International Journal of Engineering & Technology, 7 (4.35) (2018) 270-275

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper



Projection of Tsunami Wave Height at East-Coast of Peninsular Malaysia using Green's Law

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Abstract

In recent years, studies regarding a new source of tsunami-genic earthquake at South China Sea region known as Manila Trench earthquake have attracted the attention of many researchers. It is expected that this subduction zone is capable to trigger large moment magnitude earthquake and affects countries located within South China Sea. The objective of this study is to project tsunami wave height and arrival time generated from Manila Trench earthquake towards coastal areas located along east-coast of Peninsular Malaysia. This study focuses on simulating tsunami at four different moment magnitudes by using TUNA-M2 model to record wave height and arrival time at the offshore areas. Then the Green's law is used to approximate reliable tsunami wave height when approaching onshore. Results obtained in this study showed that tsunami waves from Manila Trench are estimated to arrive at coastal areas of east-coast Peninsular Malaysia between 9.1 to 10.25 hours post-earthquake occurrence. The observation points located at offshore of Kelantan are anticipated to experience the highest wave height as compared to other observation points located at offshore areas of Terengganu and Pahang. This study is important to the coastal communities as it provides vital information on possible tsunami occurrences in the future.

Keywords: *earthquake tsunami; Manila Trench, Peninsular Malaysia, TUNA-M2, Green's law*

1. Introduction

Earthquake is a coastal geological process usually occurred along the subduction zones. Most earthquakes occur when two tectonic plates collided with each other. This event generally occurred at the plate boundaries which are located along the edges of tectonic plates. The plates that collided with each other transferred the energy to seawater, creating large impulsive disturbance to the calm water surface and developed hazardous tsunami waves. This colliding event pushed a huge area of ground located under the sea impacting the water overlying it to move upwards. Some areas of seafloor were elevated and depressed by just few meters, but this is far enough to force several cubic kilometers of seawater and transmit a series of waves out of the epicenter. This series of waves creates one of the most hazardous natural disasters, known as tsunami which claimed thousands of lives. From the earthquake epicenter, this dangerous waves travel in all directions generating a big circle of waves with long wavelength and short wave period. At present, the study of tsunami generated by seismic activities has increase in numbers since this phenomenon often occurs as compared to other tsunami factors.

Throughout the history, a severe earthquake with moment magnitude of 9.0 occurred at west coast of Sumatra in the Indian Ocean on 26th December 2004. The identified cause of the earthquake is due to the release of stresses accumulated as Burma tectonic plate overrides India tectonic plate at the Indian Ocean. Almost 14 countries surrounding the source point were affected by the tsunami including Malaysia during the Sumatera-Andaman earthquake. Approximately 226,000 people were reported dead at the catastrophe and lives of millions of people have assuredly changed since the incident. The tsunami hit west-coast of Peninsular Malaysia resulting to properties destructions and loss of life of 68 people, mostly located in Penang, Langkawi, Kedah and Perak [1]. Until today, east-coast of Peninsular Malaysia is still safe from any tsunami disaster, but in recent years, there are studies that stated the existence of an earthquake epicenter located at South China Sea which can affect the east-coast of Peninsular Malaysia, recognized as Manila Trench [2][3][4]. The tsunami is expected to reach east-coast of Peninsular Malaysia within few hours. Hence, research pertaining to tsunami wave height and arrival time is essential in order to provide vital information on tsunami particularly to coastal communities.

Projection of tsunami wave height and arrival time generated from Manila Trench earthquake towards the coastal areas along east-coast of Peninsular Malaysia was simulated using TUNA-M2 model in order to obtain wave height and arrival time. The Green's law is than used to approximate reliable tsunami wave height when approaching the onshore areas. The impacts of earthquake induced tsunami from Manila Trench subduction zone to the observation points located at east-coast of Peninsular Malaysia are investigated. In this study, four different earthquake moment magnitudes namely Mw: 7.5, 8.0, 8.5 and 9.0 were chosen to be simulated at different scenarios of tsunami event.

8 observation points (point A to H in Figure 1) located at offshore areas of Kelantan, Terengganu and Pahang with water depth ranging from 50 m to 60 m were selected to capture the tsunami wave heights and arrival time. The states of Kelantan, Terengganu and Pahang located along east-coast of Peninsular Malaysia are anticipated to be affected by tsunami originated from Manila Trench. The 8 observation points were chosen based on population crowdedness and development rate at the coastal areas of these states. It should be noted that the tsunami wave height and arrival time

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were taken when the first peak of tsunami waves reaches the observation point.

2. Fault Parameters of Manila Trench

Manila Trench is one of the three subduction zones that were classified by year 2006 USGS tsunami source workshop that has the potential to harm regions within South China Sea [5]. It has been identified as the most impactful tsunami-genic earthquake source in South China Sea and is capable to create massive earthquake with moment magnitude 9.0 [6][7]. Manila Trench is situated at the west islands of Luzon and Mindoro in the Philippines with approximate length of 1500 km [8]. The formation of Manila Trench occurred at about 22 to 25 million years ago when Eurasian Plate sub-ducted underneath the Philippines Sea Plate. This subduction zone is able to generate tremendous earthquake, capable to trigger tsunami event at a high speed of approximately 700 km/h [8]. Countries located surrounding the South China Sea is expected to be affected by these dangerous waves. The return period of Manila Trench earthquake at each moment magnitude is summarized in Table 1 [9].

Table 1: Return period of Manila Trench earthquake [9]

Moment magnitude (Mw)	Return period (years)
7	6
7.5	19
8.0	63
8.5	205
9.0	667

The potential impacts of tsunami caused by seismic movements in Manila Trench towards Malaysia coastal areas have not been explored extensively. A study conducted by Mardi et al. [10] determined tsunami wave height and arrival time from Manila Trench to Malaysia's offshore blocks particularly where oil and gas activities are operated along east-coast of Peninsular Malaysia within the South China Sea. However, this technical paper covers the coastal areas located along east-coast of Peninsular Malaysia as an approach to extend the possible areas that will be affected by this dreadful disaster.

Manila Trench is divided into six main fault segments as suggested by USGS. The fault parameters at each segment included the longitude and latitude, length, strike angle, dip angle and rake angle shown in Table 2 [5]. In this study, rake angle of 90˚ is utilized in order to indicate potential worst-case scenario for tsunami event. The focal depth used in this simulation is 15 km since this value is considered in many major seismic activities at South China Sea [6].

Table 2: Fault parameters of Manila Trench [5]

Fault	Longitude	Latitude	Length (km)	Strike (deg.)	Dip (deg.)	Rake (deg.)
E1	120.5	20.2	160	10	10	90
E2	119.8	18.7	180	35	20	90
E3	119.3	17	240	359	28	90
E4	119.2	15.1	170	3	20	90
E5	119.6	13.7	140	320	22	90
E6	120.5	12.9	100	293	26	90

Another two important fault parameters namely width of segments and dislocations were referred to study conducted by Mardi et al. [2]. Mardi et al. utilized empirical equations proposed by Papazachos et al. [11] in order to calculate width of the fault segments. In the simulation, the average value of fault segment width used is 71 km. Dislocation at each segment were determined using equations (1) and (2):

$$M_o = \mu DLW \tag{1}$$

$$M_w = \frac{2}{3}\log_{10} M_o - 10.7 \tag{2}$$

where M_o is the scalar moment of an earthquake, $\mu = 3.0 \times 10^{10}\ N/M$ is the rigidity of earth mantle, D is the dislocation, L is the fault segment length, W is the fault segment width, and M_w is the moment magnitude of earthquake. The calculated dislocations at each moment magnitude are shown in Table 3.

Table 3: Fault segment dislocation at each moment magnitude [2]

Fault	Dislocation (m)			
	Mw: 7.5	Mw: 8.0	Mw: 8.5	Mw: 9.0
E1	0.585	3.292	18.514	104.112
E2	0.520	2.926	16.457	92.544
E3	0.390	2.195	12.343	69.408
E4	0.551	3.099	17.425	97.988
E5	0.669	3.763	21.159	118.985
E6	0.937	5.268	29.622	166.579

3. Methodology

3.1. Numerical Model Simulation

TUNA-M2 model was developed by researchers at Universiti Sains Malaysia (USM). It has the ability to simulate a complete tsunami process due to earthquake event. This model was developed as a depth-average two-dimensional model in order to provide adequate solutions for tsunami simulation. Three-dimensional models are rarely used at other tsunami models since excessive memory and long computational time are required [12]. TUNA-M2 was successfully applied to simulate impacts of year 2004 Andaman tsunami and has been validated by COMCOT model [12].

Since the objective of this study is to determine tsunami wave height and arrival time towards coastal areas of Peninsular Malaysia, therefore, this study is limited to simulation of tsunami due to propagation. TUNA-GE is used to simulate the initial tsunami wave generated by different earthquake sources utilizing Okada formula. While TUNA-M2, which solves linear shallow water equations (SWE) is utilized in the propagation process.

SWE is used to simulate propagation of tsunami waves across deep ocean from the source of generation to the offshore regions with depth of about 50 m at the coast of Malaysia [12]. Since the wave height is much lower than the ocean depth and the wavelength is much higher than the wave height, therefore, SWE is applicable to be used for tsunami analysis. TUNA-M2 model is able to solve SWE using explicit finite difference with staggered grids. The SWE are exhibited in Equations (3) to (5):

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{3}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/8}} M\sqrt{M^2+N^2} = 0 \tag{4}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{7/8}} N\sqrt{M^2+N^2} = 0 \tag{5}$$

g (m/s²) is the gravitational acceleration constant, $n\ (s/m^{1/3})$ is the Manning's roughness coefficient, M (m²/s) and N (m²/s) are the horizontal discharged fluxes in x- and y-directions respectively, which then relate to velocities u (m/s) and v (m/s) as stated in Equations (6) and (7), h (m) represents water depth below mean sea level (MSL), η (m) represents vertical free surface displace-

ment measured from mean sea level and D (m) = $h + \eta$ is the total water depth.

$$M = u\left(h+\eta\right) = uD \tag{6}$$

$$N = v\left(h+\eta\right) = vD \tag{7}$$

3.2. Study Area

In this study, a computational domain of 2775 km × 2775 km with a square grid size of 1500m within a rectangle bounded by 0˚N to 25˚N in latitude and 100˚E to 125˚E in longitude was chosen for propagation simulation of Manila Trench earthquake induced tsunami propagating towards the east-coast of Peninsular Malaysia. A corresponding time step of 1.0s was set for simulation purposes in order to ensure numerical stability [13]. Eight observation points (A to H) located at offshore of east-coast Peninsular Malaysia are shown in Figure 1.

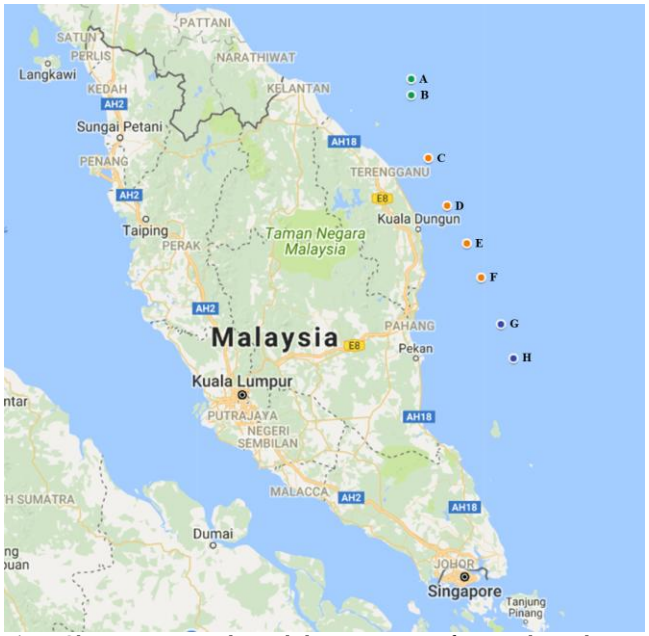


Fig 1: Observation points located along east-coast of Peninsular Malaysia.

3.3. Green's Law

As it moves across the ocean, tsunami can undergo wave shoaling and change of heights. A linear theory known as Green's Law is the expression used for shoaling, widely applied by researchers as the first approximation in calculating changes in tsunami wave height [14][15]. In this study, Green's law is utilized to predict the potential tsunami wave height as the equation is simple but reliable and it had been used in many studies to estimate wave height when approaching coastal areas. The linear theory of Green's Law is derivation of conservation on potential energy located along the ray [15]:

$$h_f = \left(d_i / d_f\right)^{0.25} h_i \tag{8}$$

where $\left(d_i / d_f\right)^{0.25}$ (dimensionless) is the shoaling coefficient of Green's law, d_i (m) is the water depth at source point, d_f (m) is water depth at any shoreward point, h_i (m) and h_f (m) are the wave heights at source point and shoreward point respectively. In this study, the observation points of water depth are between 50 m to 60 m that will be substituted into d_i. For d_f, it has been decided that the tsunami wave height to be observed when approaching toe of the beach is assumed to be at 1 m water depth while h_i is the wave height at the observation point recorded by the simulation of TUNA-M2 model.

4. Results and Discussion

The tsunami wave's propagation simulated from the source of Manila Trench earthquake across South China Sea is presented in Figure 2. Most of the countries located within South China Sea including Philippines, Hong Kong, Taiwan and Vietnam experience significant tsunami waves a few hours after the generation phase. It can be seen that tsunami waves propagate towards the eight observation points are approximately after 9 hours post-earthquake occurrences. This is because of the distance between Peninsular Malaysia and Manila Trench earthquake source.

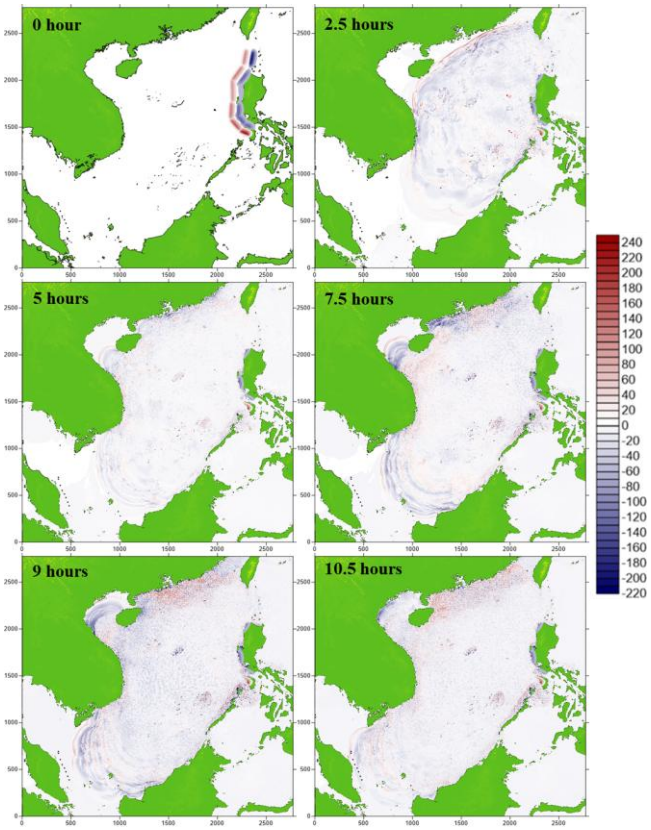


Fig 2: Time sequence for simulated tsunami waves propagation from Manila Trench earthquake source.

Figure 3 exhibits time series at the observation points (A to H) recorded by tsunami simulation of moment magnitude 9.0. Based on the graphs, it showed that all the observation points experienced leading elevation waves. The form is best characterized as the N-wave. Findings from this study established that the time arrival of tsunami waves from Manila Trench towards all observation points ranged from 9.13 h to 10.25 h.

4.1. Wave Arrival Time at Offshore Areas

Table 4 summarizes the simulated tsunami wave arrival time from Manila Trench earthquake source towards the observation points located at east-coast of Peninsular Malaysia with moment magnitudes of 7.5, 8.0, 8.5 and 9.0. The arrival time is taken when the first peak leading elevation wave arrives at each observation point. Results obtained from this study indicated that tsunami wave arrival time at different moment magnitude ranging from 7.5 to 9.0 did not exhibited significant differences. As an example, the tsunami waves hit observation point C at 9.72 h for all the moment magnitudes considered in the simulation. Other observation points

also displayed similar behavior since the tsunami waves propagate towards Peninsular Malaysia are found to show quite similar time arrival at each moment magnitude.

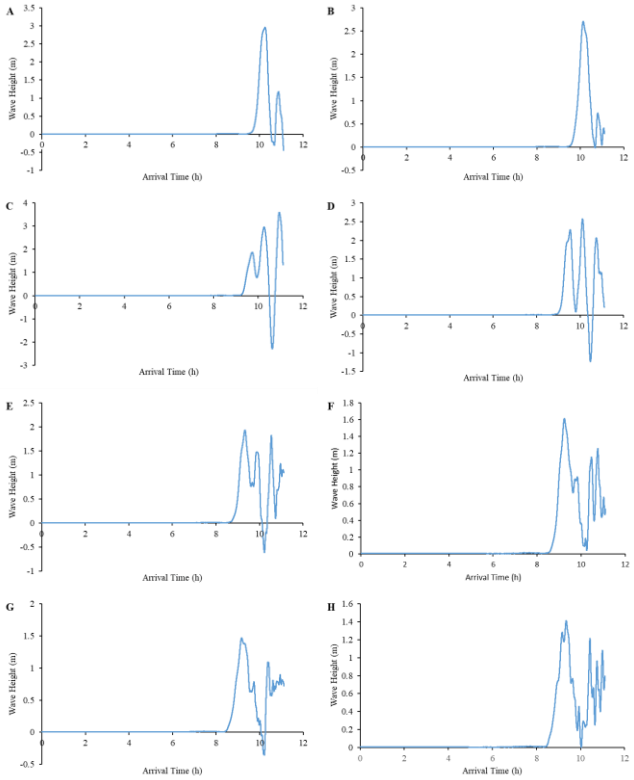


Fig 3: Simulated wave heights at observation points for earthquake tsunami of moment magnitude 9.0.

For moment magnitude 7.5, the wave arrival times are found to range from 9.1 h to 10.22 h, while the simulation for moment magnitude 8.0 and 8.5 indicated range of wave arrival time at 9.17 h to 10.27 h and 9.17 h to 10.26 h respectively. On the other hand, tsunami waves from Manila Trench at moment magnitude 9.0 reached the observation points located along east-coast of Peninsular Malaysia at almost similar time range as compared to other moment magnitudes which is between 9.17 h to 10.25 h. Hence, it can be concluded that tsunami waves originated from Manila Trench earthquake source will arrive at east-coast of Peninsular Malaysia approximately 9 hours post-earthquake occurrences. Observation point A is the last location anticipated to experience the tremendous tsunami waves at an average time of 10.25 h at all moment magnitudes, followed by point B at average time of 10.12 h. These two observation points are located in Kelantan. It can be concluded that Kelantan will be the last state located at east-coast of Peninsular Malaysia to be hit by tsunami waves generated from Manila Trench. Observation points situated at the offshore of Terengganu and Pahang are anticipated to experience tsunami waves in less than 10 h. The earliest wave is estimated to arrive at point G with average time of 9.15 h followed by point F and E at 9.22 h and 9.33 h respectively.

Table 4: Wave arrival time at observation points

Observation Point	Wave Arrival Time (h)			
	Mw: 7.5	Mw 8.0	Mw: 8.5	Mw 9.0
A	**10.22**	**10.27**	**10.26**	**10.25**
B	**10.08**	**10.13**	**10.12**	**10.13**
C	**9.72**	**9.72**	**9.72**	**9.72**
D	**9.51**	**9.53**	**9.54**	**9.54**
E	**9.29**	**9.35**	**9.33**	**9.33**
F	**9.19**	**9.22**	**9.24**	**9.24**
G	**9.10**	**9.17**	**9.17**	**9.17**
H	**9.31**	**9.36**	**9.35**	**9.36**

4.2. Wave Height at Offshore Areas

Table 5 presents results of tsunami wave height simulated using TUNA-M2 model at the observation points. In this study, the propagation simulation is set at 50 m to 60 m of water depth for all eight observation points situated along east-coast of Peninsular Malaysia. It was found that there was an incremental tsunami wave height, as the moment magnitude increases from Mw: 7.5 to Mw: 9.0. This showed that, earthquake with moment magnitude 9.0 generated the highest tsunami wave height towards observation points located at east-coast of Peninsular Malaysia followed by moment magnitude 8.5, 8.0 and 7.5 respectively. Larger moment magnitude provides larger wave height. Results obtained from moment magnitude 9.0 displayed significant tsunami wave height at east-coast of Peninsular Malaysia. These findings are worth the attention of coastal communities and relevant authorities. The two observation points located in Kelantan (A and B) are anticipated to experience the highest wave height generated from earthquake at moment magnitude 9.0. Each of these points is expected to experience tsunami wave height of 2.954 m and 2.705 m respectively. On the other hand, the leading elevation wave that propagates towards the six observation points (C, D, E, and F) located in Terengganu is anticipated to be at the range of 1.611 m to 2.284 m wave height. Point D is expected to experience the highest simulated wave height in Terengganu at 2.284 m height. It is also anticipated that tsunami waves from Manila Trench will reach observation points located in Pahang (G and H) at lower height as compared to Kelantan and Terengganu of approximately at 1.468 m to 1.41 m respectively. It is also found that the range of simulated wave height generated at moment magnitude 9.0 of Manila Trench earthquake are almost similar to the simulated wave heights of year 2004 Sumatera-Andaman tsunami that affected west-coast of Peninsular Malaysia namely Penang, Kedah and Langkawi [3].

Table 5: Simulated wave height at offshore areas

Observation Point	Wave Height (m)			
	Mw: 7.5	Mw 8.0	Mw: 8.5	Mw 9.0
A	**0.017**	**0.093**	**0.525**	**2.954**
B	**0.015**	**0.086**	**0.480**	**2.705**
C	**0.011**	**0.059**	**0.333**	**1.874**
D	**0.013**	**0.072**	**0.406**	**2.284**
E	**0.011**	**0.061**	**0.343**	**1.933**
F	**0.009**	**0.051**	**0.286**	**1.611**
G	**0.008**	**0.046**	**0.261**	**1.468**
H	**0.008**	**0.045**	**0.251**	**1.410**

On the other hand, it was found that tsunami wave heights at all observation points for moment magnitude 8.5 are less than 1 m height. The values obtained ranged from 0.251 m to 0.525 m. Point A located in Kelantan recorded the highest wave height among other points. This is followed by point B and D at 0.48 m and 0.406 m respectively. The lowest wave height is anticipated to be experienced at point H. Nevertheless, for moment magnitude 7.5 and 8.0, the leading elevation waves that propagate towards all observation points were found to be less than 0.1 m height. On the other hand, the range between 0.045 m to 0.093 m height was obtained for moment magnitude 8.0 and range between 0.008 m to 0.017 m height for moment magnitude 7.5.

4.3. Wave Height at Seashore Areas

This study proceeded by utilizing the Green's law in order to estimate tsunami waves heights that approach the coastline of east-coast Peninsular Malaysia. Thus, evaluation of tsunami wave's height upon arriving at the toe of the beach is important to the coastal communities. The prediction of tsunami wave height by using Green's law is reliable as it had been widely applied by researchers around the world. Rudyanto [16] found the consistency in comparing the results of tsunami wave heights at the coast

recorded from the tsunami simulation by using TUNAMI-N2 model and those obtained from the application of Green's law. Hettiarachchi [17] utilized the Green's law to extrapolate the tsunami wave height from 30 m water depth to 1 m water depth in order to determine the threat when approaching the coast.

In this study, the green's law is used to estimate the tsunami wave height at 1 m water depth based on the results of wave height recorded by using TUNA-M2 model at 50 m to 60 m water depth. By applying equation (8), wave heights at all eight observation points were calculated at 1 m water depth. Table 6 exhibits the results calculated for tsunami wave heights at 1 m water depth for point A to H for all moment magnitudes. The results showed that tsunami heights at 1 m water depth were amplified higher than the wave heights of 50 m to 60 m water depth. Since heights of tsunami waves were mainly influenced by moment magnitude of earthquake, Mw 9.0 provided the highest height of tsunami waves towards east-coast of Peninsular Malaysia.

Similar to simulation results obtained at the offshore, observation point A contributed the highest wave height at 8.187 m followed by another point located in Kelantan at 7.433 m. The observation points located in Terengganu were anticipated to experience wave heights ranging from 4.305 m to 6.163 m when approaching seashore areas. Tsunami waves that hit point G and H in Pahang were anticipated at the height of 4.069 m and 3.749 m respectively. The range of wave height at moment magnitude 9.0 is found to be between 3.749 m to 8.187 m. At these wave heights, it can be concluded that tsunami waves will incur devastating damages at east-coast of Peninsular Malaysia. Heights of the waves are found to range from 0.667 m to 1.455 m at moment magnitude 8.5. While for moment magnitude 8.0, the wave heights were found at less than 0.3 m with the range of 0.12 m to 0.258 m. On the other hand, the lowest wave height of tsunami generated from Manila Trench arriving at 1 m water depth along east-coast of Peninsular Malaysia's was found to be between 0.021 m to 0.047 m at moment magnitude 7.5.

Table 6: Wave heights at 1 m water depth located along east-coast of Peninsular Malaysia

Observation Point	Wave Height (m)			
	Mw: 7.5	Mw 8.0	Mw: 8.5	Mw 9.0
A	**0.047**	**0.258**	**1.455**	**8.187**
B	**0.041**	**0.236**	**1.319**	**7.433**
C	**0.030**	**0.162**	**0.915**	**5.149**
D	**0.035**	**0.194**	**1.095**	**6.163**
E	**0.030**	**0.167**	**0.938**	**5.288**
F	**0.024**	**0.136**	**0.764**	**4.305**
G	**0.022**	**0.127**	**0.723**	**4.069**
H	**0.021**	**0.120**	**0.667**	**3.749**

Green's law is a classic linear theory which expresses changes in wave height of periodic waves on plane beaches [18]. This theory showed that the evolution of wave height is based on shoaling coefficient due to the changes of water depth as wave travelled from offshore towards the onshore. Figure 4 displays shoaling coefficient for waves that travelled from the observation points (50m to 60 m water depth) towards 1 m water depth, based on changes of wave heights at moment magnitude 8.5. Note that, the shoaling coefficient ranges from 2.66 to 2.77. Hence, the wave heights that travelled from 50 m to 60 m of water depth towards 1 m water depth, can be amplified by a factor ranging between 2.66 to 2.77.

5. Conclusion

This study is carried out as an initiative to estimate tsunami wave heights when the waves approach the coastal areas of east-coast Peninsular Malaysia. Manila Trench subduction zone has been identified to be a potential source of earthquake that could generate massive tsunami at the regions within South China Sea. A total of 8 observation points located in Kelantan, Terengganu and Pahang were chosen with 50 m to 60 m water depth, selected for the propagation simulation using TUNA-M2 model. Results from earthquake of four different moment magnitudes were investigated in terms of tsunami wave heights and arrival times.

Results from this study showed that earthquake with moment magnitude 9.0 from Manila Trench generates the highest wave heights towards east-coast of Peninsular Malaysia, followed by moment magnitudes 8.5, 8.0 and 7.5. It can be concluded that, the larger the moment magnitude, the higher the occurrence of tsunami wave propagated towards the coastal areas. In addition, the results displayed that observation points located in Kelantan are anticipated to experience higher wave heights as compared to other locations in Terengganu and Pahang. The time range of tsunami waves arriving at the observation points did not show significant difference at each moment magnitudes. The simulation showed tsunami waves that travelled from Manila Trench towards east-coast of Peninsular Malaysia took about 9.1 h to 10.25 h post-earthquake occurrences.

The study then proceeded to estimate tsunami wave heights when approaching the coastline. Green's law was applied in order to predict possible tsunami heights at 1 m water depth. Tsunami wave heights at observation points were amplified by a factor ranging between 2.66 to 2.77 when arrived at 1 m water depth. The range of wave height at moment magnitude 9.0 is between 3.749 m to 8.187 m. Point A is anticipated to experience the highest wave height, while Point H will experience the lowest simulated wave height. At moment magnitude 8.5, the range of wave height is between 0.667 m to 1.455 m while for moment magnitude 8.0 and 7.5, the wave heights are less than 0.3 m and 0.05 m respectively. This study is pertinent as it provides vital information for coastal communities to prepare possibility of tsunami occurrences in the future.

Further study will be carried out to estimate height of tsunami wave run-up and inundation distance from Manila Trench as source of earthquake using numerical model and equations.

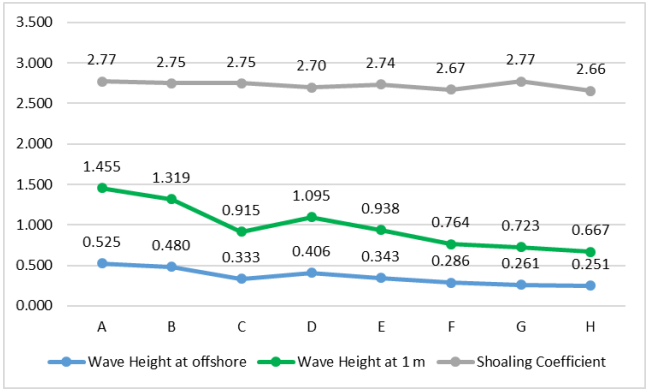


Fig 4: Shoaling coefficient for waves travelled from observation points towards 1 m water depth of coastal areas.

Acknowledgement

This study is funded by TNB Seeding Fund. Project code U-TG-CR-18-03: Institute of Power Energy (IPE), Universiti Tenaga Nasional, Malaysia and special acknowledgement to BOLD Scholarship 2017/18, Universiti Tenaga Nasional. The authors would like to specify sincere gratitude to USM on the collaboration.

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