Tsunami hazard from the subduction Megathrust of the South China Sea: Part II. Hydrodynamic modeling and possible impact on Singapore

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A B S T R A C T

USGS has identified certain section of the Manila (Luzon) trench as a high-risk earthquake zone. This zone is where the Eurasian plate is actively subducting eastward underneath the Luzon volcanic arc on the Philippine Sea plate. An earthquake of magnitude 9.0 could be generated based on the worst case scenario rupture of Manila Trench. In this paper, the possible impact of this worst case scenario rupture on Singapore is investigated using a numerical model. It is found that (1) it takes about 12 h for the tsunami waves generated at Manila Trench to arrive at Singapore coastal waters; (2) the wave period of the tsunami wave, i.e., time interval between two peaks, is about 5 h; (3) the maximum water level rise in Singapore generated at Manila Trench to arrive at Singapore coastal waters; (2) the wave period of the tsunami wave, i.e., time interval between two peaks, is about 5 h; (3) the maximum water level rise in Singapore water is about 0.8 m; and (4) the maximum velocity associated with the tsunami waves is about 0.5 m/s, which is not likely to have significant impact on the port operations in Singapore.

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1. Introduction

Coastal areas and shorelines are exposed to potentially damaging effects from severe environmental conditions associated with long waves, such as tsunamis and storm surges, which may lead to wave run-up and landward inundation. After the devastating Indian Ocean tsunami in 2004 (see Titov et al. (2005), Choi et al. (2005), Narayan et al. (2005), for example), tsunami forecast and mitigation have been implemented by many coastal nations in and around the Indian and Pacific Oceans. Economic and long-term social impacts of tsunamis, as shown in the 2004 Asian tsunami, have been devastating (see Yalciner et al. (2005)). The goal of Operational Tsunami Prediction and Assessment System (OTPAS) in Singapore is to build Singapore’s capabilities in earthquake and tsunami modeling and forecasting by integrating cutting-edge scientific knowledge, software, equipment, monitoring stations, infrastructure and telecommunications in an automatic/semi-automatic warning system for Singapore. Recently USGS has identified the Manila (Luzon) trench as a high-risk earthquake zone, where the Eurasian plate is actively subducting eastward underneath the Luzon volcanic arc on the Philippine Sea plate. This subduction zone can also rupture and generate large tsunamis in the future that will have significant impacts on the countries in the South China Sea region. The rupture characterization of Manila Trench and the resulting tsunami waves in South China Sea are reported in Megawati et al. (2009). In this paper, we will focus on the numerical modeling of tsunami waves and the possible impact to Singapore.

The tsunami-induced devastation at any particular location is a function of the velocity, acceleration, and the elevation of water level as tsunami waves interact with natural and man-made coastal structures. The economic costs of strengthening local infrastructures and evacuating coastal areas are very high. More importantly, severe tsunamis and storm surges can cause significant losses in human lives. Singapore also has in its southern coastline, an estuarine reservoir – the Marina Bay, which is isolated from the sea by a tidal barrage with gates. Large waves overtopping the tidal barrage/gate could also set up other shock waves which could propagate deeper inland. The impact of the return waves could be equally devastating. Furthermore, the current associated with the tsunami waves could cause collision of ships mooring in the harbor. In this study, we will focus on the possible impact of the tsunami waves generated by the worst case scenario rupture at Manila Trench (see Megawati et al. (2009)), which could trigger an earthquake of magnitude 9.0. A clear understanding of the behavior of tsunami waves in Singapore coastal water is critical in developing appropriate warning system and evacuation strategies for Singapore.

Although field measurements of run-up of several recent tsunamis exist, they are insufficient because of the nature of after-the-event field surveys. Very little information about temporal variations can be obtained (except tide gauge data) and the data are often extremely spatially sparse. Furthermore, the source of tsunami generation cannot be accurately specified, since any information in deep...
water is difficult to obtain. Physical experimentation is valuable but it is costly and slow, and requires high-resolution, real-time capture of multidimensional data. It is also ephemeral, in that there is only one brief opportunity to capture suitable data for a particular run. Numerical experiments offer an attractive alternative. An excellent recent review on tsunami simulation can be found in Gisler (2008). One recent experimental study of non-breaking tsunami wave run-up on a plan beach is reported in Gedik et al. (2005). One breaking criterion for solitary waves on slopes was given by Grilli et al. (1997). A good discussion on breaking tsunami run-up was provided by Heller et al. (2005) and Li and Raichlen (2003). In this paper, we shall use a numerical model to investigate the characteristics of the tsunami waves in Singapore coastal water.

The outline of this paper is as follows: Section 2 briefly introduces the numerical model for studying tsunami waves in Singapore coastal water; Section 3 discusses the compilation of the geometrical data for the study; Section 4 presents and discusses the main results, and finally Section 5 summaries the main conclusions from this study.

2. Numerical model

Recently, as a result of a strong effort by the tsunami community, several two- and three-dimensional numerical models have been developed to study the generation and propagation of tsunami waves, and to quantify the interactions of tsunamis with shorelines. Example models include MOST described by Titov et al. (1997) and Tang et al. (2006), AnuGA described by Nielsen et al. (2005), COMCOT (Cornell Multi-grid Coupled Tsunami Model) described by COMCOT User Manual (2007) and Wang and Liu (2006), Tsunami-N2 developed at the Tohoku University, Japan.

The numerical model adopted in this study is COMCOT, which has been widely 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). With the flexible nested grids setup, we are able to perform simulations from near-coast regions to far-field regions. In this study, the wave breaking is not considered, thus the energy dissipation comes solely from the bottom friction.

COMCOT adopts the leap-frog time-differencing scheme to solve the following nonlinear shallow water equations on staggered grids

\[ \frac{\partial h}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0 \]  
\[ \frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left( \frac{P^2}{H} \right) + \frac{\partial}{\partial y} \left( \frac{PQ}{H} \right) - fQ + gh \frac{\partial h}{\partial x} + \tau_x h = 0 \]  
\[ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{PQ}{H} \right) + \frac{\partial}{\partial y} \left( \frac{Q^2}{H} \right) + fP + gh \frac{\partial h}{\partial y} + \tau_y h = 0 \]

where \( P \) and \( Q \) are fluxes in \( x \) and \( y \) directions, respectively. The instantaneous water depth is \( H = h + \eta \), with \( \eta \) being the surface displacement and \( h \) being the still water depth. In Eqs. (2.2),(2.3), \( g \) is the gravitational acceleration, and \( f \) is the Coriolis parameter describing the effects of earth rotation on wave propagation. For given Manning’s coefficient \( n \), the bottom shear stresses, \( \tau_x \) and \( \tau_y \), can be modeled by

\[ \tau_x = \frac{gh^2}{H^{5/3}} P \sqrt{P^2 + Q^2} \]  
\[ \tau_y = \frac{gh^2}{H^{5/3}} Q \sqrt{P^2 + Q^2} \]  

On open boundaries, radiation boundary conditions are used to eliminate the reflection from artificial boundaries.

In this paper we are interested in the numerical simulation of the tsunami waves excited by a hypothetical worst case scenario earthquake and the impact to the coastal area of Singapore. The simulation area covers the domain from Java, Indonesia, to Japan. In order to calculate the tsunami propagation from Manila Trench to Singapore coastal water, four nested grids are adopted. The grid resolution varies from 2.5 to 0.06 min from Grid 0 to Grid C. The number of grid cells varies from 1075 × 1275 for Grid 0 to 516 × 356 for Grid C. The total number of grid cells is 1,924,346. In Grids 0, A and B where water depth is of \( O \) (1000 m) and the wave height is of \( O \) (1–10 m), the nonlinear terms and the friction terms in Eqs. (2.2) and (2.3) can be ignored safely based on the following simple order of magnitude estimate

\[ \frac{\partial P}{\partial t} / \left( \frac{\partial}{\partial x} \left( \frac{P^2}{H} \right) \right) \gg 1, \quad \frac{\partial P}{\partial t} / \left( \frac{\partial}{\partial y} \left( \frac{PQ}{H} \right) \right) \gg 1 \]  
\[ \frac{\partial Q}{\partial t} / \left( \frac{\partial}{\partial x} \left( \frac{PQ}{H} \right) \right) \gg 1, \quad \frac{\partial Q}{\partial t} / \left( \frac{\partial}{\partial y} \left( \frac{Q^2}{H} \right) \right) \gg 1 \]  
\[ \frac{\partial P}{\partial t} / \left( \frac{\partial}{\partial x} \left( \frac{PQ}{H} \right) \right) / \tau_x H \gg 1, \quad \frac{\partial Q}{\partial t} / \left( \frac{\partial}{\partial y} \left( \frac{Q^2}{H} \right) \right) / \tau_y H \gg 1 \]

In this study, linear shallow wave equations are solved in spherical coordinates on Grid 0, Grid A, and Grid B, while the nonlinear shallow water equations are solved in Cartesian coordinates on Grid C. The detailed grid information can be found in Table 1. Nonlinear model is taken into account on Grid C with the bottom friction option being turned on. The Manning’s relative roughness coefficient used in Grid C is 0.013 (Table 1) (See Fig. 1).

The rupture model for the worse case scenario has been discussed in Megawati et al. (2009), where the earthquake fault parameter values used in the present simulation are listed in Table 1. The earthquake magnitude for this worst case scenario is \( M_w = 9.0 \). The initial surface profile for this worst case scenario is shown in Fig. 2. We used Okada (1985)’s model to calculate the initial free surface near the source. The maximum free surface elevation can be more than 15 m for the worst case scenario rupture at Manila Trench. This paper will focus on the tsunami waves in Sin-

Table 1

<table>
<thead>
<tr>
<th>Grid</th>
<th>Grid 0</th>
<th>Grid A</th>
<th>Grid B</th>
<th>Grid C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid cells (lon. × lat.)</td>
<td>1075 × 1275</td>
<td>520 × 360</td>
<td>515 × 355</td>
<td>516 × 356</td>
</tr>
<tr>
<td>Lat. Scope (Deg)</td>
<td>97.0106–139.9706</td>
<td>102.6406–113.0206</td>
<td>103.4526–105.5086</td>
<td>103.6031–104.1181</td>
</tr>
<tr>
<td>Lon. Scope (Deg)</td>
<td>-9.9743 to 40.9857</td>
<td>0.1757–7.3557</td>
<td>0.5877–2.4037</td>
<td>1.1382–1.4932</td>
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<td>1.2</td>
<td>0.24</td>
<td>0.06</td>
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<tr>
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<tr>
<td>Grid ratio</td>
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<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Time step (sec)</td>
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<td>1</td>
<td>0.2</td>
<td>0.05</td>
</tr>
<tr>
<td>Coordinates</td>
<td>Spherical</td>
<td>Spherical</td>
<td>Spherical</td>
<td>Cartesian</td>
</tr>
<tr>
<td>Governing equation</td>
<td>Linear SWE</td>
<td>Linear SWE</td>
<td>Linear SWE</td>
<td>Nonlinear SWE</td>
</tr>
<tr>
<td>Manning coefficient</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.013</td>
</tr>
</tbody>
</table>
Singapore coastal waters, including the arrival time, period between two peaks, maximum wave height distribution, and the velocity distribution in Singapore water.

3. Bathymetrical and topographical data

Bathymetrical data for the region outside of Singapore was derived from a public archive, ETOPO2, which is freely available from National Geophysical Data Center (NGDC), National Oceanic Atmospheric Administration (NOAA). ETOPO2 data has visible artifacts due to imperfect data integration. It is necessary to smooth the bottom bathymetrical data by removing rectangular artifacts so that they would not cause anomalous wave reflections. The bathymetrical data in Singapore water was complied from local survey data. Fig. 3 shows the bottom bathymetry in Singapore water after smoothing.

For further investigation, 3 virtual gauges are deployed in the study area. Gauge 1 is located near Marina Bay and Sentosa resort; Gauge 2 is located close to Johor Strait; and Gauge 3 is located close to Changi Airport, as shown in Fig. 3.

4. Results and discussion

Fig. 4 shows the time history of water levels recorded at three virtual wave gages shown in Fig. 3. The time zero denotes the instant when the rupture at Manila Trench occurs. It can be seen that it takes about 12 h for the tsunami waves to arrive at Singapore after traveling over a distance of 8000 km. This gives Singapore enough time to issue a warning and prepare evacuation if necessary. The maximum water level rise for the worst case scenario studied here is about 0.8 m at Marina Bay, about 0.7 m at both Johor Strait and Changi Airport. The period between two adjacent tsunami wave peaks is about 5 h, which is much longer than the period of typical tsunami waves. In a sense this is also good news for Singapore as it allows affected areas to have enough time to prepare for the subsequent attacks. Note that before the first peak arrives the coastal water does not retreat first. It takes about 1.5 h for the water level to reach the first peak. The tsunami wave impact can last more than 2 days, which could have adverse impact on Singapore. It should be mentioned that the effects of tides and the roughness related to coastal structures are not considered in our simulation. The local water level rise and the tsunami-induced inundation are sensitively dependent on the detailed local bathymetry and topography, which are not available now.

The map of maximum water level rise is shown in Fig. 5, which reveals the information on the tsunami energy distribution and magnitude. This figure shows that the maximum water level rise 40 h after the worst case scenario rupture of Manila Trench. In general, the water level rise in the area along the Singapore coast varies from 0.3 to 0.8 m. Near Jurong Island the maximum water level rise is about 0.6 m, while the maximum water level rise near Marina Bay could be as large as about 0.8 m. The largest water level rise in Johor Strait could go up to 0.7 m, because of the Johor causeway which stops the water and causes the water to pile up in front of the dam. Most coastal structures along the Singapore coast are
designed to resist a water level rise of 1.5 m, thus major flooding due to the tsunami waves is not expected in Singapore.

In addition to the damage caused by the large wave amplitude, which could cause flooding and destruction of coastal structures, the current induced by the tsunami waves could also cause damages to certain extent. The current associated with tsunami waves could cause ships to break away from their moorings, resulting in collision among ships, and damage to quay cranes and docks. Those damages could cause the port operations to be suspended and ships in the harbors to move out to the open seas. To assess the possible impact of the current associated with the worst case scenario tsunami waves, we examine the velocity distribution in Singapore water.

The depth-averaged mean velocity components, \( u \) and \( v \), can be calculated by the two flux components, \( P \) and \( Q \)

\[
\frac{u}{H} = \frac{P}{H}, \quad \frac{v}{H} = \frac{Q}{H}
\]

where \( H \) is the instantaneous water depth. The vertical structure of the current system cannot be resolved in the present model.

Fig. 6 shows the velocity distribution in Singapore coastal water 13.9 h after the rupture of Manila Trench. It can be seen that the maximum velocity associated with the tsunami waves is about 0.5 m/s, which occurs in Johor Strait and in some shallower parts of Singapore waters. In waters near Marina Bay and Jurong Island, the maximum velocity is between 0.2 and 0.25 m/s. Since the typical tidal current in Singapore water is about 1 m/s, it is expected that the current velocity associated with the tsunami waves is likely to have only minimum impact on the port operations in Singapore. The possible impact of the tsunami currents on ships mooring in the coastal waters where the velocity is about 0.5 m/s, however, needs further studies.

The period between the first two peaks in Singapore water is about 5 h, which is longer than what we would expect for typical tsunami waves. To investigate this interesting phenomenon, four virtual wave gauges (S01–S04) are deployed along the path of wave propagation from Manila trench to Singapore. The locations of these virtual wave gauges are shown in Fig. 7. S01 and S02 are in the region of Grid C, while S03 is in the region of Grid A. Gage S04 is in the region of Grid B.

Fig. 8 shows the time-history of the surface elevation for each virtual gauge shown in Fig. 7. Wave components of period less than 1 h can be observed in the region close to the rupture zone. From the initial surface elevation, it can be estimated that the initial tsunami would have a period of \( O(30) \) min. As waves propagate away from Manila Trench, tsunami waves of period less than 1 h travel over the vast reaches of relatively deep ocean. Starting from the gauge S03, tsunami waves enter the shallow water area, and short waves start merging to form a series of waves of longer period. The wave period changes from less than 1 h at the gauge S01 to about 5 h at the gauge S04. Currently there is no definite explanation to the long wave-period in shallower water found in this study. When
waves enter the shallower water, nonlinear wave-wave interactions become important. Two possible hypotheses are given here. It is well-known that the nonlinear wave-wave interactions among the wave components in an irregular sea may generate the so-called frequency down-shift phenomena (see Hara and Mei (1991)), for which wave energy transfers from short waves to long waves. It is possible that the long wave-period found in our simulation (1991), for which wave energy transfers from short waves to long waves. It may be concluded that major damage related to the tsunami event due to the rupture of Manila Trench is unlikely.

5. Conclusions

In this study, the worse case scenario (earthquake magnitude $M_w = 9.0$ at Manila Trench) is studied numerically. It takes about 12 h for the first peak of the tsunami waves to travel a distance of 8000 km from Manila Trench to Singapore. This indicates that Singapore has plenty of time to be prepared for the tsunami generated by the rupture of Manila Trench. The maximum water level rise recorded by the virtual wave gauges is 0.8 m in Singapore for the worst case scenario reported herein. The wave period (the time interval between two wave peaks) is about 5 h, and it takes about 1.5–2 h for the water level to reach the first peak. The maximum water particle velocity is 0.5 m/s in Singapore water. It may be concluded that major damage related to the tsunami event due to the rupture of Manila Trench is unlikely.

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References


