Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2022, 9(3):16-26

Research Article ISSN: 2394 - 658X

Initial Tsunami Levels in the Manila Trench (Philippines) from Potential Megathrusts and 1 in 100 Year and 1 in 1000 Year Return Period Earthquakes

M A Sarker (PhD)

Technical Director, Royal HaskoningDHV, Westpoint, Peterborough Business Park, Lynch Wood, Peterborough PE2 6FZ, United Kingdom
E-mail: zaman.sarker@rhdhv.com

ABSTRACT

A potential Megathrust in the Manila Trench (Taiwan-Philippines) with earthquake magnitude Mw ≥ 9.0 cannot be ruled out. In this paper initialtsunami levels from potential Megathrusts (Mw 9.35 and 9.34) in the Manila Trench have been presented following approaches from previous studies by various authors. Then initial tsunami levels from an 1 in 100 year return period earthquake have been presented to support design of marine structures and facilities. Finally, initial tsunami levels from an 1 in 1000 year return period earthquake have been presented to support emergency and rescue planning and operation.The initial tsunami levels have been generated using the MIKE21 Toolbox of DHI. These initial tsunami levels can be used to drive a tsunami propagation model to derive tsunami levels at anywhere around the South China Sea region. The methodology described in this paper for generating initial tsunami levels in the Manila Trench could also be applied to this type of events at other sites around the world.

Key words: Tsunami, Natural Hazards, Megathrust, Manila Trench, South China Sea, Numerical Modelling, Port Development, Royal HaskoningDHV

1. INTRODUCTION

1.1 The Manila Trench

The Manila Trench as in Figure 1 (from Qiu et al., 2019) is an oceanic trench in the Pacific Ocean located west of the islands of Luzon and Mindoro in the Philippines. The trench extends from southern Taiwan to the southern tip of Luzon Island in the Philippines along the eastern margin of the South China Sea (SCS). The depth of Manila Trench is around 4.8km to 4.9km with the deepest point of 5.4km whereas the average depth of the South China Sea is from 4 km to 5 km (Liu et al, 2007).

The Manila Trench is created by subduction in which the Sunda Plate (part of Eurasian Plate) is subducting under the Philippine Mobile Belt producing this almost north-south trending trench. The convergent boundary is terminated to the north by the Taiwan collision zone, and to the south by the Mindoro terrane (Sulu-Palawan block colliding with south-west Luzon) (Wikipedia, 2021). The South China Sea plate subducted eastwards under the Philippine Sea Plate at the Manila Trench (Ku and Hsu 2009). Manila Trench is near north-south direction with a length of about 900km. The seismic focal depth along the trench becomes deeper from north to south (Hou et al., 2020). The convergence rate across the Manila Trench is about 8 cm/year (Megawati et al., 2009). The convergence rate in the northern zone (18°-23°N) is 90 mm/year eastward, in the middle zone (15°-18°N) is 60 mm/year eastward and in the southern zone (12°-15°N) is 50 mm/year north-eastward (Li et al. 2016).

1.2 Historical Megathrusts Worldwide since 1900

Large tsunamis are commonly generated by Megathrust (a giant earthquake) ruptures that occur along convergent plate boundaries (i.e. subduction zones) devastating near-field and far-field coastal countries. The Megathrusts worldwide since 1900 are listed in Table 1.

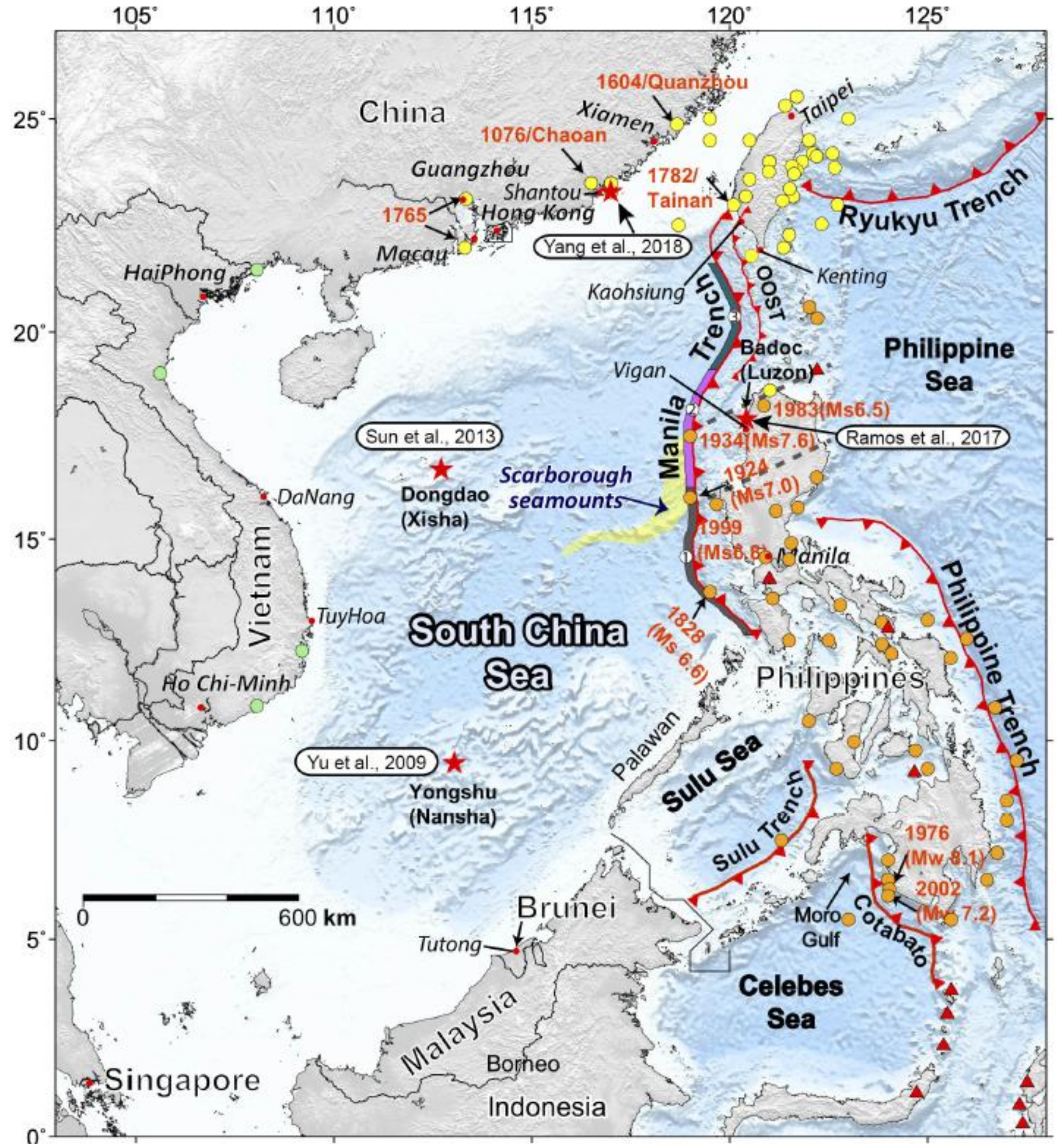

Fig. 1 Manila Trench [Source –Qiu et al. (2019), permission obtained]

Table 1 – List of the historical megathrusts worldwide since 1900

No.	Date and Year	Location	Magnitude (Mw)
1	4 November 1952	Kamchatka in far eastern Russia	8.8–9.0
2	22 May 1960	Chile	9.5
3	28 March 1964	Alaska	9.2
4	26 December 2004	Sumatra-Andaman along the Sunda Trench	9.2
5	27 February 2010	Maule in Chile	8.8
6	11 March 2011	Tohoku-Oki along the n-w border of Pacific Ocean	9.0

1.3 Potential Megathrust in the Manila Trench

The Megathrusts listed in Table 1and their associated subduction zones have been intensively studied whereas the Manila Subduction Zone (MSZ) receives less attention although it shares many similarities with megathrust systems where large tsunamigenic earthquakes have occurred (Qiu et al., 2019 from Hsu et al., 2012, 2016).

The subduction thrust under the Manila Trench has accumulated strain over a period of 440-years or more and could become another Megathrust (Wu and Huang, 2009; Megawati et al., 2009). Before the 2004 Megathrust there was doubt whether the Sunda Trench could sustain such a large earthquake. The 2004 event highlights the possibility of a similar Megathrust in the Manila Trench whose length is similar to the length of the Sunda Trench.

The Manila Subduction Zone has been identified as a high hazardous tsunamigenic earthquake source in the South China Sea region. No earthquake larger than Mw = 7.6 has been recorded in the past 100 years in this region (Liu et al., 2009). As reported in Liu et al. (2009) the largest earthquake in the Manila Subduction Zone in the past 100 years is about Mw = 7.5 (the 1999 Chi–Chi earthquake was Mw = 7.6 and the 1934 earthquake offshore from the northern Luzon was Mw = 7.5). The above suggests a high probability for a Megathrust in the Manila Trench with the magnitude and tragedy similar to the 2004 Indian Ocean tsunami.

As reported in Qiu et al. (2019), both historical earthquake records and modern seismicity databases indicate an absence of earthquakes larger than Mw = 7.6 in the region since the Spanish colonization of Luzon in the 1560s. The rate of plate convergence across the Manila trench is up to 90–100 mm per year which is faster than the convergence rate of the Sumatra, Japan, and Nankai subduction zones, all of which have hosted giant earthquakes in the past few decades. Therefore, a megathrust in the Manila Trench with potential Mw = 8.5+ cannot be ruled out. The above information was obtained from Qiu et al. (2019).

1.4 Impacts of a Potential Megathrust in the Manila Trench

The potential for a tsunami event originating along the Manila Trench similar in scale to the 2004 event has been forecasted. The forecasted earthquake along the Manila Trench has been predicted to be of magnitude Mw 9.3 (stronger than the Mw 9.2 magnitude of the 2004 event). This massive earthquake, which would be the second strongest in recent history, would have a total length of 990km and a maximum wave height of 9.3 metres. This event would cause serious flooding, especially in Taiwan, and could affect regions up to 8.5 km inland (Wu and Huang, 2009). The predicted tsunami would reach the southern coast of Thailand in around 13 hours and reach Bangkok in 19 hours. This disaster would also affect the Philippines, Vietnam, Cambodia and China (Ruangrassamee and Saelem, 2009).

The energy of the 2004 tsunami was distributed over a vast water body of the Indian Ocean and its beyond killing 230,000 – 280,000 people in 14 countries, displacing over a million people and damaging about US$15 billion (Sarker, 2019). The energy from a similar scale tsunami in the Manila Trench will primarily affects the countries bordering the South China Sea. If a large megathrust earthquake (e.g., Mw > 9) occurs within the South China Sea basin then the impact would be amplified and much more devastating as the South China Sea is only about 1/20 the size of the Indian Ocean (Qiu et al., 2019). The South China Sea coastline is one of the world's most densely populated region with more than 80 million people living in the surrounding coastal towns and cities (Qiu et al., 2019). The South China Sea coastline also hosts a high density of major infrastructure (such as seaports, airports and nuclear power plants). Even a moderate tsunami wave height will result to a large-scale disaster in many economically important coastal cities in the region such as Hong Kong and Macau which are only a couple of metres above the sea level (Liu et al, 2007).

As reported in Hou et al. (2020) from Mori et al. (2011), the Japan tsunami in 2011 killed at least 15,641 people and 5,007 people disappeared. It was deadliest natural disaster of Japan after the World War II. The post-disaster survey showed 10m-40m tsunami runup heights in many areas [in (Hou et al. (2020) from Mori and Takahashi 2012)]. Coastal areas of Fukushima, Iwate and Miyagi County were devastated by the tsunami. Most of the Sendai Airport runway was inundated and a nuclear leakage accident took place at the Fukushima Nuclear Power Plant. The above information was obtained from Hou et al. (2020). Similar if not worse disaster is expected from a Megathrust in the Manila Trench.

1.5 Previous Studies on the Manila Trench

In the 2006 USGS Tsunami Source Workshop (Kirby et al., 2006), three subduction zones namely, a) the Manila Subduction Zone b) Ryukyu Subduction Zone and c) N. Sulawesi Subduction Zone, were identified in the region as having high potentials to generate hazardous tsunamis (Liu et al., 2009). Tsunamis generated from the Ryukyu Subduction Zone mostly propagate into the Pacific Ocean due to the strike angle of the potential thrust faults in this region. On the other hand, tsunamis generated from the N. Sulawesi Subduction Zone are most likely trapped inside the Celebes Sea. Neither of these two sub-duction zones will have significant impacts on the countries surrounding the South China Sea (Liu et al., 2009). The 2006 Tsunami Source Workshop of USGS (Kirby et al., 2006) has divided the Manila Trench into six sub-faults as shown in Table 2.

Wu and Huang (2009) created and simulated a hypothetical Megathrust in the Manila Trench (as in Table 3) with Mw 9.35, fault length 990 km, fault width 200 km, focal depth 40 km and dislocation (slip) 20 m based on the information of the 1960, 1964 and 2004 Megathrusts listed in Table 1. Megawati et al. (2009) and Hou et al. (2020) modelled magnitude Mw 9.0 earthquake along the Manila Trench. Qiu et al. (2019) considered various rupture scenarios along the Manila Trench and simulated earthquake magnitudes Mw up to 9.18. Li et al. (2016) considered earthquakes Mw up to 9.0 in their study.

Ren and Liu (2015) carried out numerical modelling of a tsunami generated by earthquake Mw 9.3 using six sub-faults. They obtained latitude, longitude, dip angle and rake angle from USGS (Kirby et al., 2006) and strike angle from Wu and Huang (2009). Ren and Liu (2015) obtained the rest of the parameters from Nguyen et al. (2014) who developed a worst case source model along the Manila Trench.The final parameters used by Ren and Liu (2015) are shown in Table 4. The focal depth of the earthquake was not mentioned in Ren and Liu (2015) and, therefore, the author of this paper assumed it to be 40km from Wu and Huang (2009). The author of this paper calculated the earthquake magnitude with the

parameters in Table 4 from Ren and Liu (2015) and found Mw = 9.34 (which will be reported in the subsequent sections for consistency).
In the western North Pacific region, an earthquakewith magnitude Mw less than 5.3 normally does not generate a tsunami, and an earthquake with focal depth greater than 69 km generally does not trigger a tsunami (Hou et al., 2020).
The arrival time of a tsunami is defined as the instant when the water surface is elevated more than 1 cm above the mean sea level due to the arrival of the leading tsunami wave (Liu et al., 2009).

1.6 The Present Study

In this paper initial tsunami levels from potential Megathrust (Mw 9.35 and 9.34) in the Manila Trench have been presented following approaches from Kirby et al. (2006), Wu and Huang (2009) and Ren and Liu (2015). Then initial tsunami levels from an 1 in 100 year return period earthquake have been presented to support design of marine structures and facilities. Finally, initial tsunami levels from an 1 in 1000 year return period earthquake have been presented to support emergency and rescue planning and operation.
The general definition of tsunami level and tsunami wave height is illustrated in Figure 2. The flowchart in Figure 3 illustrates the steps and the software involved in a typical tsunami modelling study. The MIKE21 Toolbox developed by DHI was usedto generate the initial tsunami levels.

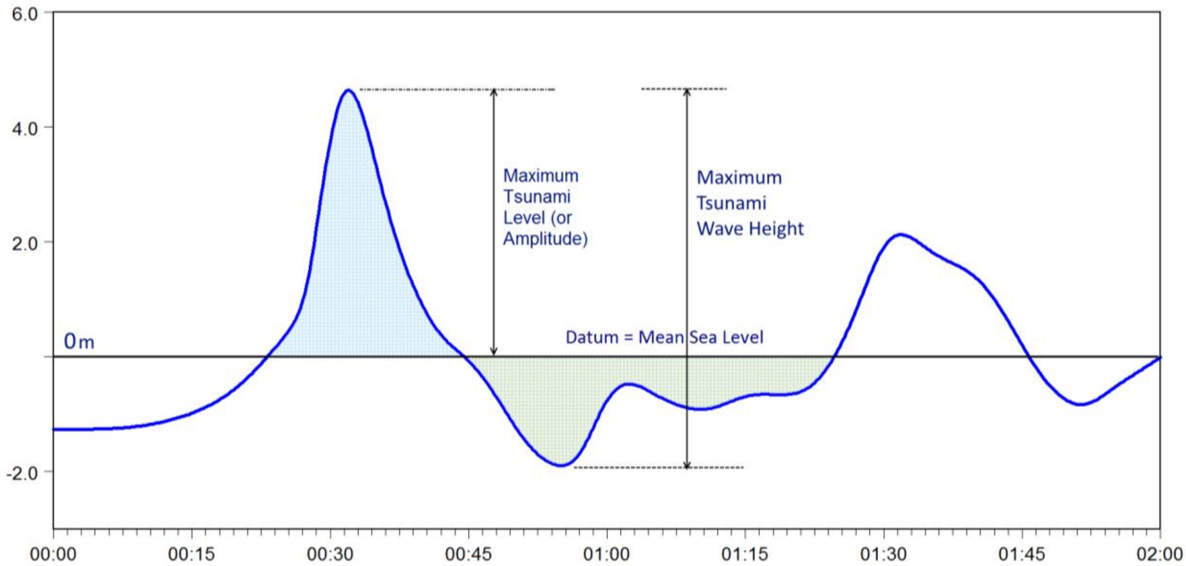

Fig. 2 General definition of tsunami level and tsunami wave height

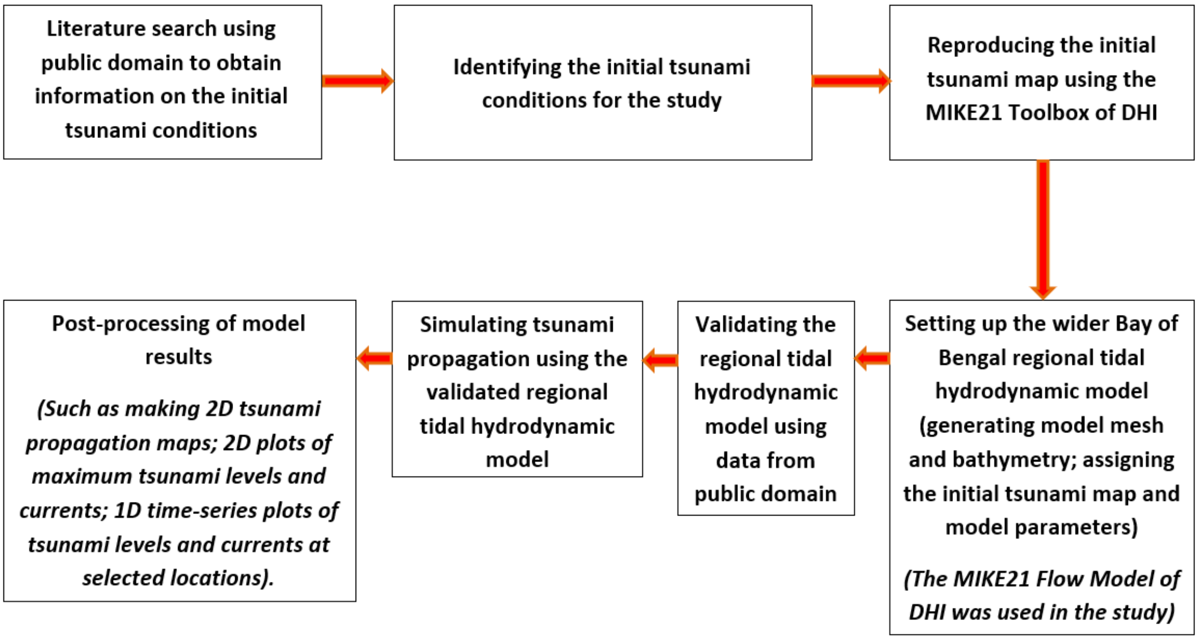

Fig. 3 Steps and software used in a typical tsunami modelling study

2. SELECTION OF EARTHQUAKE PARAMETERS

2.1 Potential Megathrust [Mw 9.35 and 9.34]

The location (latitude and longitude), length, strike angle, dip angle and rake angle of the six sub-faults were obtained from the 2006 Tsunami Source Workshop of USGS (Kirby et al., 2006) as shown in Table 2. The strike angles of the sub-faults issued by USGS ((Kirby et al., 2006) deviate from the seabed topography and, therefore, Wu and Huang (2009) slightly modified the sub-fault orientation to make these close to reality. Table 3 shows the strike angles modified by Wu and Huang (2009). The 1960, 1964 and 2004 Megathrusts have similar length varying from 740 to 1300 km, similar width varying from 200 to 300 km, and similar earthquake magnitude ranging from Mw = 9.0 to 9.5. Based on the information of these three Megathrusts, Wu and Huang (2009) created and simulated a hypothetical Megathrust in the Manila Trench with Mw 9.35, fault length 990 km, fault width 200 km, focal depth 40 km and dislocation (slip) 20 m. The final parameters used by Wu and Huang (2009) are provided in Table 3. Figure 4 shows the six sub-faults by Wu and Huang (2009) as in Table 3. Mw 9.34 from Ren and Liu (2015) as in Table 4 was also considered in the present study.

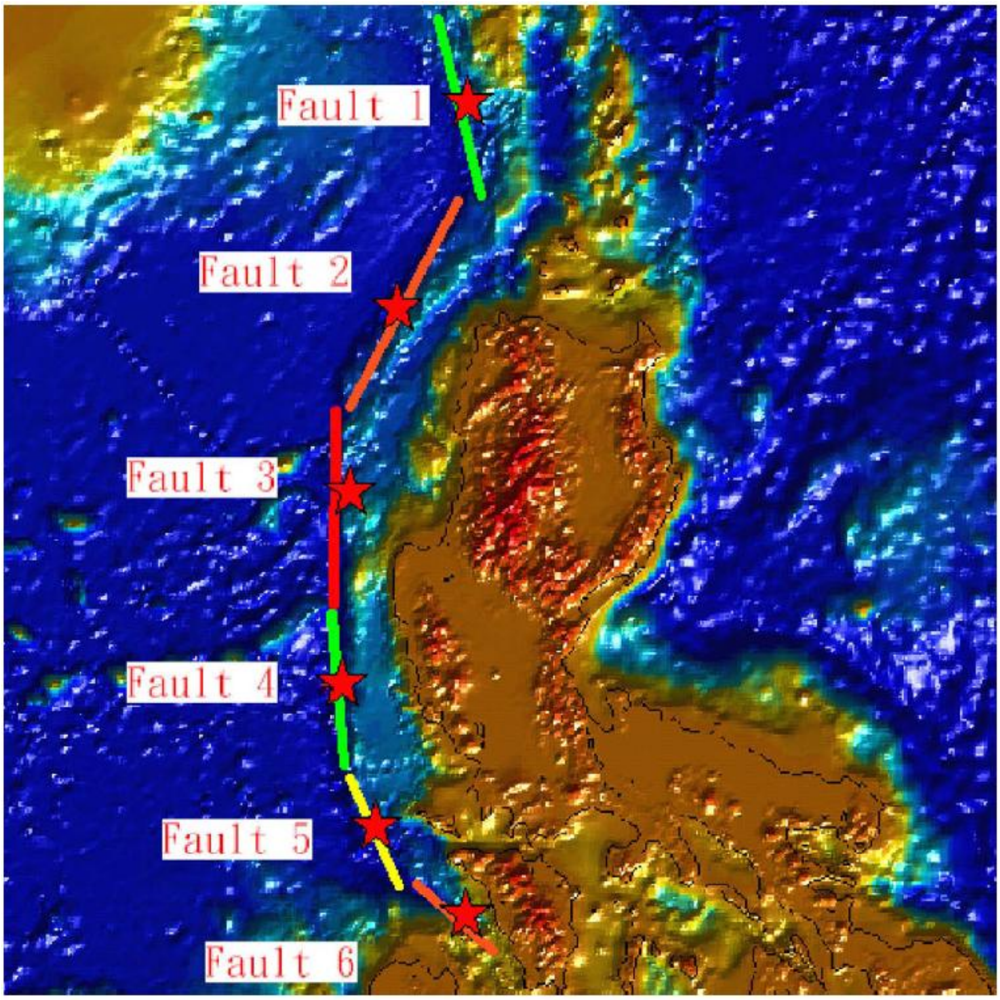

Fig. 4 Sub-faults from Kirby et al. (2006) with orientations modified by Wu and Huang (2009) [Source - Wu and Huang (2009), permission obtained]

The author of this paper suggests use of varying width and slip of the sub-faults instead of using constant values as in Table 3 byWu and Huang (2009). On the other hand Ren and Liu (2015) have concentrated the energy to sub-faults 2 and 3. It requires some sensitivity trials to decide the critical location of the higher energy for a particular project site.

Table 2 – Hypothetical fault planes along Manila Trench issued by USGS (Kirby et al., 2006)

Sub-faults	Latitude (°N)	Longitude (°E)	Length (km)	Strike (°N)	Dip (°)	Rake (°)
1	20.2	120.5	160	10	10	90
2	18.7	119.8	180	35	20	90
3	17.0	119.3	240	359	28	90
4	15.1	119.2	170	3	20	90
5	13.7	119.6	140	320	22	90
6	12.9	120.5	100	293	26	90

Table 3–Hypothetical fault parameters of the Manila Trench (Mw 9.35) from Wu and Huang (2009)

Sub-faults	Latitude (°N)	Longitude (°E)	Length (km)	Width (km)	Depth (km)	Slip (m)	Strike (°N)	Dip (°)	Rake (°)
1	20.2	120.5	160	200	40	20	354	10	90
2	18.7	119.8	180	200	40	20	22	20	90
3	17.0	119.3	240	200	40	20	2	28	90
4	15.1	119.2	170	200	40	20	356	20	90
5	13.7	119.6	140	200	40	20	344	22	90
6	12.9	120.5	100	200	40	20	331	26	90

Table 4 – Hypothetical fault parameters of the Manila Trench (Mw 9.34) from Ren and Liu (2015)

Sub-faults	Latitude (°N)	Longitude (°E)	Length (km)	Width (km)	Slip (m)	Strike (°N)	Dip (°)	Rake (°)
1	20.2	120.5	190	120	25	354	10	90
2	18.7	119.8	250	160	40	22	20	90
3	17.0	119.3	220	160	40	2	28	90
4	15.1	119.2	170	90	28	356	20	90
5	13.7	119.6	140	110	12	344	22	90
6	12.9	120.5	95	80	5	331	26	90

2.2 1 in 100 year earthquake [Mw 8.5]

Tsunami levels and forward velocity for an 1 in 100 year return period earthquake are required for designing marine structures and facilities.Therefore, initial tsunami levels were generated for an 1 in 100 year earthquake.

The earthquake magnitude (Mw) for various return periodsfor Philippines were obtained from Rong et al. (2014) and are provided in Table 5 and illustrated in Figure 5.

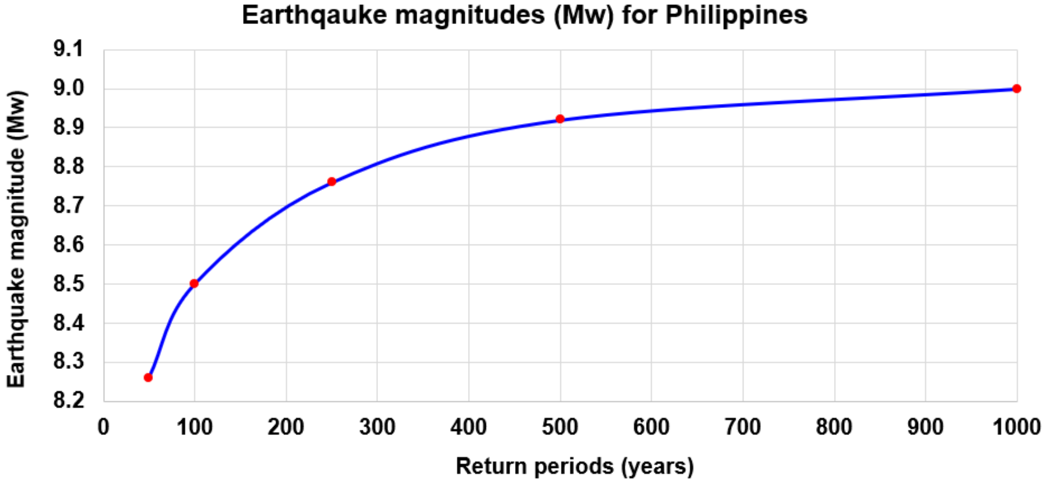

Fig. 5 Earthquake magnitudes (Mw) in Philippines for various return periods (data source -Rong et al., 2014)

Table 5 – Earthquake magnitudes for various return periods (Rong et al., 2014)

Return periods	Earthquake magnitudes (Mw)
1 in 50 year	8.26
1 in 100 year	8.50
1 in 250 year	8.76
1 in 500 year	8.92
1 in 1000 year	9.00

All parameters (except width and slip) were obtained from Table 2. Width and slip (or dislocation) were obtained from Liu et al. (2009). The final parameters for an 1 in 100 year earthquake are shown in Table 6. The resulting earthquake magnitude (as calculated by the author of this paper) is about Mw 8.5.

Table 6 – Fault parameters of an 1 in 100 year earthquake Mw 8.5 in the Manila Trench

Sub-faults	Latitude (°N)	Longitude (°E)	Length (km)	Width (km)	Depth (km)	Slip (m)	Strike (°N)	Dip (°)	Rake (°)
1	20.2	120.5	160	35	40	6.68	354	10	90
2	18.7	119.8	180	35	40	5.94	22	20	90
3	17.0	119.3	240	35	40	4.45	2	28	90

4	15.1	119.2	170	35	40	6.29	356	20	90
5	13.7	119.6	140	35	40	7.63	344	22	90
6	12.9	120.5	100	35	40	10.69	331	26	90

2.3 1 in 1000 year earthquake [Mw 9.0]

Tsunami levels for an 1 in 1000 year earthquake are required to support emergency and rescue planning and operation. Therefore, initial tsunami levels were also generated for an 1 in 1000 year earthquake.

All parameters (except width and slip) were obtained from Table 2. Width and slip were estimated to generate an earthquake magnitude Mw 9.0. The final parameters for an 1 in 1000 year earthquake are shown in Table 7.

Table 7 – Fault parameters of an 1 in 1000 year earthquake Mw 9.0 in the Manila Trench

Sub-faults	Latitude (°N)	Longitude (°E)	Length (km)	Width (km)	Depth (km)	Slip (m)	Strike (°N)	Dip (°)	Rake (°)
1	20.2	120.5	160	150	40	6	354	10	90
2	18.7	119.8	180	150	40	6	22	20	90
3	17.0	119.3	240	150	40	6	2	28	90
4	15.1	119.2	170	150	40	10	356	20	90
5	13.7	119.6	140	150	40	20	344	22	90
6	12.9	120.5	100	150	40	10	331	26	90

3. GENERATION OF INITIAL TSUNAMI LEVELS

It is assumed that the initial sea surface riseis the same as the final seafloor deformation after the earthquake. This is a reasonable assumption because the duration of an earthquake is generally short and the size of the rupture area is much larger than the water depth. Consequently there is not enough time for the water above the deformed seafloor to drain out. The seismic rupture is much faster thanwater wave propagation.

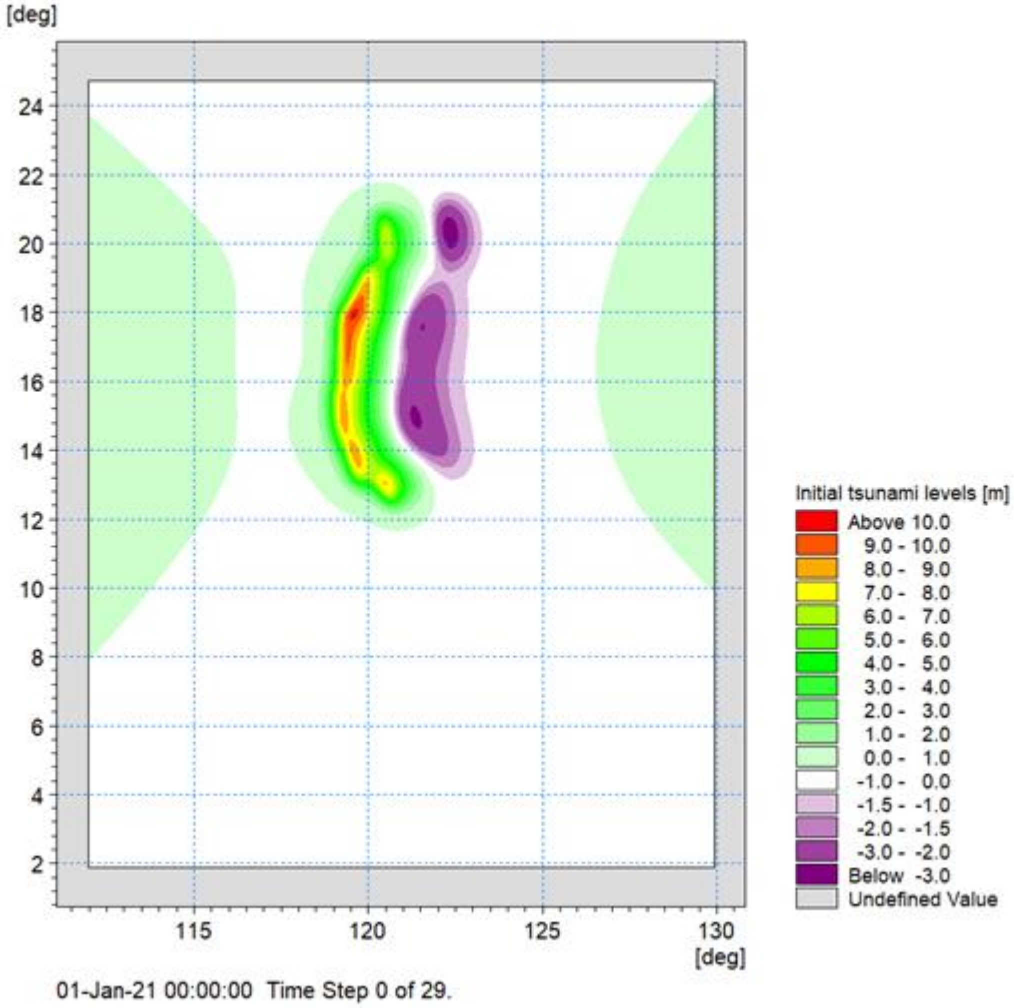

Fig. 6 Initial tsunami levels for a potential megathrust in the Manila Trench generated by Royal HaskoningDHV [Mw 9.35] for the parameters from Wu and Huang (2009)

Initial tsunami levels were generated for the earthquakes parameters in Tables 3, 4, 6 and 7 using the MIKE21 Toolbox developed by DHI (DHI, 2021).Square grid size of 10kmx10km was used for the domain to generate the initial tsunami levels. Initial tsunami levels for each sub-fault were generated separately and were then summed up to obtain the combined initial tsunami levels. Figures 6, 7, 8 and 9 show the initial tsunami levels for Mw = 9.35, 9.34, 8.50 (1 in 100 year) and 9.0 (1 in 1000 year) respectively. The maximum initial tsunami level for each of the conditions are provided in Table 8. It should be noted that the maximum initial tsunami level and its location for a given Mw will vary due to the distribution of the length, width and dislocation (slip) of the sub-faults (as seen in Table 8 for Mw 9.35 and 9.34).

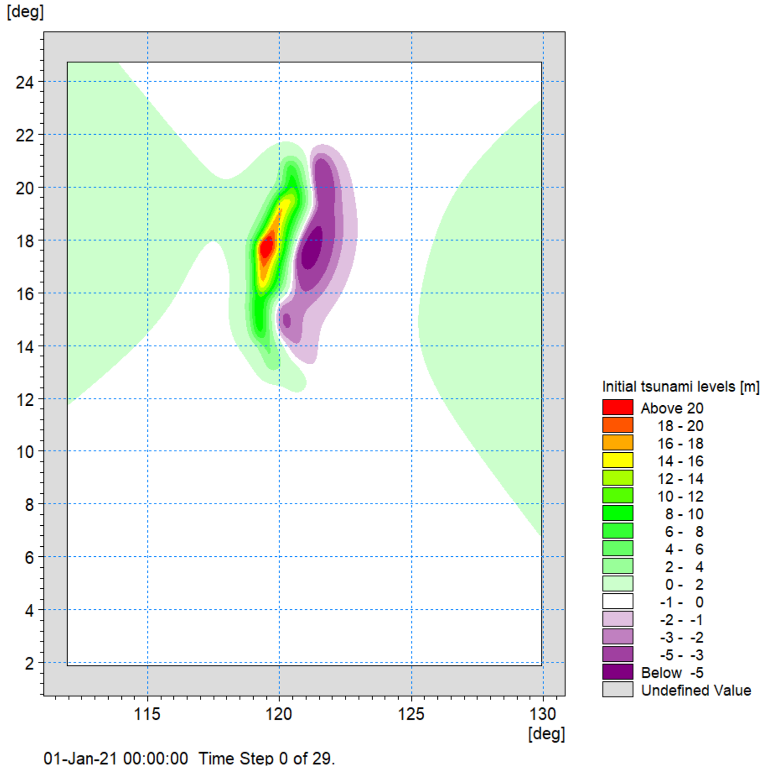

Fig. 7 Initial tsunami levels for a potential megathrust in the Manila Trench generated by Royal HaskoningDHV [Mw 9.34] for the parameters from Ren and Liu (2015)

Table 8 – Maximum initial tsunami levels

Earthquake magnitude (Mw)	Maximum initial tsunami levels (m)
9.35	10.4
9.34	24.5
8.5 (1 in 100 year)	2.0
9.0 (1 in 1000 year)	7.8

4. VALIDATION OF INITIAL TSUNAMI LEVELS

The maximum initial tsunami levels from the present study for earthquake magnitudes Mw = 9.35 and 8.5 were compared in Table 9 with those found by various previous authors. An approximately 2m maximum initial tsunami level was extracted from the black and white plot in Liu et al. (2009) which is very similar to the value from the present study. However, the present study seems to overestimate the maximum initial tsunami level for Mw 9.35. The colour scale in the seafloor deformation plot by Ren and Liu (2015) has an upper value of 20m and it is difficult to judge the maximum value from this plot.

Overall a reasonably good agreement was found between the maximum initial tsunami levels from the present study and those from the previous studies. Therefore, it was concluded that the initial tsunami levels generated in the present study are suitable to drive a tsunami propagation model with reasonable confidence.

Table 9 – Comparison of maximum initial tsunami levels

Authors	Maximum initial tsunami levels (m)		
	Mw = 9.35	Mw = 9.34	Mw = 8.5
Wu and Huang (2009)	9.3	-	-
Ren and Liu (2015)	-	>20.0	-
Liu et al. (2009)	-	-	2.0
Present study	10.4	24.5	2.0

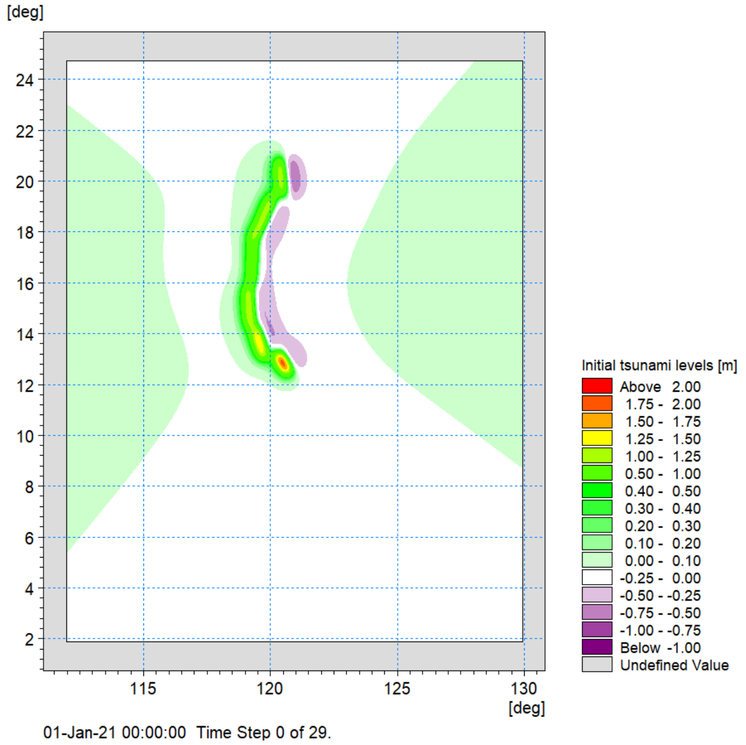

Fig. 8 Initial tsunami levels for an 1 in 100 year earthquake Mw 8.5 in the Manila Trench generated by Royal HaskoningDHV for the parameters from Liu et al. (2009)

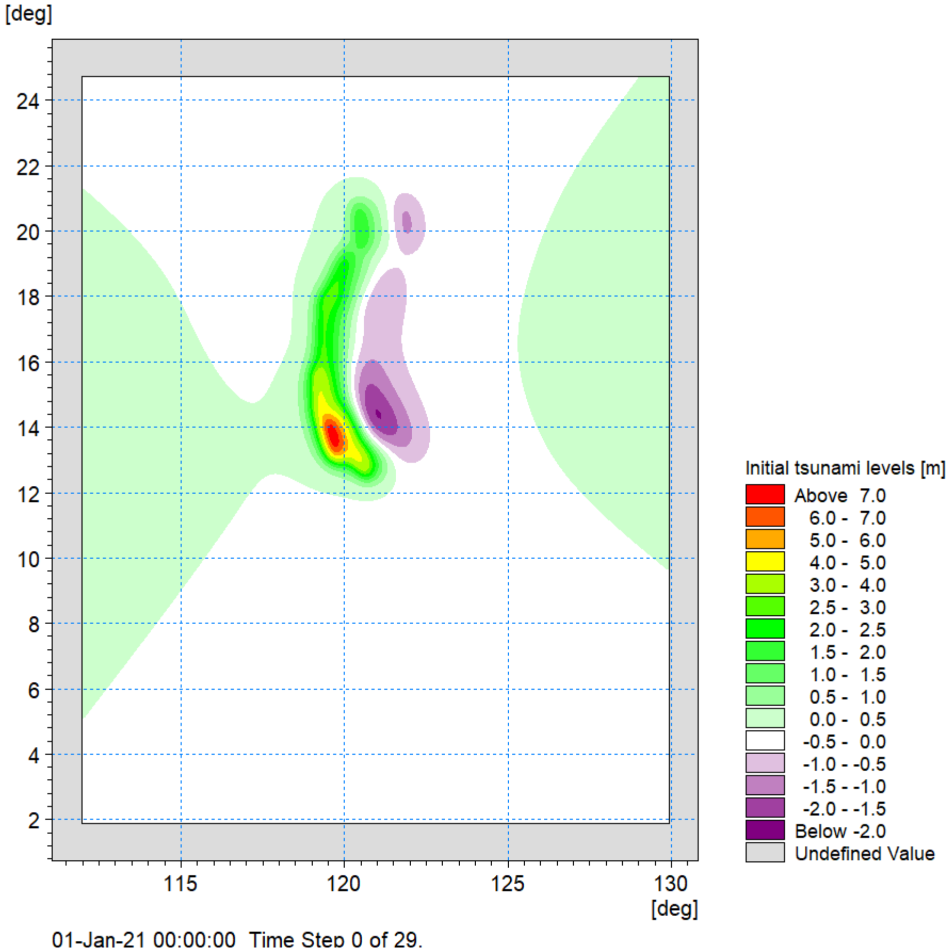

Fig. 9 Initial tsunami levels for an 1 in 1000 year earthquake Mw 9.0 in the Manila Trench generated by Royal HaskoningDHV

5. SUMMARY AND FINDINGS

Literature search suggests that a potential Megathrust in the Manila Trench with Mw ≥ 9.0 cannot be ruled out. Initial tsunami levels for Mw 9.35, 9.34, 8.50 (1 in 100 year) and 9.0 (1 in 1000 year) were generated in the present study using the MIKE21 Toolbox.

Maximum initial tsunami levels of 10.4m, 24.5m, 2.0m and 7.8m were found from the present study for Mw 9.35, 9.34, 8.50 and 9.0 respectively. These initial tsunami levels from the present study compare reasonably well with the values from previous studies by other authors. Therefore, the initial tsunami levels generated in the present study are suitable to drive a tsunami propagation model with reasonable confidence.

The maximum initial tsunami level and its location for a given Mw will vary due to the distribution of the length, width and dislocation (slip) of the sub-faults.

Acknowledgements

The author would like to thank Royal HaskoningDHV (an independent, international engineering and project management consultancy company, www.royalhaskoningdhv.com) for giving permission to publish this paper. The author would like to thank his colleague Debra Griffin for carrying out the proof reading of this manuscript. The author would also like to thank the external reviewer(s) who provided valuable comments to improve the paper.

REFERENCES

[1]. Qiu, Q., Li, L., Hsu, Y-J, Wang, Y., Chan, C-H., and Switzer, A. D. (2019). Revised earthquake sources along Manila trench for tsunami hazard assessment in the South China Sea. Natural Hazards and Earth System Sciences, 19, 1565–1583, https://doi.org/10.5194/nhess-19-1565-2019, 2019.

[2]. Jackson, A. (2019). Manila Trench, 29 July 2019, https://www.intelligentliving.co/wp-content/uploads/2019/07/Manila-Trench.jpg.

[3]. Liu, Y., Santos, A., Wang, S. M., Shi, Y, Liu, H. and Yuen, D. A. (2007). Tsunami hazards along Chinese coast from potential earthquakes in South China Sea. Physics of the Earth and Planetary Interiors, Volume 163, Issues 1-4, 15 August 2007, Pages 233-244. https://doi.org/10.1016/j.pepi.2007.02.012.

[4]. Wikipedia (2021). Manila Trench. https://en.wikipedia.org/wiki/Manila_Trench#CITEREFLiuSantosWangShi2007.

[5]. Ku, C.Y. and Hsu, S.K. (2009). Crustal structure and deformation at the northern Manila Trench between Taiwan and Luzon islands. Tectonophysics. 466(3–4):229–240.

[6]. Hou, J., Yuan, Y., Li, T. and Ren, Z. (2020). Tsunami hazard analysis for Chinese coast from potential earthquakes in the western North Pacific. Geomatics, Natural Hazards and Risk (Taylor & Francis), Volume 11, Number 1, page 967-983, DOI: 10.1080/19475705.2020.1766579.

[7]. Megawati, K., Shaw, F., Sieh, K., Huang, Z., Wu, T-R, Lin, Y., Tan, S., K. and Pan, T-C. (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 36 (2009) 13–20.

[8]. Li, L., Switzer, A. D., Chan, C-H, Wang, Y., Weiss, R. and Qiu, Q. (2016). How heterogeneous coseismic slip affects regional probabilistic tsunami hazard assessment: A case study in the South China Sea. Journal of Geophysical Research: Solid Earth, 121, 6250–6272, doi:10.1002/ 2016JB013111.

[9]. Hsu, Y.-J., Yu, S.-B., Song, T.-R. A., and Bacolcol, T. (2012). Plate coupling along the Manila subduction zone between Taiwan and northern Luzon. Journal of Asian Earth Sciences, 51, 98–108, https://doi.org/10.1016/j.jseaes.2012.01.005, 2012.

[10]. Hsu, Y.-J., Yu, S.-B., Loveless, J. P., Bacolcol, T., Solidum, R., Luis Jr., A., Pelicano, A., and Woessner, J. (2016). Interseismic deformation and moment deficit along the Manila subduction zone and the Philippine Fault system. J. Geophys. Res.-Solid, 121, 7639–7665, https://doi.org/10.1002/2016JB013082, 2016.

[11]. Wu, T-R, and Huang, H-C (2009). Modelling tsunami hazards from Manila trench to Taiwan. Journal of Asian Earth Sciences, Volume 36, Issue 1, 4 September 2009, Pages 21-28. https://doi.org/10.1016/j.jseaes.2008.12.006.

[12]. 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, 36 (2009) 2–12.

[13]. Ruangrassamee, A. and Saelem, N. (2009). Effect of Tsunamis generated in the Manila Trench on the Gulf of Thailand. Journal of Asian Earth Sciences, Volume 36, Issue 1, 4 September 2009, Pages 56-66. https://doi.org/10.1016/j.jseaes.2008.12.004.

[14]. Sarker, M. A. (2019). Numerical Modelling of the 2004 Indian Ocean Tsunami by Royal HaskoningDHV. International Journal of Innovative Studies in Sciences and Engineering Technology (IJISSET), Volume 5, Issue 7, 2019, ISSN 2455-4863 (Online), www.ijisset.org.

[15]. Mori N., Takahashi T. (2012). Nationwide post event survey and analysis of the 2011 Tohoku earthquake tsunami. Coastal Eng J. 54(1):1250001–1–1250001-27.

[16]. Mori N., Takahashi T., Yasuda T. and Yanagisawa H. (2011). Survey of 2011 Tohoku earthquake tsunami inundation and run-up. Geophys Res Lett. 38(7):1–6.

[17]. Kirby, S. et al. (2006). USGS Tsunami Sources Workshop (2006): Great Earthquake Tsunami Sources: Empiricism and Beyond, April 21-22 2006.
[18]. Ren, Z-Y and Liu, H. (2015). Numerical study of potential extreme tsunami hazard in South China Sea, 7th International Conference on Fluid Mechanics (ICFM7), Procedia Engineering 126 (2015) 332 – 338, doi: 10.1016/j.proeng.2015.11.201.
[19]. Nguyen, P. H., Bui, Q., C., Vu, P. H. and Pham, T. T. (2014). Scenario-based tsunami hazard assessment for the coast of Vietnam from the Manila Trench source, Physics of the Earth and Planetary Interiors 236(2014) 95-108.
[20]. Rong, Y., Jackson, D. D., Magistrale, H. and Goldfinger, C. (2014). Magnitude Limits of Subduction Zone Earthquakes. Bulletin of the Seismological Society of America, Vol. 104, No. 5, pp. 2359-2377, 16 September 2014, https://doi.org/10.1785/0120130287.
[21]. DHI (2021). MIKE Zero Toolbox User Guide, Agern Alle 5, DK-2970 Hosholm, Denmark.