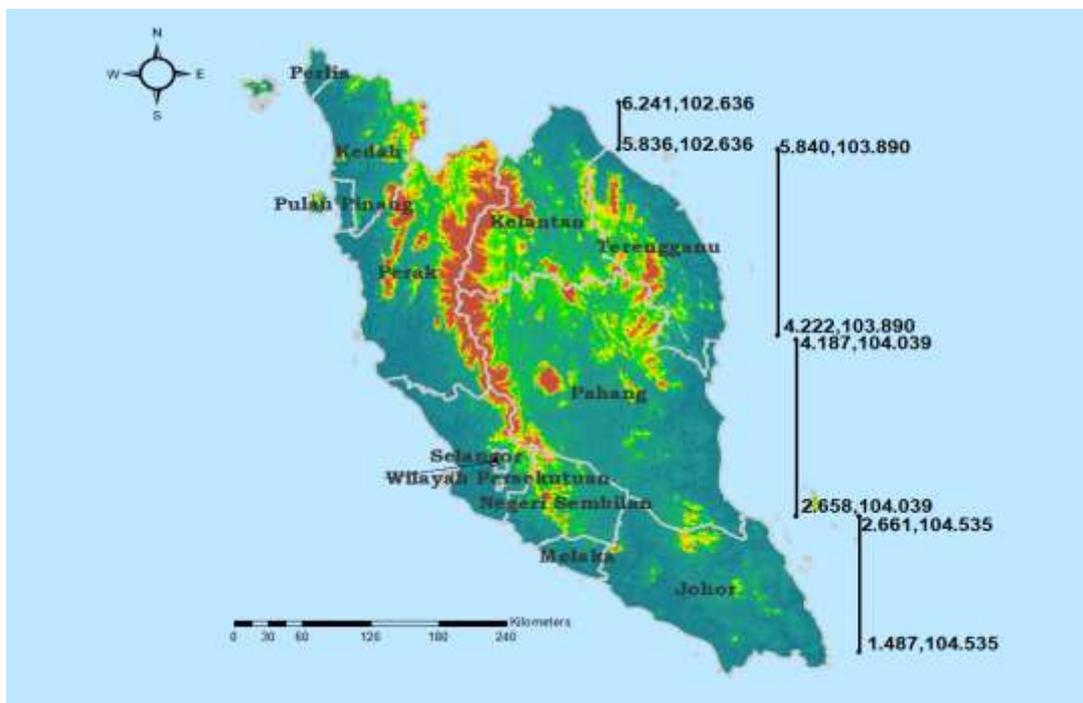

Figure 3 Peninsular Malaysia study domain in spherical coordinates

Table 1 The hypothetical fault parameters of Manila trench (Hong Nguyen *et al.*, 2014)

Fault	Long.	Lat.	Length (km)	Width (km)	Dislocation (m)	Depth (km)	Strike (°)	Dip (°)	Rake (°)
1	120.5	20.2	190	120	25	30	354	10	90
2	119.8	18.7	250	160	40	30	22	20	90
3	119.3	18.7	220	160	40	30	2	28	90
4	119.2	15.1	170	90	28	30	356	20	90
5	119.6	13.7	140	110	12	30	344	22	90
6	120.5	12.9	95	80	5	30	331	26	90

Table 2 Summary of TUNA-M2 simulation

Location	Range of Wave Height (m)	Arrival Time (hr)
Kelantan (K)	0.92-1.96	11.30-12.42
Pahang (P)	0.16-0.65	9.22-11.03
Terengganu (T)	0.39-1.55	9.19-12.16
Johor (J)	0.09-0.56	9.55-12.08
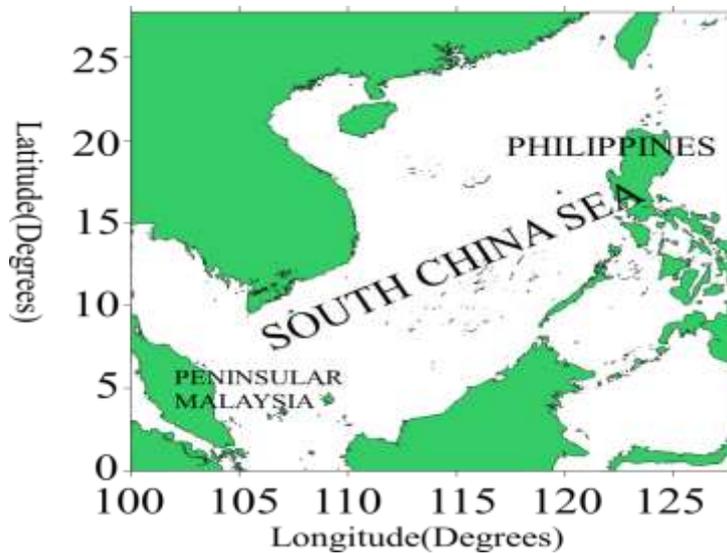
Figure 4 Study domain for TUNA-M2 simulation
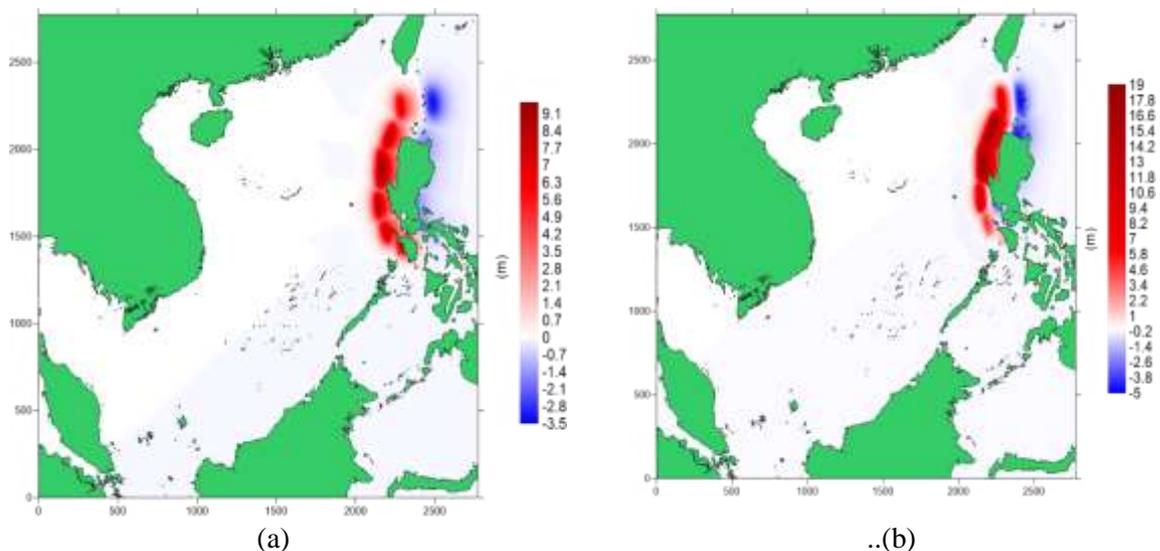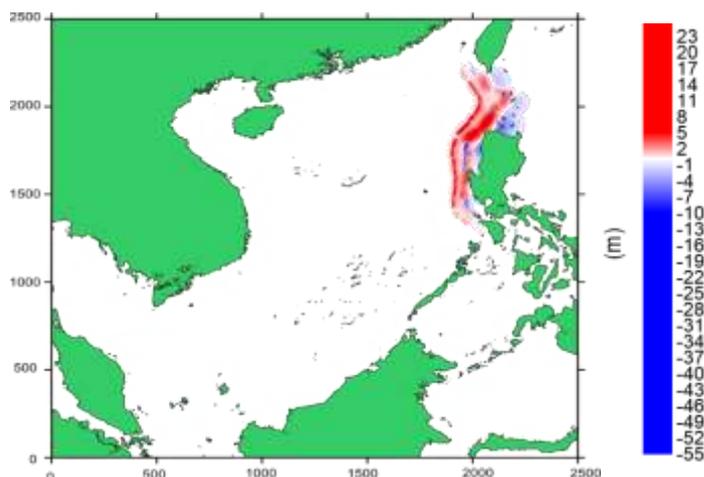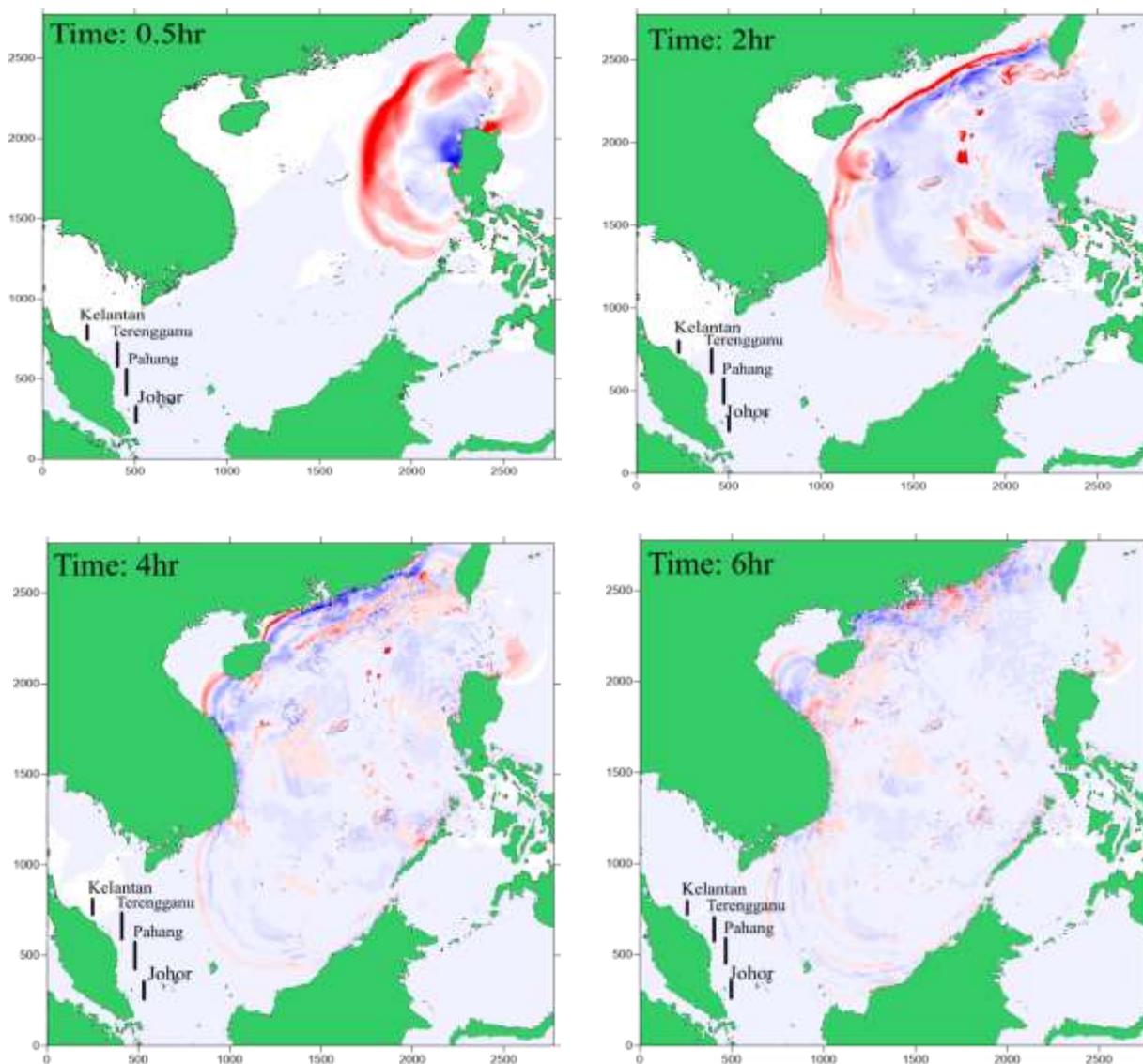

(a)

..(b)

Figure 5 Source generation (a) Nguyen et.al. (2014); (b) Wu and Huang (2009); (c) Megawati et.al
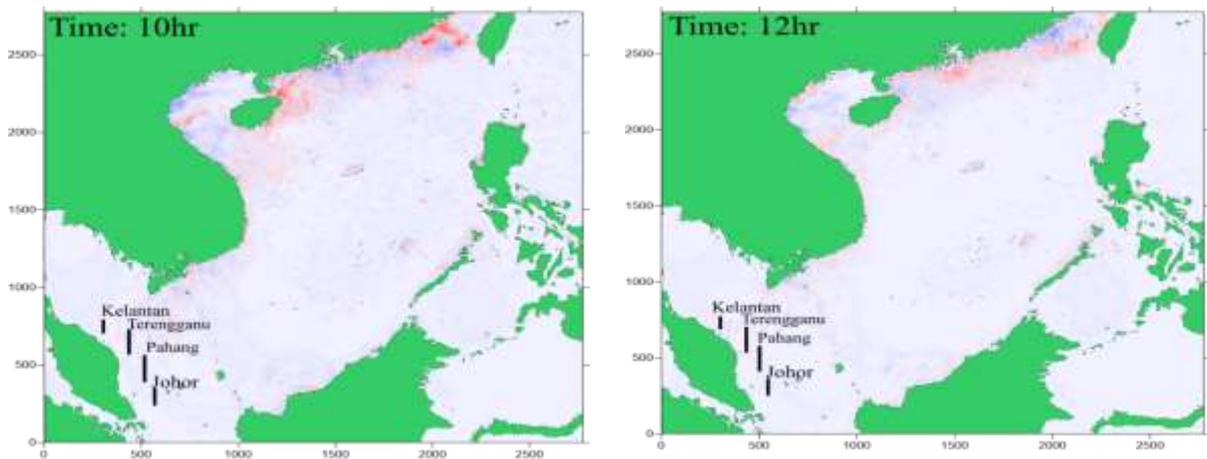(2009)

Figure 6 Propagation snapshots at (a) 0.5hr; (b) 2hr; (c) 4hr; (d) 6hr; (e) 8hr; (f) 10hr; (g) 12hr

3. RESULTS

In this simulation, the tsunami wave height and arrival time were taken when the wave reaches its first peak point within the specified boundary as shown in Figure 3. Table 2 shows the summary on the range of tsunami wave height and its arrival time at the states located along east coast of Peninsular Malaysia. Based on these results, it can be deduced that the tsunami wave generated from Manila Trench will first move through the coastline of Pahang first followed by Johor, Terengganu, and lastly Kelantan. The propagation snapshots are illustrated in Figure 6. The wave height and arrival results are shown in Figure 7 and 8.

Figure 7 Wave height for Kelantan, Terengganu, Pahang and Johor located at east coast of Peninsular Malaysia.

Figure 8 Wave arrival time for Kelantan, Terengganu, Pahang and Johor located at east coast of Peninsular Malaysia

4. DISCUSSION

Based on Table 2 and Figure 7, it can be concluded that Kelantan will experience the highest wave height (1.96m) followed by Terengganu (1.55m), Pahang (0.65m) and Johor (0.56m). Since Pahang and Johor are expected to experience low wave height at 0.65m and 0.56m respectively, it is also concluded that the coast line of Pahang and Johor are not subjected to critical wave height during the propagation phase of a tsunami event. On the other hand, coastal areas of Kelantan and Terengganu are identified as hazardous areas upon the generation of earthquake from Manila Trench.

Meanwhile, in terms of wave arrival time shown in Figure 8, Pahang is expected to experience the wave at the earliest duration in comparison to other states located at the east coast of Peninsular Malaysia. The waves are estimated to arrive at 10.28 hr at the coast line of Pahang, followed by Johor at 12.08 hr, Terengganu at 12.16 hr, and lastly Kelantan at 12.42 hr. These results are inline to findings by Mardi et al. (2015). Despite the waves arriving first at Pahang and Johor, these two states did not experience typically high wave height in comparison to Kelantan and Terengganu. This is due to the bathymetry of the boundary chosen for these two states to fulfil the criteria for the TUNA-M2 simulation. The bathymetry effects majority of the results from this study. The wave height is dependent on the bathymetry of the boundary, whereas the arrival time is based on current velocity from the tsunami source. In this case, the current velocity is not the main focus of the study which explains the exclusion from these findings.

However, findings from this study further support the fault parameters established by Nguyen et.al. (2014). Various factors that contributed to this analysis included the fault parameters and tsunami source model used since value of its length, width, and depth differs from other studies.

5. CONCLUSIONS

Peninsular Malaysia is geographically connected to SCS, which has been the centre of attention for future tsunami events. It is expected that the tsunami generation will start at Manila Trench and then propagate towards SCS before reaching the shorelines of east coast Peninsular Malaysia. The results proved that Kelantan and Terengganu are to experience wave height higher than Pahang and Johor at seismic activity of Mw=9.3 simulated in this study. In terms of arrival times, the simulated wave is expected to reach the coastline of Pahang as early as 10hr. Meanwhile, Kelantan, Terengganu, and Johor are to experience the wave at 12 hr upon the earthquake generated at Manila Trench. In addition, the run-up phase of this tsunami simulation will be investigated in future research.

ACKNOWLEDGEMENTS

REFERENCES

[1]   Bautista, B. C. *et al.* (2001) 'A new insight on the geometry of subducting slabs in Northern Luzon, Philippines', *Tectonophysics*, 339(3–4), pp. 279–310. doi: 10.1016/S0040-1951(01)00120-2.

[2]   Galgana, G. *et al.* (2007) 'Analysis of crustal deformation in Luzon, Philippines using geodetic observations and earthquake focal mechanisms', *Tectonophysics*, 432(1–4), pp. 63–87. doi: 10.1016/j.tecto.2006.12.001.

[3]   Hong Nguyen, P. *et al.* (2014) 'Scenario-based tsunami hazard assessment for the coast of Vietnam from the Manila Trench source', *Physics of the Earth and Planetary Interiors*. Elsevier B.V., 236, pp. 95–108. doi: 10.1016/j.pepi.2014.07.003.

[4]   Jingming, H. *et al.* (2016) 'Tsunami hazard assessment along the Chinese mainland coast from earthquakes in the Taiwan region', *Natural Hazards*. Springer Netherlands, 81(2), pp. 1269–1281. doi: 10.1007/s11069-015-2133-8.

[5]   Koh, H. L. *et al.* (2009) 'Simulation of Andaman 2004 tsunami for assessing impact on Malaysia', *Journal of Asian Earth Sciences*, 36(1), pp. 74–83. doi: 10.1016/j.jseaes.2008.09.008.

[6]   Liu, P. L. F., Wang, X. and Salisbury, A. J. (2009) 'Tsunami hazard and early warning system in South China Sea', *Journal of Asian Earth Sciences*. Elsevier Ltd, 36(1), pp. 2–12. doi: 10.1016/j.jseaes.2008.12.010.

[7]   Ludwig, W. J., Hayes, D. E. and Ewing, J. I. (1967) 'The Manila Trench and West Luzon Trough-I. Bathymetry and sediment distribution', *Deep-Sea Research and Oceanographic Abstracts*, 14(5), pp. 533–544. doi: 10.1016/0011-7471(67)90063-0.

[8]   Mardi, N. H. (2014) 'Tsunami Forecasting due to Seismic Activity from Manila Trench of Malaysia Offshore Oil Blocks', 2014, pp. 8–12.

[9]   Mardi, N. H., Malek, M. A. and Liew, M. S. (2017) 'Tsunami simulation due to seaquake at Manila Trench and Sulu Trench', *Natural Hazards*. Springer Netherlands, 85(3), pp. 1723–1741. doi: 10.1007/s11069-016-2661-x.

[10]   Megawati, K. *et al.* (2009) 'Tsunami hazard from the subduction megathrust of the South China Sea: Part I. Source characterization and the resulting tsunami', *Journal of Asian Earth Sciences*. Elsevier Ltd, 36(1), pp. 13–20. doi: 10.1016/j.jseaes.2008.11.012.

[11]   Teh, S. Y. *et al.* (2009) 'Analytical and numerical simulation of tsunami mitigation by mangroves in Penang, Malaysia', *Journal of Asian Earth Sciences*. Elsevier Ltd, 36(1), pp. 38–46. doi: 10.1016/j.jseaes.2008.09.007.

[12]   Terry, J. P. *et al.* (2017) 'Past and potential tsunami sources in the South China Sea: A brief synthesis', *Earth-Science Reviews*. Elsevier B.V., 167, pp. 47–61. doi: 10.1016/j.earscirev.2017.02.007.