Hydrodynamics Modeling of the Potential Tsunami Hazard from the Megathrust in South China Sea and the Possible Impact on Taiwan

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Abstract

The 2006 dual Ping-tung earthquakes highlighted the potential tsunami hazard from Manila trench. Lessons learned from the 2004 Aceh-Andaman tsunami, one shall understand the worst-case scenario in advance. In this study, we created a hypothetical earthquake tsunami scenario along the Manila trench based on the faults parameters issued by USGS and Harvard CMT. The magnitude of the scenario earthquake is Mw = 9.35. The total fault length is 990 km. The maximum initial free-surface height is 9.3 m. The profile is provided in this paper. An open source code, COMCOT, is adopted to perform the simulation for the tsunami propagation, runup, and inundation around Taiwan.

The result shows that the maximum wave height is about 11 m in southern Taiwan. Because of the edge wave effect, the southwest coast of Taiwan has a serious flooding. The tsunami inundation is able to reach 8.5 km inlandward. Due to the refraction effect, 8 m wave height is observed in the northeast coast of Taiwan. The detailed tsunami behavior around Taiwan is described in the context.

Key word: Taiwan tsunami, numerical simulation, COMCOT, Manila trench, edge wave.

1. Introduction

The Southern-west (SW) Taiwan has been considered as a region of tectonic escape because of infrequent intense seismic activities (Lacombe et al., 2001). However, the SW Taiwan is not immune to the attacks of large earthquakes. One piece of the evidence is the Ping-tung dual earthquakes on 26 December 2006. Two Mw = 7.0 offshore earthquakes with 8 minutes offset along with the 40 cm tsunami record highlighted the potential tsunami hazard on SW Taiwan coast.

Motivated by the Ping-tung dual earthquakes, we wish to understand the potential devastating tsunami event and the hazard to Taiwan. The epicenters of 2006 dual Ping-tung earthquakes is located at the north end of Manila (Luzon) trench, where the Eurasian plate is actively subducting eastward underneath the Luzon volcanic arc on the Philippine Sea plate. The east-dipping is initiated in the Miocene (22-25 Ma) and remains active to the present day (Yumul et al,, 2003; Queano et al., 2007). Recently, the USGS assessed Manila trench as a high risk zone to be a tsunami source. USGS Tsunami Sources Workshop 2006 further indentified six hypothetical fault planes based on the trench azimuth and the fault geometries (Table 1 and Figure 1A).

To study the potential devastating hazard in SW Taiwan, the historical tsunami might be able to provide useful information. The 2004 Sumatra-Andaman earthquake and Indian Ocean tsunami is one notorious reference (Titov et al., 2005; Choi et al., 2005). With a similar length to the 1,500 km Aceh-Andaman Megathrust, the subduction thrust under Manila Trench which has accumulated strain over a 440-year period could become another Megathrust.

In this study, we referred to the three largest earthquakes in history, Harvard CMT database, as well as the fault parameters issued by USGS, to create the worst-case scenario on the Tsunami Trench and to study the hazard on SW Taiwan. A numerical approach is adopted. The tsunami initial condition, maximum wave height, arrival time, wave period, and tsunami behavior in Taiwan water area is addressed and discussed.

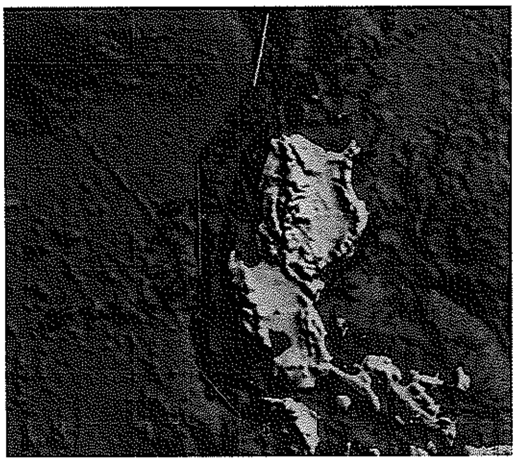


Figure 1A: Fault distriputation along Manila Trench. (Map provided by USGS)

Table 1. Hypothetical Fault Planes along Manila Trench issued by USGS

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

2. Fault parameters of Manila Megathrust

To characterize hypothetical fault planes along the Manila Megathrust, the historical largest tsunami earthquakes are referred. Table 2 showes the earthquake parameters of the three largest tsunami earthquakes. All three earthquakes have similar length varying from 740 to 1300 km, and similar width varying from 200 to 300 km. The earthquake magnitude ranged from Mw = 9.0 to 9.5. Using all of the information and referring to the fault geometry, a set of hypothetical fault of Manila Megathrust is nailed down (Table 3).

Table 2. Earthquake parameters of the three largest tsunami earthquakes

Date	Location	(Lon,lat)	Mw	Length (km)	Width (km)	Ddislocation (m)	Focal Depth (km)	Maximum water height (m)
1960/5/22	Chile	(74.5,39.5)	9.5	1000	300	No data	60	25
1964/3/28	Alaska	(-147.5,61.1)	9.2	540-740	300	18-22	23	67
2004/12/26	Sumatra	(95.98,3.3)	9	1300	200	20	28.6	50

(Data source: Catalog of Tsunamis in the Pacific Ocean, and Harvard CMT)

After identifying the earthquake parameters, the detailed fault parameters, such as the strike, dip, and rake angles of each fault segment. We adopted the fault parameters from the 2006 Tsunami Source Workshop which divided the Manila Trench into 6 segments. The adopted parameters are the epicenters, length, dip angle, and rake angle. The width is determined on Table 3. The Strike angle is referred to Harvard CMT record. The parameters used in this paper are shown on Table 4 and Figure 1B.

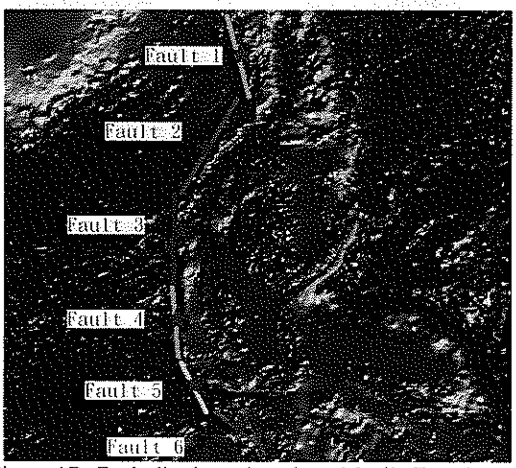


Figure 1B: Fault distriputation along Manila Trench used in present study.

Table 3. The earthquake parameters of Manila Fault

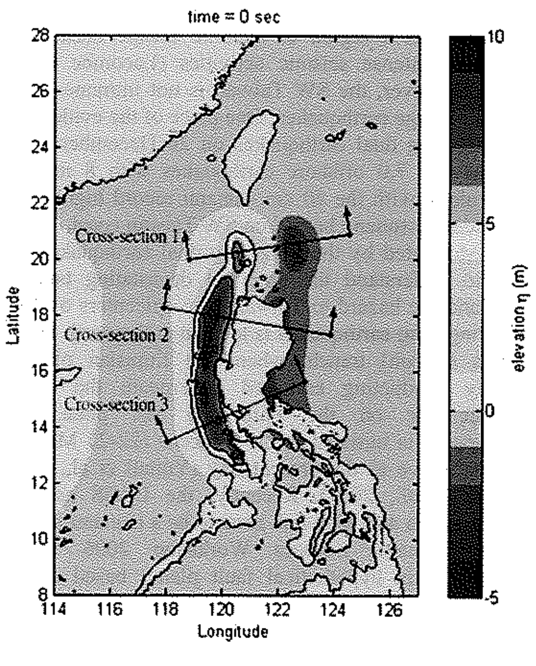
Manila Fault	Mw	Length (km)	Width (Km)	Dislocation (m)	Depth (km)
Total	9.35	990	200	20	40

The worst-case scenario is then created based on the parameters on Table 4. The tectonic movement is calculated based on the elastic dislocation theory proposed by Manshinha and Smylie (1971). We then followed the conventional approach to performing hydrodynamic simulation using the static deformation field as the initial condition. The approach is validated by the general rule that seismic rupture is much faster than water wave propagation. The initial free-surface profile is shown in Figure 2.

Table 4. The hypothetical fault parameters of Manila Trench

Fault	Longitude	Latitude	Length (km)	Width (km)	Dislocation (m)	Depth (km)	Strike (degree)	Dip (degree)	Rake (degree)
1	120.5	20.2	160	200	20	40	354	10	90
2	119.8	18.7	180	200	20	40	22	20	90
3	119.3	17	240	200	20	40	2	28	90
4	119.2	15.1	170	200	20	40	356	20	90
5	119.6	13.7	140	200	20	40	344	22	90
6	120.5	12.9	100	200	20	40	331	26	90

The maximum initial wave height is about 9.3 m (Figure 2, cross-section 2). For the fault 1 (Figure 1B), which is closest to Taiwan, the maximum initial wave height is about 8.1 m (Figure 2, cross-section 1).



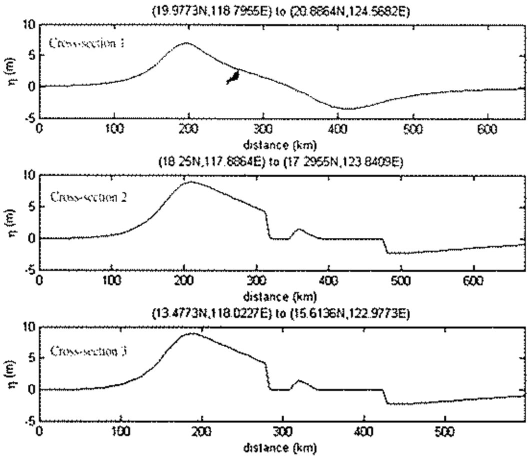


Figure 2: Initial free-surface profile (upper) and three cross-section profiles (lower)

3. Tsunami Propagation Model

The numerical approach is adopted in this study. The well validated open source code, COMCOT (Cornell Multi-grid Coupled Tsunami Model), is chosen to perform the whole simulation. The COMCOT model has been used to investigate tsunami events, such as the 1992 Flores Islands (Indonesia) tsunami (Liu et al., 1994; Liu et al., 1995), the 2003 Algeria Tsunami (Wang and Liu, 2005) and more recently the 2004 Indian Ocean tsunami (Wang and Liu, 2006). The COMCOT model is capable of solving both linear and nonlinear shallow water equations (SWE) on spherical and Cartesian coordinate systems. The nested grid is able to provide tsunami information at both the large scale deep-water region and small scale near-shore coastal region. COMCOT also provides the moving boundary algorithm to simulate the tsunami inundation (Wang and Liu 2006). The linear SWE which considers the Coriolis force is shown in Equation (1) and (2):

$$\frac{\partial \eta}{\partial t}+\frac{\partial P}{\partial x}+\frac{\partial Q}{\partial y}=0 \quad (1)$$

$$\frac{\partial P}{\partial t}+gH\frac{\partial \eta}{\partial x}-f\left(\frac{Q}{H}\right)=0$$
$$\frac{\partial Q}{\partial t}+gH\frac{\partial \eta}{\partial y}+f\left(\frac{Q}{H}\right)=0 \quad (2)$$

where: x, y are the horizontal coordinates,

η is the free-surface displacement,

$H=\eta+h$ is the total water depth,

h is the still water depth,

$P=Hu$, $Q=Hv$ are the horizontal volume discharges,

g is gravity, t is time,

f is the Coriolis coefficient.

The nonlinear SWE which considers the bottom friction is shown in Equation (3) and (4)

$$\frac{\partial \eta}{\partial t}+\frac{\partial P}{\partial x}+\frac{\partial Q}{\partial y}=0 \quad (3)$$

$$\frac{\partial P}{\partial t}+\frac{\partial}{\partial x}\left(\frac{P^2}{H}\right)+\frac{\partial}{\partial y}\left(\frac{PQ}{H}\right)+gH\frac{\partial \eta}{\partial x}+\tau_x=0$$
$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{PQ^2}{H}\right)+\frac{\partial}{\partial y}\left(\frac{Q^2}{H}\right)+gH\frac{\partial \eta}{\partial y}+\tau_y=0 \quad (4)$$

where τ_x and τ_y are the bottom frictions.

The bottom friction comes form Manning's formula and is expressed as:

$$\tau_x=\frac{gn^2}{H^{7/3}}P\left(P^2+Q^2\right)^{1/2},\tau_y=\frac{gn^2}{H^{7/3}}Q\left(P^2+Q^2\right)^{1/2} \quad (5)$$

In this paper, the linear spherical SWE model is used to simulate the distance tsunami away from Taiwan, and the nonlinear Cartesian SWE with bottom friction is used to simulate the near-field tsunami.

4. Bathymetry and Grid Setup

To simulate both far-field and near-field tsunami propagation, 4 grid layers are adopted and referred as Grid 1, 2, 3A, and 3B (Figure 3). The grid information as well as the governing equations are shown on Table 5. Grid 3A and 3B are set at the SW Taiwan to study the tsunami amplification and runup.

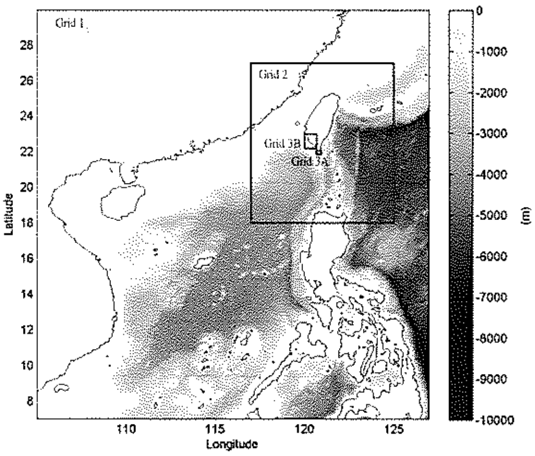


Figure 3: Computational domain and nested grids.

Table 5. The grid information of 4 gird layers.

	Grid 1	Grid 2	Grid 3A	Grid 3B
Coordinate	Spherical	Cartesian	Cartesian	Cartesian
Governing Equation	Linear SWE	Linear SWE	Nonlinear SWE	Nonlinear SWE
Grid size	2 min	1 min	7.5 sec	7.5 sec
Use bottom friciton	No	No	Yes	Yes
Manning's roughness coefficient	None	None	0.03	0.03
Cell number in x direction	660	480	128	328
Cell number in Y direction	690	540	104	400
Cell Number	455400	259200	13312	131200
			Total Cell Number	859112

5. Results and Discussion

To study the tsunami characteristics in Taiwan, several virtual wave gauges are installed. Figure 4 shows the virtual gauge location and the time-history free-surface elevation. Time zero denotes the instant when rupture at the Manila Trench occurs. It takes about 20 minutes for the first wave to arrive Kenting, a famous tour spot in Taiwan. The wave period is about 25 minutes at wg_3A_2 and wg_3A_3, and about 20 minutes at wg_3A_1. Due to the shallow water depth, a longer wave period is found at wg_3A_4. The maximum wave height is recorded at wg_3A_3, where the largest tourist population is located. At wg_3A_3, the first peak occurs at time = 23 minutes with wave height about 5 m. The maximum wave height happened at time = 40 minutes with wave height 11 m.

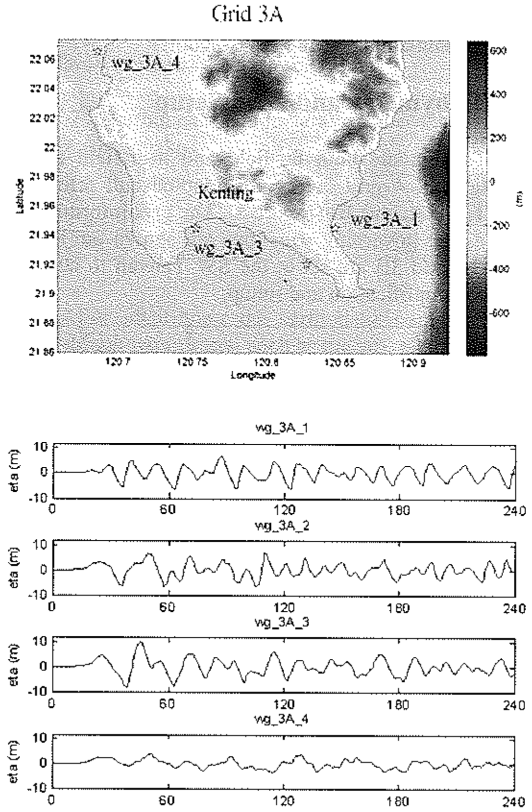


Figure 4. The virtual gauge location on Grid 3A and time-history free-surface elevation.

Figure 5 shows the virtual gauge results on Grid 3B. The leading wave height is 4 m at wg_3B_3 where Kao-hsung, the second largest city in Taiwan, is located. Because of the shallow water on the west coast of Taiwan, the period of tsunami wave becomes long. The wave period variation can be observed from wg_3B_1 to wg_3B_4. The wave period varies from 25 minutes at wg_3B_1 to 1 hour at wg_3B_4. The leading wave height of all four gauges is about 4 m. The edge wave effect is obvious at wg_3B_1. The wave amplitude oscillates up-and-down for 2 hours. The maximum wave height occurs at time = 140 minutes.

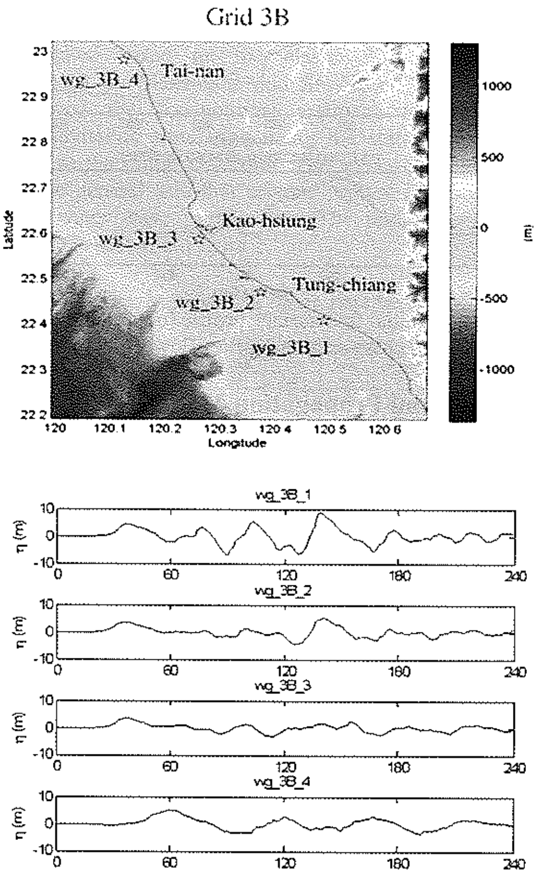


Figure 5. The virtual gauge location on Grid 3B and time-history free-surface elevation.

Figure 6 shows the maximum free-surface elevation and inundation area on Grid 3A, 3B, and 2. The map of free-surface elevation reveals the energy distribution and tsunami inundation. The map also indicates the dimension of the tsunami hazard. The tsunami hazard is significant at SW Taiwan. The inundation distance is about 0.5 km at Houbihu and 1 km at Ocean Museum (Figure 6A). Serious inundation with 8.5 km distance (Figure 6B) can be seen in Tungkang, 2 km in Kao-hsiung, and 4 km in Tan-nan (Figure 6B). Another serious flooding area is located in I-lan city (Figure 6C). Because of the cliff bathymetry on the east coast of Taiwan, the tsunami waves are able to travel northward with little energy losses. The northward propagating waves then concentrates in I-lan city due to the shallow and mild bathymetry. The simulation result shows that the wave height reaches 8 m in I-lan city.

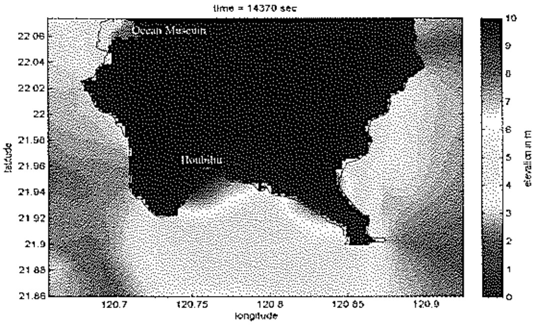


Figure 6A. Maximum free-surface elevation and inundation area on Grid 3A.

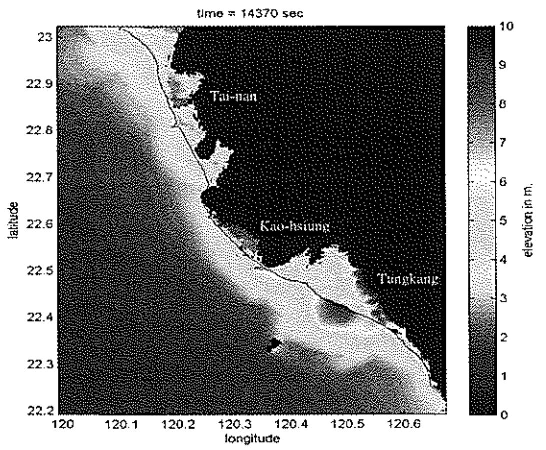


Figure 6B. Maximum free-surface elevation and inundation area on Grid 3B.

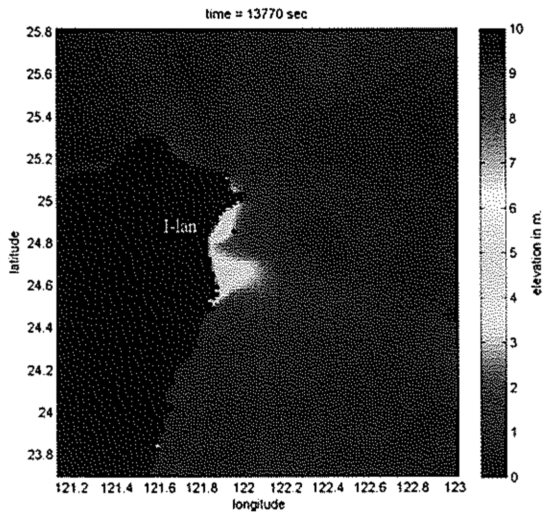


Figure 6C. Maximum free-surface elevation on Grid 2.

The current generated by tsunami could cause the ship to break away from the mooring. The resulting damage is ship oscillation, and collision with other ship or dock. The damage could cause the suspension of the harbor operation. The near-shore current speed induced by tsunami event is shown in Figure 7. The speed is at the range of 1 m/s, or 36 km/hr.

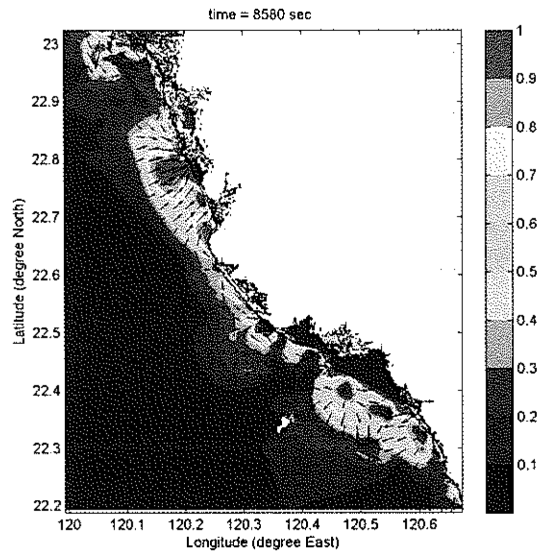


Figure 7. The velocity distribution at SW Taiwan. The color bar denotes the magnitude of the velocity vector.

6. Conclusion

From the hazard mitigation point of view, we shall clearly understand the potential devastating tsunami hazard. In this study, we created a worst-case scenario of tsunami earthquake excited by Manila Megathrust. The fault parameters are referred to the data issued by USGS, historical tsunamis, and Harvard CMT. The earthquake magnitude, Mw, is 9.35. The Total length of the Manila Megathrust is 990 km which is very close to the 2004 Sumatra-Andaman earthquake.

The initial tsunami profile was provided. The maximum initial wave height was 9.3 m (Figure 2). The tsunami propagation, runup, and inundation were studied numerically by COMCOT open source code. We focused the discussion on the Taiwan coastal region. The tsunami behavior around Taiwan is described carefully. In southwest Taiwan, the tsunami hazard is mainly caused by the edge wave effect. The maximum wave height is 11 m recorded at the wave gauge wg_3A_3 (Hobihu) (Figure 4). The wave height along SW Taiwan varies from 4 m to 10 m (Figure 5). Serious inundation is observed in Tungkung, Kao-hsiung, and Tai-nan (Figure 6B). The tsunami wave also attacked I-lan city in the northeast of Taiwan. The wave height was able to reach 8 m. It might be concluded that the tsunami hazard from Manila Megathrust is devastating in Taiwan, especially to the southwest and northeast coasts.

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