

Article

Scenario-Based Hazard Assessment of Local Tsunami for Coastal Areas: A Case Study of Xiamen City, Fujian Province, China

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Abstract: In this study, three worst-case credible tsunamigenic scenarios (Mw8.0) from Xiamen fault 1 (XF 1), Xiamen fault 2 (XF 2) and Xiamen fault 3 (XF 3) located off the coast of Xiamen were selected to assess the local tsunami hazard for Xiamen city, Fujian province, China. The GeoClaw model was utilized to compute the propagation and inundation of the tsunami for each scenario. The simulation results show that local tsunamis from XF 1–3 hit Xiamen within 1.5 h of earthquakes. The highest level of tsunami hazard in Xiamen is level II, which corresponds to an inundation depth ranging from 1.2 to 3.0 m. The areas with tsunami hazard level II in each scenario are primarily concentrated in the coastal areas of southern Haicang district and eastern Siming district, which are in the primary propagation direction of the tsunami. Since XF 2 and XF 3 are aligned almost parallel to the coastline of Xiamen, local tsunamis from XF 2 and XF 3 could cause more serious hazards to the coastal areas of Xiamen city. This work provides a typical case for researchers to understand the local tsunami hazard assessment for coastal cities. The research results can provide scientific references for the development of tsunami hazard assessment and early warning systems for coastal cities in southeastern China.



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Keywords: local tsunami; numerical modeling; hazard assessment; Xiamen city

1. Introduction

Tsunamis are widely recognized as one of the most destructive natural disasters, posing a significant threat to human life and property safety. Although tsunamis can be generated by earthquakes, submarine landslides, volcanic eruptions, and meteorite impacts [1–4], earthquakes are responsible for generating around 80% of all tsunamis, as indicated by the global historical record [5]. For example, the 2004 Indian Ocean tsunami and the 2011 Great East Japan tsunami were megatsunamis triggered by earthquakes, all of which caused huge human and economic losses [6,7]. These catastrophic tsunami events have caused countries around the world to pay great attention to the hazard assessment of earthquake-induced tsunamis in coastal areas.

There are two dominant approaches used for tsunami hazard assessment, the probabilistic tsunami hazard assessment (PTHA) and the scenario-based tsunami hazard assessment (also known as deterministic tsunami hazard assessment, DTHA). PTHA, which typically considers all potential tsunami events to assess the probability of a tsunami wave height exceeding the threshold level at a particular site over a certain period in the future, has been used in many previous studies. Horspool et al. [8] performed a probabilistic tsunami hazard assessment for Indonesia based on tsunamis generated from local, regional, and distant sources. The results suggest that Sumatra, Java, and northern Papua

have a 1–10% probability of experiencing a tsunami of height greater than 3.0 m per year. Liu et al. [9] developed a PTHA framework for the southeastern coastal region of China based on regional and local tsunami sources. The results showed that southern and central Fujian provinces had the highest hazard level. Scenario-based tsunami hazard assessment methods [10,11], which evaluate the tsunami hazard at a specific site by qualitatively defining and simulating a worst-case credible tsunamigenic scenario in one tsunami source qualitatively, have been widely used in many coastal countries in recent years. For example, Al-Habsi et al. [12] selected two worst-case credible tsunamigenic scenarios from western and eastern segments of the Makran subduction zone and simulated the tsunamis in each scenario for the Qurayyat region, northeast Oman. Based on the simulation results, tsunami hazard maps were produced for Qurayyat in each scenario. Santos et al. [13] took the 1755 Lisbon earthquake–tsunami event as the worst tsunami scenario and used the TUNAMI-N2 model to simulate the generation and propagation of the tsunami. They conducted a tsunami hazard assessment at Oeiras municipality (Portugal) based on the tsunami arrival time and water level height. Fan et al. [14] used the COMCOT model to simulate a worst-case local tsunami scenario caused by the maximum credible earthquake (Mw8.0) occurring at the Quanzhou fault along China's southeast coast and conducted a tsunami hazard analysis of the coastal area of Putian City based on the tsunami inundation depth. The results of these studies are essential for the prevention and mitigation of tsunami disasters in the affected regions.

China's coastline is 18,000 km long, and coastal areas are economically developed [15]. To predict and prevent possible future tsunami hazards, researchers have conducted numerous studies on potential earthquake-induced tsunami hazards in and around China's sea area [9,16–20]. The Ryukyu Trench and Manila Trench, as the main regional tsunami sources in China, have received extensive attention for a long time [21–25]. In addition, there are eight local tsunami sources near the continental shelf in the South China Sea [26,27]. Tsunamis from these local potential sources could affect coastal cities in southeast China. Xiamen is situated on the southeast coast of Fujian province in China and is one of the first groups of special economic zones established by the country, with a developed and densely populated economy. Three of the known potential local tsunami sources identified by previous studies [26,27] are located off Xiamen, which are Xiamen fault 1 (XF 1), Xiamen fault 2 (XF 2) and Xiamen fault 3 (XF 3). The local tsunamis from XF 1–3 could cause severe damage to coastal areas of Xiamen due to the short distance between the tsunami sources and the city's coastline and limited emergency response time. Therefore, it is necessary to conduct the hazard assessment of local tsunami for Xiamen city.

In this study, three worst-case credible tsunamigenic scenarios from XF 1–3 were selected to assess the local tsunami hazard for Xiamen city. The magnitude of the tsunamigenic earthquake in each scenario was determined as Mw8.0 according to the upper-limit earthquake magnitude of the local source. We then simulated the propagation and inundation of the local tsunami for each scenario based on the GeoClaw model. Finally, we produced the local tsunami hazard maps for Xiamen city based on the simulation results. The results will be beneficial for coastal cities in developing refined tsunami disaster contingency plans.

2. Study Area

Xiamen is in the southeast of Fujian province, adjacent to the Taiwan Strait to the east, and bordering Zhangzhou and Quanzhou (Figure 1). It is an important foreign trade port and a popular tourist city in China. Xiamen is administratively divided into six districts, namely Siming, Huli, Jimei, Haicang, Tong'an, and Xiang'an (Figure 1c). Xiamen's topography is mostly flat, with slightly higher elevation in the northwest and lower elevation in the southeast. The elevation of the coastal area is below 10 m. The flat terrain of Xiamen's coastal area makes it susceptible to potential tsunami events, which may cause significant damage to ports and coastal scenic areas.

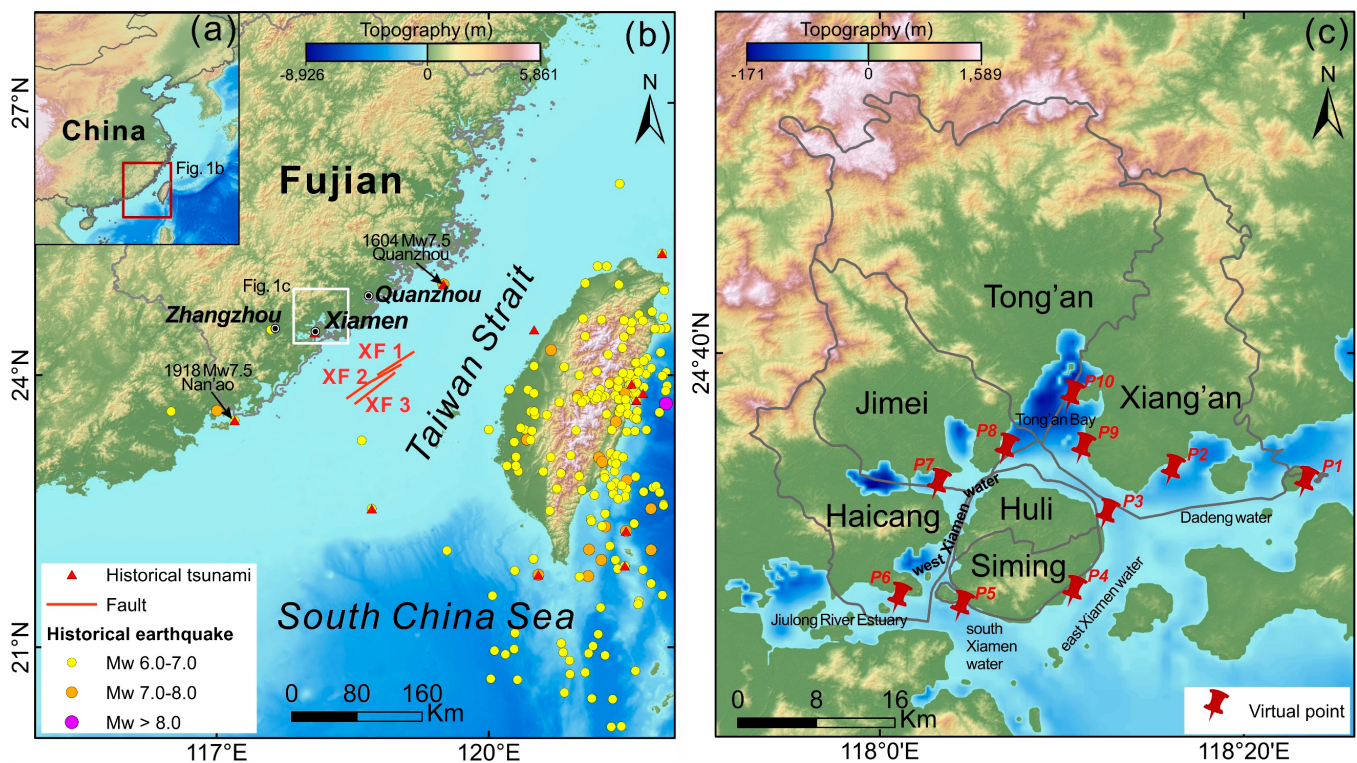


Figure 1. (a) Location of the study area. (b) Location of the local tsunami sources considered in present study and historical earthquakes and tsunamis occurred in the vicinity of the southeastern coast of China (1000 BC to 2023 AD). (c) Administrative divisions of Xiamen City and 10 virtual points in the model. XF 1: Xiamen fault 1; XF 2: Xiamen fault 2; XF 3: Xiamen fault 3.

Figure 1b shows the earthquake-induced tsunamis and earthquakes with magnitudes of 6.0 or higher occurred in the vicinity of the southeastern coast of China between 1000 BC and 2023 AD. Historical tsunami data were collected from the Global Historical Tsunami Database, which is released by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (www.ngdc.noaa.gov (accessed on 20 March 2023)), and historical earthquake data were obtained from the earthquake catalog of the United States Geological Survey (www.earthquake.usgs.gov (accessed on 21 March 2023)) and the earthquake statistical data recorded by the China Earthquake Networks Center (www.ceic.ac.cn (accessed on 20 March 2023)). Throughout history, the waters near Xiamen have experienced several tsunamis. In 1604, a tsunami was induced by a Mw7.5 earthquake that occurred along the coast of Quanzhou [14,28]. In 1918, a descending tsunami induced by the Mw7.5 earthquake off the coast of Nan'ao Island affected several cities along the coast of southern China [29,30]. These historical events indicate that Xiamen may be affected by local tsunamis from adjacent sea areas. By analyzing the Seismic Ground Motion Parameter Zonation Map of China (GB 18306-2015) and taking into account the regional geological structure, seismic activity, and stress field distribution, Ren et al. [27] identified eight potential local tsunami sources in the southeast coast of China. The Xiamen fault 1–3 (XF 1–3), located off Xiamen city, are three of the eight local sources, as shown in Figure 1b. Building on the findings of Ren et al. [27], we simulated the propagation and inundation of tsunamis triggered by the maximum credible earthquakes in XF 1–3, respectively. A total of ten evenly distributed virtual points (Figure 1c) were selected at a water depth of 10 m in the waters around Xiamen to analyze the tsunami wave propagation characteristics off the coast of Xiamen.

3. Data and Methods

3.1. Data

Detailed and accurate bathymetry and topographic data are required to obtain good results for tsunami simulations. The bathymetry and topographic data used in this study are shown in Table 1. Bathymetry data were obtained from the General Bathymetric Chart of Oceans 2022 (GEBCO_2022) data jointly released by the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC). Topographic data were obtained from ASTER Global Digital Elevation Model V3 (ASTER GDEM V3) data jointly released by National Aeronautics and Space Administration (NASA) and the Ministry of Economy, Trade and Industry (METI) of Japan. The modelling domains are formed from these two data for tsunami modelling.

Table 1. Bathymetry and topographic data for tsunami modelling.

Name	Type	Coordinates	Resolution
GEBCO_2022	Bathymetric data	Geographic	15 arc second (~460 m)
ASTER GDEM V3	Topographic data	Geographic	1 arc second (~30 m)

3.2. Methods

3.2.1. Design of the Earthquake Scenarios

Table 2 provides a list of the notation of parameters used in this study. Supposing that XF 1, XF 2 and XF 3 are all thrust-type faults, three worst-case credible tsunamigenic scenarios from XF 1–3 were selected. Referring to the upper-limit earthquake magnitude of these three local sources proposed by Ren et al. [27], the magnitude of the tsunamigenic earthquake in each scenario is determined as Mw8.0. The fault strike, rake, dip and source depth were set to the values provided by Ren et al. [27].

Table 2. Notations.

Notation	Definition
Mw	Seismic moment magnitude
L	Length of the fault plane
W	Width of the fault plane
M ₀	Seismic moment
D	Average coseismic slip
μ	Shear rigidity of the Earth's crust
t	Time
h	Total water depth
b	Bottom elevation function
u	Depth-averaged velocities in x directions
v	Depth-averaged velocities in y directions
g	Gravity acceleration
n	Manning coefficient
τ _x	Bottom friction terms in x directions
τ _y	Bottom friction terms in y directions

The fault length and width are estimated by the empirical relationship formula proposed by Blaser et al. [31]:

$$\log L = -2.37 + 0.57 \times Mw \quad (1)$$

$$\log W = -1.86 + 0.46 \times Mw \quad (2)$$

where Mw is the seismic moment magnitude, L is the length of the fault plane and W is the width of the fault plane.

The average slip was estimated using the following equation [32]:

$$M_0 = \mu LWD \quad (3)$$

where M_0 is the seismic moment, D is the average coseismic slip and μ is the shear rigidity of the Earth's crust. In this study, μ was set to 35 GPa for the Chinese mainland [9,27]. M_0 could be estimated based on the conversion relationship between M_w and M_0 [33]:

$$M_w = \frac{2}{3} \log M_0 - 10.7 \quad (4)$$

The earthquake parameters used in each scenario are shown in Table 3. We simply adopted the instantaneous rupture as the fault rupture model. Previous numerical simulation studies of earthquake-induced tsunamis have extensively used instantaneous rupture models [15,34]. In recent years, it has been demonstrated that the tsunami wave height is sensitive to the fault rupture process [35,36]. However, considering the complexity of the fault rupture process and the difficulty of accurate prediction, the use of instantaneous rupture without the support of more observational data is acceptable in this study.

Table 3. Earthquake parameters used in each scenario.

Scenario	Location	M_w	Length (km)	Width (km)	Strike (°)	Dip (°)	Rake (°)	Depth (km)	Slip (m)
S1	XF 1	8.0	155	66	58	60	90	20	3.13
S2	XF 2	8.0	155	66	57	60	90	20	3.13
S3	XF 3	8.0	155	66	53	60	90	20	3.13

3.2.2. Tsunami Numerical Model

The propagation and inundation of tsunamis are simulated in this paper using the GeoClaw numerical model [37]. The GeoClaw model is grounded on the nonlinear shallow water equation, which implements a high-resolution finite volume method on a rectangular grid and adopts adaptive mesh refinement (AMR). The nonlinear effects of tsunami wave propagation in coastal oceans are considered in the model. The 2D nonlinear shallow water equations are written as

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \quad (5)$$

$$\frac{\partial(hu)}{\partial t} + \frac{\partial}{\partial x} \left(hu^2 + \frac{1}{2}gh^2 \right) + \frac{\partial(huv)}{\partial y} = -gh \frac{\partial b}{\partial x} - \tau_x \quad (6)$$

$$\frac{\partial(hv)}{\partial t} + \frac{\partial(huv)}{\partial x} + \frac{\partial}{\partial y} \left(hv^2 + \frac{1}{2}gh^2 \right) = -gh \frac{\partial b}{\partial y} - \tau_y \quad (7)$$

where t represents time, $h(x, y, t)$ is total water depth, $b(x, y)$ is the bottom elevation function, $u(x, y, t)$ and $v(x, y, t)$ denote the depth-averaged velocities in x and y directions respectively, g is the acceleration due to gravity. The bottom friction terms could be written as

$$\tau_x = \frac{gn^2}{h^3} hu \sqrt{(hu)^2 + (hv)^2} \quad (8)$$

$$\tau_y = \frac{gn^2}{h^3} hv \sqrt{(hu)^2 + (hv)^2} \quad (9)$$

where n is the Manning coefficient and represents the roughness of the bottom.

In this study, the computational domain ranges from 115° E to 122° E and 20° N to 28° N (Figure 1b). Three mesh layers were used to simulate for the AMR, with a ratio of 1:8:15. The resolution of the coarsest grid was set to 2 arcmin; the resolution of the finest

grid was set to 1 arcsec. Referring to the model setup of Li et al. [30] in simulating the impact of the 1918 Nan'ao earthquake-induced tsunami on the southeast coast of China, we set the Manning coefficient as 0.013 in the computational domain. The computing platform used for the numerical simulation was an Inter (R) Xeon (R) Silver 4216 CPU @ 2.10 GHz with 64 gigabytes of memory and 32 cores. The simulation time was 6 h from the beginning of the earthquake.

4. Results

4.1. Characteristics of Tsunami Wave Generation and Propagation

The initial sea surface elevation was calculated using the Okada model [38] based on earthquake source parameters. Figure 2a–c show that negative waves close to -2.0 m appear on the landward side and positive waves close to 2.5 m on the seaward side in the direction perpendicular to the fault for each scenario. The wave height is uniformly distributed along the strike of the fault.

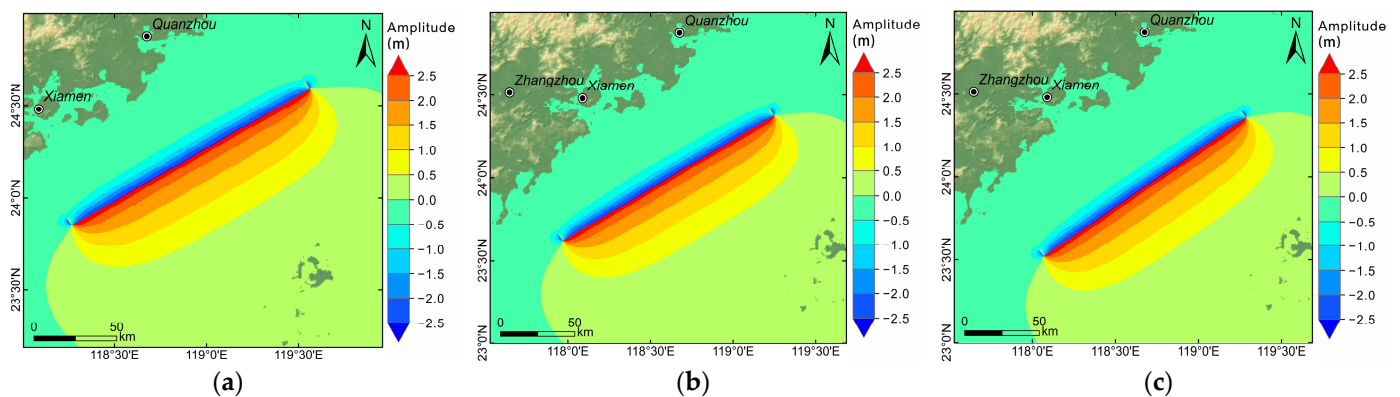


Figure 2. Spatial distributions of initial sea surface elevation for S1 (a), S2 (b) and S3 (c) scenarios.

As shown in Figure 3a–c, due to the close location between tsunami sources, the tsunami in each scenario reaches the nearest coast of Xiamen within 1.5 h of the earthquake and spreads to all coasts of Xiamen about 2 h later. Figure 3a shows that the tsunami from XF 1 hits the coast of Zhejiang province 4 h after the earthquake and reaches the coast of Guangdong province 2 h later. Figure 3b,c show that the tsunamis from XF 2 and XF 3 arrive at the coast of Zhejiang province 4.5 h after the earthquake and spread to the coast of Guangdong province 1.5 h later. Moreover, the decisive effect of submarine topography on tsunami propagation can be seen in Figure 3. Since the speed of tsunami propagation is proportional to the square root of the water depth, tsunami waves propagate faster in deep ocean areas than in near-shore waters. This is also reflected by the denser isochrones on the coastal shelf in Figure 3a–c. In summary, we conclude that the continental slope and shelf area slows down the propagation speed of the tsunami and the time to reach the coast.

Figure 4 shows that the surface elevation timeseries for each scenario at 10 virtual points around the Xiamen coast. The phenomenon of water recession is first observed in the coastal areas of Xiamen after the earthquake. The tsunami from XF 1 takes the shortest time to reach Xiamen, and the tsunami from XF 3 arrives at the coastline of Xiamen the latest. In each scenario, the tsunami first spreads to Dadeng waters (P1) and east Xiamen waters (P4) within 1.5 h of the earthquake. Then, the tsunami propagates to west Xiamen waters (P7) and south of Tong'an Bay (P10), which are in the inner part of Xiamen city, two hours later. Since the tsunamigenic earthquakes have the same magnitude, the tsunami amplitudes at the same virtual point for all scenarios do not differ significantly, and only the maximum tsunami amplitude is slightly higher in the S2 and S3 scenarios (Figure 4). Therefore, we believe that the nearshore tsunami wave amplitude is affected by the magnitude of the earthquake. In addition, the tsunami displays different waveforms at different virtual points of the same scenario but shows significant waveform similarity at

the same virtual point of different scenarios (Figure 4). Combined with the characteristics of Xiamen's coastal terrain, we conclude that coastal terrain is an important influence on the propagation of tsunamis in the nearshore.

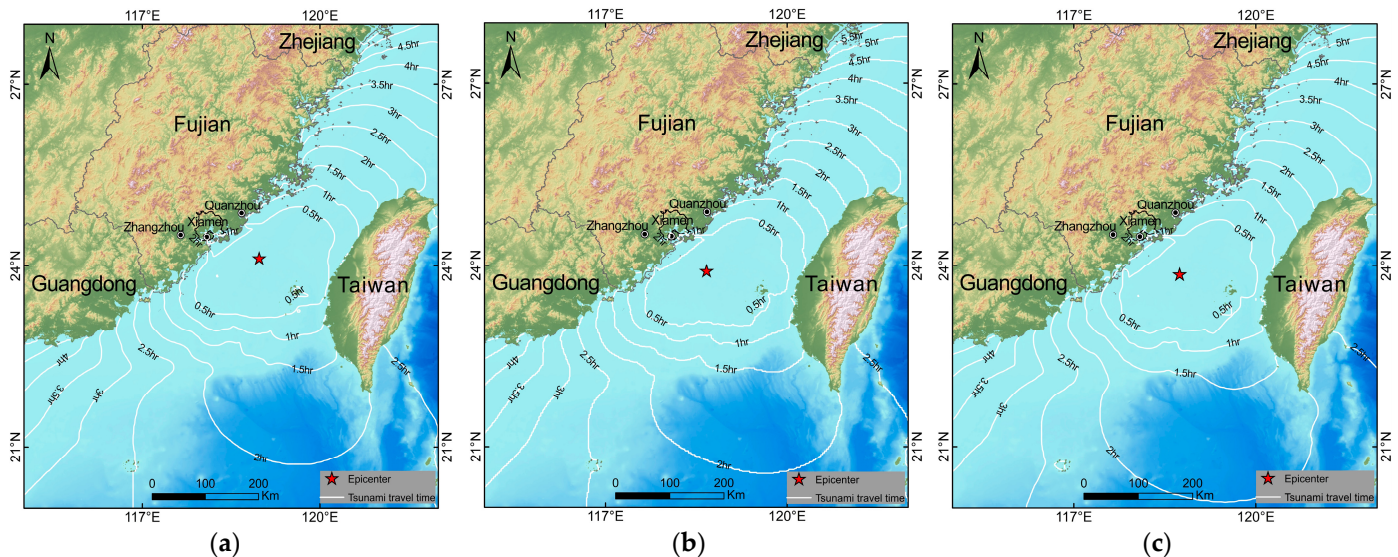


Figure 3. Tsunami travel time for S1 (a), S2 (b) and S3 (c) scenarios.

The tsunami wave height at the virtual points located in Dadeng waters (P1, P2), west Xiamen waters (P7) and Tong'an Bay (P8, P9, P10) does not exceed 1.2 m for all three scenarios, as shown in Figure 4. The maximum water surface elevation at P5 located in south Xiamen waters is 1.3 m, 1.6 m and 1.6 m for S1, S2 and S3 scenarios, respectively. The maximum water surface elevations at P6 located in the Jiulong River estuary are 1.0 m, 1.4 m and 1.2 m for S1, S2 and S3 scenarios, respectively. The maximum surface elevation at P4 located in east Xiamen waters reaches 1.4 m for the S1 scenario and 1.7 m for both S2 and S3 scenarios. This indicates that due to the closer proximity to the tsunami sources, the east Xiamen waters may experience greater tsunami wave amplitude in a shorter period and vessels located in these waters may be affected.

4.2. Spatial Distribution of the Maximum Amplitude

Figure 5 displays the way in which the maximum tsunami amplitude is spatially distributed in the near field for each scenario. It shows that tsunami waves propagate along the vertical direction of the fault towards the coastal area of mainland China and the deep-sea area in the southeast for each scenario, respectively. The coastal cities most severely affected by the tsunami in southeastern China are mainly Xiamen, Zhangzhou and Quanzhou. Most of the tsunami propagation to Xiamen is blocked by Kinmen island and Liehyu island, but tsunami waves can still surge into Xiamen city waters via Xiamen Bay and Weitou Bay. Figure 5a shows the maximum amplitude distribution of the tsunami for the S1 scenario, with the maximum wave height reaching about 4 m near the eastern coast of Quanzhou, Kinmen island, and Liehyu island. Binhai Street of Siming district may encounter a maximum tsunami amplitude of about 2 m, and the maximum amplitude near the coast of Haicang Street in Haicang district is about 1 m (Figure 6a). For the S2 scenario, the northeastern part of Zhangzhou, Kinmen island, Liehyu island, and the southern part of Quanzhou are most affected, with the maximum tsunami amplitude reaching about 5 m (Figure 5b). The maximum amplitude reaches 2.5–3 m near shore at Binhai Street and 1.5 m near shore at Haicang Street (Figure 6b). For the S3 scenario, the maximum amplitude at the nearshore of Zhangzhou, Kinmen island, Liehyu island and Quanzhou is about 5 m (Figure 5c). The maximum amplitudes at the coast of Binhai Street and Haicang Street are about 2.5 m and 1.5 m, respectively (Figure 6c). Compared to XF 1, XF 2 and

XF 3 are significantly farther away from Xiamen, but the maximum tsunami amplitudes near Xiamen are larger for scenarios S2 and S3. The same results were obtained for the analysis of the surface elevation timeseries for all virtual points (Figure 4). This is because XF 2 and XF 3 are aligned parallel to the coastline, resulting in tsunami energy being able to concentrate more on the coasts of the southeastern Siming district and the southern Haicang district, which are close to Xiamen Bay.

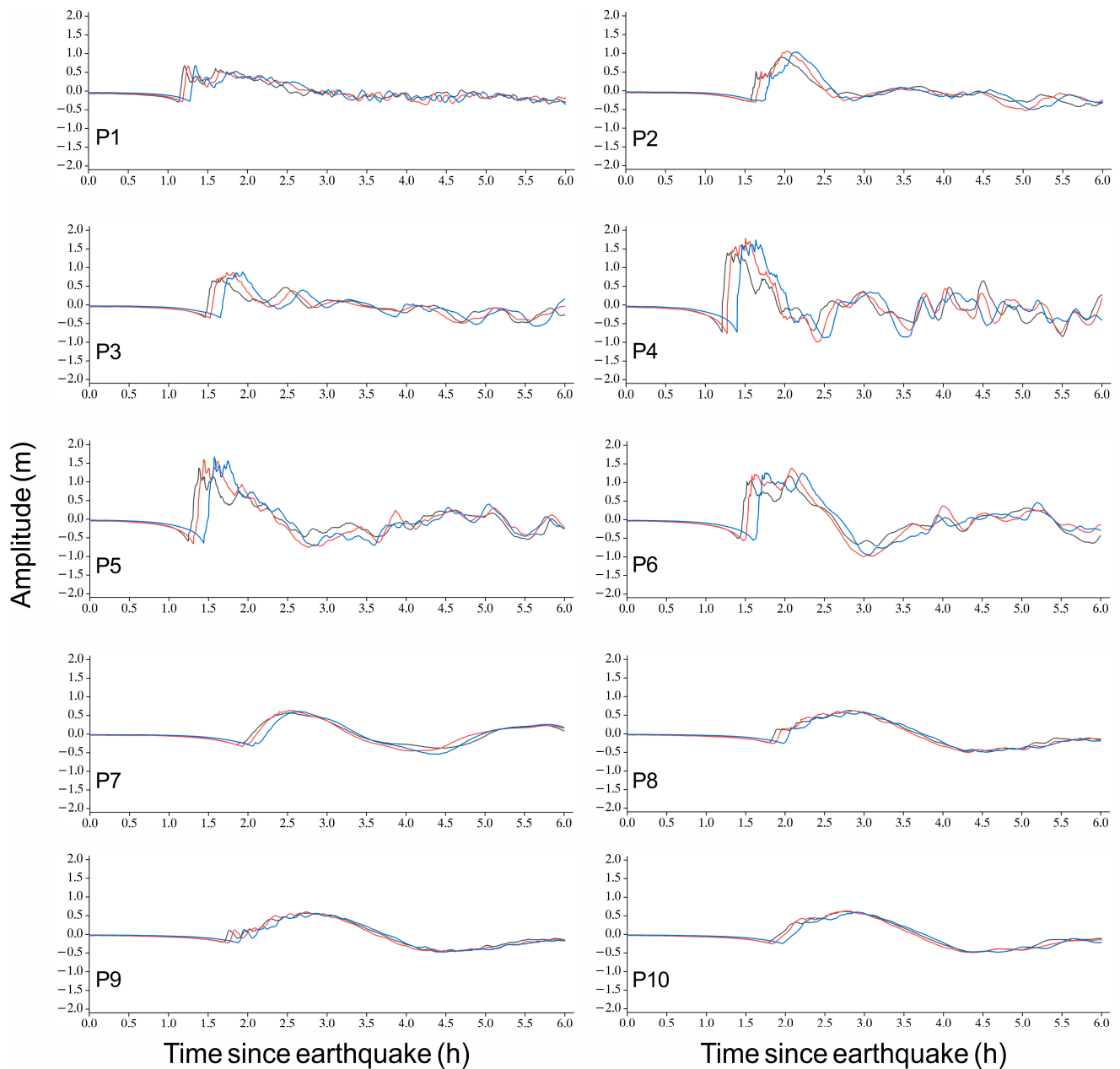


Figure 4. Surface elevation timeseries at the 10 virtual points around the Xiamen coast. The black line represents the surface elevation at the virtual point for S1 scenario. The red line represents the surface elevation at the virtual point for S2 scenario. The blue line represents the surface elevation at the virtual point for S3 scenario.

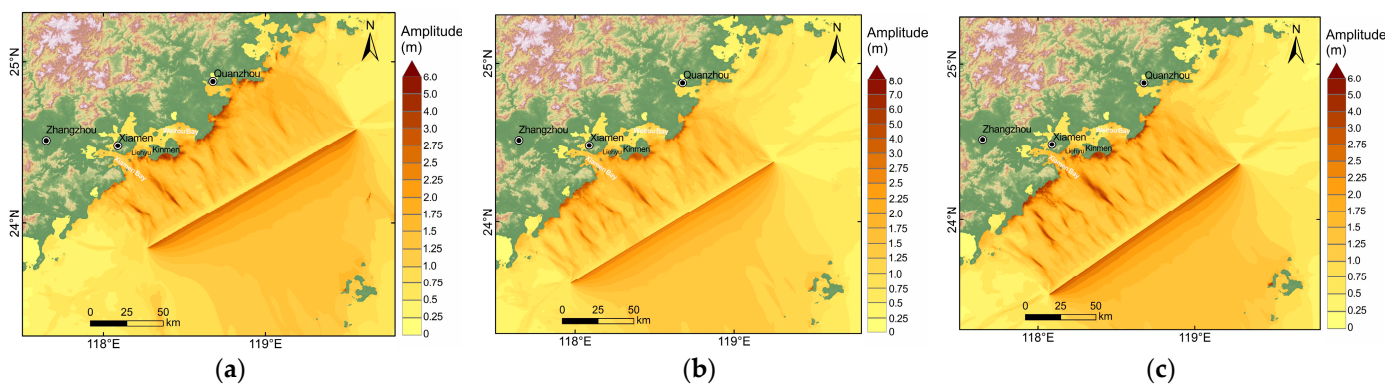


Figure 5. Spatial distributions of maximum tsunami amplitude for S1 (a), S2 (b) and S3 (c) scenarios in the near field.

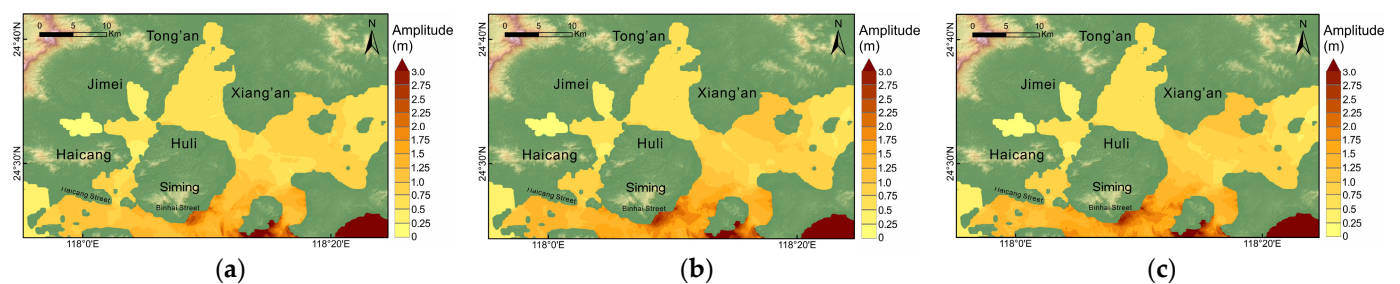


Figure 6. Spatial distributions of maximum tsunami amplitude for S1 (a), S2 (b) and S3 (c) scenarios near Xiamen.

4.3. Tsunami Hazard Analysis

Referring to the Technical Directives for Tsunami Risk Assessment and Zoning of China—Part 3: Tsunami [39], we obtained the tsunami hazard maps of Xiamen for all three scenarios based on tsunami inundation depths. Figure 7a–c show that there are no areas with tsunami inundation depths more than 3 m in Xiamen for all three scenarios. Most of Xiamen has tsunami hazard levels of Level III and IV, with tsunami inundation depths below 1.2 m. For S1 scenario (Figure 7a), the total inundation area of Xiamen is 117.18 km², and the area at tsunami hazard level II reaches 2.04 km². For S2 scenario (Figure 7b), the total inundation area of Xiamen is 117.45 km², and the area at tsunami hazard level II reaches 8.93 km². For S3 scenario (Figure 7c), the total inundation area of Xiamen is 117.31 km², and the area at tsunami hazard level II reaches 7.71 km². The statistical results of the inundation area for the three scenarios indicate that the area at the tsunami hazard level II in Xiamen is larger for the S2 and S3 scenarios; local tsunamis from XF 2 and XF 3 may cause more severe hazards to the coastal areas of Xiamen compared to XF 1. It is recommended to pay more attention to the local earthquakes occurring in XF 2 and XF 3. In addition, Figure 7a–c show that the highest hazard level is level III in Jimei and Tong'an districts, located northwest of Xiamen. This is because most of the tsunami waves propagating towards these two districts are blocked by the Xiang'an, Huli and Siming districts, so the coastal areas of the Jimei and Tong'an districts will not be directly affected by the tsunami. The areas with the tsunami hazard level II are primarily concentrated on the coast of the southern Haicang district, the eastern Siming district, and Xiang'an district, which are in the primary propagation direction of the tsunami. Considering that there are many marinas as well as tourist-preferred beaches along the coast of Haicang district and Siming district, authorities should pay attention to tsunami disaster prevention and mitigation planning in these areas.

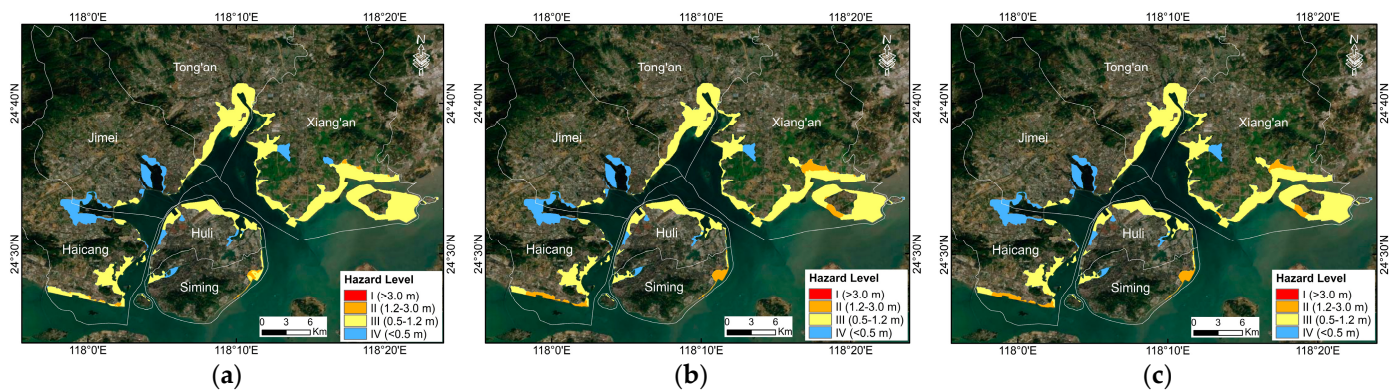


Figure 7. Tsunami hazard maps for S1 (a), S2 (b) and S3 (c) scenarios in terms of tsunami inundation depth.

5. Discussion

The spatial distribution of the maximum wave amplitude in the coastal areas of Xiamen for the three scenarios indicates that the strike of the fault is a controlling factor for the size and impact range of the tsunami. The more parallel the earthquake fault alignment is to the coastline of the affected area, the greater the nearshore tsunami wave amplitude in the affected area and the higher the tsunami hazard level. This conclusion is consistent with the findings of Hou et al. [40], Mao et al. [41] and Ren et al. [27]. The influence of other earthquake parameters on the results of tsunami simulations has also received attention. Li et al. [30] quantitatively analyzed the influence of the change in fault dip angle and rake angle on the tsunami. They proposed that the increase in dip angle will increase the amplitude of initial negative wave. The change in fault rake angle will affect the vertical seabed displacement, thus determining the size of the tsunami. In the study conducted by Fan et al. [14], the sensitivity of maximum tsunami amplitude and coastal inundation to rake and strike angle was investigated. They deduced that the tsunami hazard of affected area is more influenced by the rake angle than by the strike angle for a local fault based on analysis of the distribution of maximum tsunami amplitude in the near shore. These studies assumed that other parameters remained constant and analyzed only the effect of changes in individual earthquake parameters on the maximum tsunami amplitude or inundation. However, the fault geometry and size that have the greatest impact on the generation and propagation of earthquake-induced tsunamis are jointly determined by earthquake parameters such as strike angle, dip angle, rake angle, fault length, fault width and slip amount [42]. Therefore, to accurately assess the impact of earthquake parameter uncertainty on tsunami hazard assessment, the interaction between the source parameters is also a factor that must be considered.

The results of the tsunami hazard analysis of Xiamen city show that the highest tsunami hazard level is level III in the coastal areas of the Jimei and Tong'an districts, while most of the tsunami hazard level II areas are concentrated in the Siming, Haicang and Xiang'an districts. This indicates that even within the same city, tsunami prevention measures in different regions may vary greatly due to coastal terrain [14,43,44]. Therefore, it is necessary to conduct refined tsunami hazard and risk assessments for important coastal cities and develop specialized emergency plans for high-risk areas to minimize potential significant losses in the future.

Our simulation results suggest that Xiamen would be hit by local tsunamis from XF 1–3 within 1.5 h of the earthquake. Such a short emergency response time requires authorities to issue rapid and accurate tsunami warnings. Traditional tsunami warning methods simulate nearshore tsunami wave amplitude and inundation based on estimates of the seismic slip distribution [45]. This method can provide fast forecasts for earthquake-induced tsunamis, but it is difficult to guarantee the accuracy of the forecasts [46]. Offshore tsunami measurements can provide direct tsunami monitoring information before the

tsunami reaches the nearshore [47]. Based on offshore tsunami observations, the source information can be estimated to calculate the tsunami wave field [48], or the tsunami wave field can be constructed directly without considering the source information [49]. Therefore, tsunami warning systems based on offshore observations can provide more accurate tsunami forecasts and are an important complement to traditional warning methods [50]. Currently, coastal countries such as the United States and Japan have established offshore observation networks for rapid and accurate tsunami warning [51,52]. To better ensure the safety of people's lives and properties, the coastal cities in southeast China should emphasize the construction of tsunami observation networks and tsunami warning systems based on offshore observation in the future.

This paper has several limitations. Since the near-shore bathymetry of Xiamen is not open-source, we chose to simulate tsunami propagation using GEBCO_2022, a currently commonly used open-source bathymetry dataset, but with lower resolution (~460 m). The results of Xie et al. [53] suggest that the tsunami hazard may be over/underestimated using low-resolution near-shore bathymetry data. In the future, we will consider taking higher resolution nearshore bathymetry data to improve the accuracy of tsunami inundation simulations. In addition, tsunami protection facilities such as breakwaters are not considered in the simulation of tsunami inundation. Previous studies have shown that breakwaters can be effective in weakening the energy of near-shore tsunami waves [54,55]. Therefore, the simulated inundation area in this study may be larger than the actual situation. The earthquake parameters used in this study refer to the values provided by Ren et al. [27]. Detailed marine geophysical surveys are necessary to gain a better understanding of the fault geometry characteristics of potential local tsunami sources such as XF 1, XF 2 and XF 3 that could affect Xiamen, and to reduce uncertainties in the assessment of the local tsunami hazard for Xiamen. In addition, the tsunami hazard assessment in this study only considered tsunamis triggered by earthquakes. Wang et al. [4] showed that tsunami wave amplitudes up to 13.0 cm were monitored in and around Lingding Bay in China after the 2022 Tonga volcanic eruption. Tsunami hazard assessment for coastal areas should consider the tsunamis from nonseismic origins in the future.

6. Conclusions

There are multiple local tsunami sources near the continental shelf of the South China Sea that pose a potential tsunami threat to coastal areas. To predict and prevent possible tsunami disasters in the future, it is necessary to carry out the hazard assessment of local tsunami for important coastal cities. In this study, three worst-case credible tsunamigenic scenarios (Mw8.0) from Xiamen fault 1 (XF 1), Xiamen fault 2 (XF 2) and Xiamen fault 3 (XF 3) were selected to assess the local tsunami hazard for Xiamen city. The propagation and inundation of the tsunami for each scenario was simulated based on the GeoClaw model. The simulation results indicated that the tsunamis from XF 1–3 would be the first to hit the coast of Dadeng island in Xiamen within 1.5 h and spread to all coasts of Xiamen about 2 h later. Tsunamis from XF 2 and XF 3 could reach heights exceeding 1.7 m in the east Xiamen water within 1.5 h. This may have an impact on vessels sailing in this area. The highest tsunami hazard of the southern coast of Haicang district and part of the eastern coast of Siming district reached level II, with an inundation depth of 1.2–3.0 m. Since the fault strikes of XF 2 and XF 3 are almost parallel to Xiamen's coastline, local tsunamis from XF 2 and XF 3 could cause more severe damage. Authorities should pay close attention to the seismic activity of XF 2 and XF 3. This work simulated the propagation of tsunamis triggered by Mw8.0 earthquakes occurring on three offshore faults, revealing the maximum local tsunami inundation depth and hazard that Xiamen city may experience, and provides a typical case for researchers to understand the local tsunami hazard assessment for coastal cities. The results can provide scientific references for the development of tsunami hazard assessment and early warning systems for coastal cities in southeastern China.

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