

# Tsunami risk along Vietnamese coast

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**Abstract:** Results of the analysis of field survey data and historic literature documents in Vietnam reveal that there is evident of past tsunami attacking Vietnamese coast. However, the evident is still not strong enough to confirm the occurrence of past tsunami events in Vietnam. On the other hand, results of preliminary paleo-tsunami study also show that there are possibilities of tsunami occurrence at Vietnam coast in the past. The analysis on the seismic activities and structure of tectonic plates in the South China Sea (SCS) reveals that there are four areas in the sea with possibilities of having tsunami earthquakes. Based on the computed results by validated models on the generation of the tsunami by earthquake and the propagation of tsunami in the SCS, it was found that significant tsunami at Vietnamese coast could be generated by an earthquake with magnitude of larger than 7 at the fault along Central Vietnam shelf, and by an earthquake with magnitude of larger than 8 at the Manila Trench. If an earthquake with the magnitude of 7.5 happens at south Hainan Island, the maximum height of tsunami at Vietnamese coast can be more than 1.5m. If the earthquake with magnitude of 8.5 happens at Manila Trench, the maximum tsunami height from Da Nang to Quang Ngai can be more than 4m, and at some places, can be more than 5m. The coast with the maximum tsunami height of more than 1m stretches about 1000km, from Quang Binh to Binh Thuan. Then, it can be concluded that the risk of tsunami in Vietnam is not very large, but exists, and it is necessary to prepare for the disaster.

**Keywords:** Vietnamese coast, tsunami risk, numerical model

## 1. Introduction

This paper presents analysis results of the authors and other researchers in Vietnam about the tsunami risk at the Vietnamese coastal areas. The paper also provides preliminary study results on the tectonic plate structures and seismic activities, and earthquake parameters needed for tsunami generation calculation in the SCS.

## 2. Tsunami risk at Vietnamese coastal areas

In Vietnam, there are only few tidal gauge stations along the coast with sparse data recording. Thus, the water level data, obtained from such tidal gauges, are not reliable enough for tsunami analysis. Therefore, for most cases, tsunami data were only obtained through public survey in coastal resident communities. There are also several historic literature documents about tsunami in Vietnam. Based on the research results of Nguyen Dinh Xuyen (2007), there are five tsunami events at the Vietnamese coast with most reliable information. The first event is abnormal high waves attacking Tra Co coast (Figure 1) in 1978. According to the information from coastal resident community, during a fine day, waves with height of 2 m to 3 m attacked the coast several times, damaged house walls and trees near the coast. To confirm the possibility of the tsunami at the coast, the first author of this report did a survey at the coast during March, 2008. It was found during the survey that waves only caused inundation in a very narrow area, with the largest inundation distance of several ten meters from the water line. Also, infiltrated waves dissipated onshore very rapidly. By comparing damage by the waves with damage by a typical tsunami with the same height (such as the tsunami in West Java July, 2006), it can be remarked that it is difficult to conclude that the above mentioned waves are tsunami. The waves might be wind waves in combination with wave/wind setup and high flood tide.

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The second event of tsunami attacking Vietnamese coast, according to Nguyen Dinh Xuyen (2007), happened in a year at the end of the 19th century and the beginning of the 20th century. The event happened during a fine day, when waves with the height of half bamboo tree height (more than 3m) attacked the coast of Dien Chau, North Central Vietnam (Figure 1). The waves caused inundation with maximum inundation distance of more than 1km from the coast and the inundation depth of more than 1.5m. The waves damaged many houses, but it was uncertain how many people were killed. The examination of all earthquakes in the SCS during the period from 1880 to 1920 shows no earthquake that could generate significant tsunami at the Vietnamese coast. Thus, Nguyen Dinh Xuyen (2007) suggested that the waves might be generated by submarine landslide.



Figure 1. Locations with possible tsunami attack

The third tsunami event at Vietnamese coast was recorded by Dr. Armand Krempt (the assistant of Dr. A. Yersin) (Nguyen Dinh Xuyen, 2007).

According to the record, during 1923, high waves attacked the coast of Nha Trang, a tourist city at Central Vietnam. The waves damaged horse breeding facility of Dr. Yersin, located at the distance of about 5 to 6 m from the water line. This event was related to the eruption of Hon Tro Volcano, which caused an earthquake with the magnitude of 6.1 Richter. However, the investigation by a team from Center for Marine and Ocean-Atmosphere Interaction Research found no documents showing the tsunami event. On the other hand, the second author of this report did a survey at Binh Thuan Province coast (including Mui Ne in Figure 1) by interviewing old local residents. Many answered that during the year of 1923, just after with the eruption of the Hon Tro Volcano, strong tsunami attacked Mui Ne (Figure 1).

The fourth possible tsunami event was recorded in a Vietnamese history book. Cao Dinh Trieu et al (2007) reported that a Vietnamese history book named “Dai Nam Thuc luc Chinh bien” documented that “September 1877, there was an earthquake at Binh Thuan, and from then to December, there were totally three times (of earthquakes). During the first earthquake, river water rise up, brick houses vibrated; the second and third earthquakes were weaker”. According to Cao Dinh Trieu et al (2007), NOAA estimated that this earthquake has the intensity of 7 Richter.

The fifth possible tsunami event was also recorded in a Vietnamese history book. According to Nguyen Dinh Xuyen (2007), in other Vietnamese history book named “Lich

trieu Hien chuong Loai chi”, in 1882, there was an earthquake, following high waves, with many sounds of explosion within one day.

A group of researchers at the Institute of Geophysics, Vietnam Academy of Science and Technology, including Cao Dinh Trieu, Trinh Thi Lu and others (2007) carried out Paleo-tsunami research to find evident of tsunami attacking Vietnamese coast. During November - December 2005 and March - April, 2006, the Institute of Geophysics dispatched two survey groups to find evident of tsunami along Vietnamese coast. The survey team investigated excavation sites at six points: Cua Lo, Song Cau, Nha Trang, Phan Rang, Phan Thiet (Figure 1) and took samples at different sediment layers for the analysis. They found that a huge tsunami with the maximum height of 18m attacked a coast of more than 1000 km length at Central Vietnam, (Figure 2). However, Vu Thanh Ca and Nguyen Dinh Xuyen (2008).

With all the above mentioned investigation results, it could be stated that there were possibilities of the events of tsunami attacking Vietnamese coast. However, there is not enough reliable evident to confirm the fact, and therefore, significant researches are still needed.

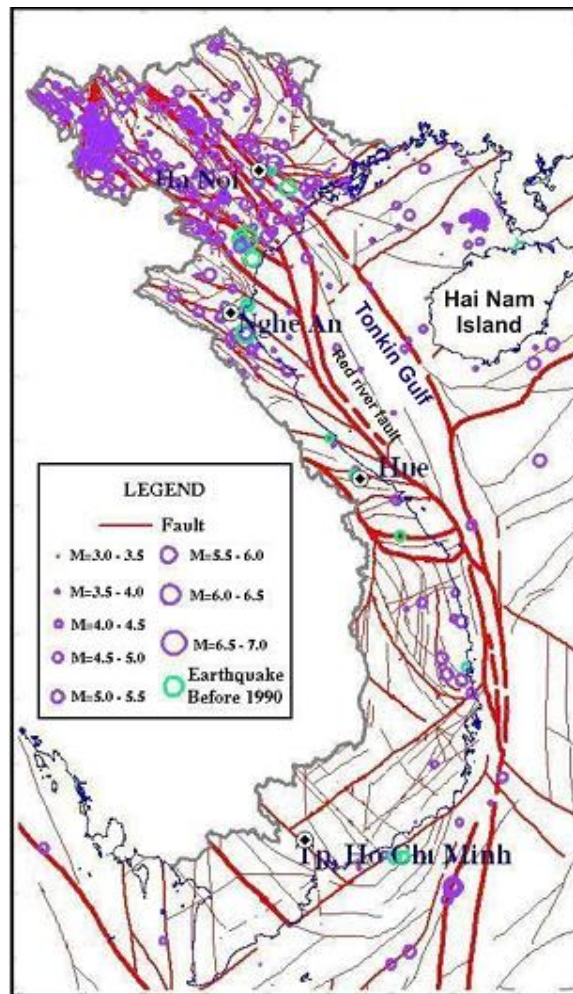


Figure 2. Faults and seismic activities in the West South China Sea

### 3. Tectonic structure and seismic activities in the SCS

Recently the USGS issued a report assessing the potential risk as a tsunami source along the entire Pacific subduction zones (Kirby et al, 2005). It identified the Manila (Luzon) trench as a high risk zone, where the Eurasian plate is actively subducting eastward underneath the Luzon volcanic arc on the Philippine Sea plate. Two other medium risk subduction zones in the neighboring area are also identified. Along the Ryukyu trench, the Philippine Sea plate subducts northward beneath the Ryukyu Arc on the Eurasian plate, while along the North Sulawesi trench, the Pacific-Philippine, Indo-Australian Plates and the Sunda Block meet. These subduction zones can also rupture and generate large tsunamis in the future that will have significant impacts on the countries in the SCS region (Liu, 2007). However, even in these areas, the tectonic structures and earthquake activities are still poorly understood. In other areas of the SCS, there is very little understanding about tectonic structures and earthquake activities.

The South East Asia in general and SCS in particular has a complex tectonic structure, as cited by different authors (Bautista et al, 2001; Brais et al, 1993; Schoenbohm et al, 2006; Zhu and Chung, 1995). It is the transition zone between Eurasian plate in the west, Philippine Sea plate in the east, and Australian Plate in the south - east. The different plates move relatively to each others. Based on HS2 NUVEL-1 model, the absolute motion of the Philippine Sea plate is around 7cm/year in the region northeast of Luzon Island and progressively increases to around 9cm/year in the region southeast of Mindanao. The Eurasian plate, on the other hand, moves in an almost similar direction at a very slow rate of around 1 cm/year (Bautista et al, 2001). The India-Australian plate moves to the north-north-east direction and collides with the Eurasian plate. The relative convergence of the plates creates sub-duction systems. Together with the convergence and sub-duction system, the extensional mechanism creates various faults in the sea.

Nguyen Dinh Xuyen (2007) and Nguyen Van Luong et al (2007), used earthquake data recorded by seismograph, survey and official record prior to instrument, found that from 1485 to 2003, in the Tonkin Gulf, there are totally 127 earthquakes with the magnitude of  $2.0 \leq M \leq 6.5$  and the focal depth of  $H \leq 35$ km (Figure 2). As shown in Figure 2, strong earthquakes in the north SCS concentrate along the faults. South Hainan Island, the fault has a strike slip pattern, begins at south Hainan Island and stretches in the northeast direction to Zhongsha buoyant plate at the north of SCS. In the period from 1900 to 2003, there were 16 earthquakes recorded in the area with  $M \leq 6.8$  and  $H \leq 30-35$  km. Based on the analysis of the tectonics of the area and historical earthquakes, Nguyen Van Luong et al (2007) and Nguyen Dinh Xuyen (2007) predicted that the maximum earthquake in the area has the  $M_{\max} = 7.0$  and  $H = 30$  km with return period of 650 years.

The Xisha Trough, formed by northeast and near west-east faults with strike slip and normal extension, begins from about  $112^{\circ}$  E and extends until the west of the Luzon Island. In the areas, during the period from 1900 to 2003, there are 21 earthquakes with  $M \leq 6.8$  and  $H \leq 33$  km. According to Nguyen Van Luong et al (2007), the maximum earthquake has  $M_{\max} = 7.2$ , and  $H(M_{\max}) = 33$  km with return period of 625 years.

In the offshore of South Central Vietnam, there were 64 earthquakes with  $M \leq 6.1$  and  $H \leq 33$  km. The earthquakes offshore of Central Vietnam have either tectonic or volcanic origins. For examples, the earthquakes of August 2005 ( $M=5.1$ ), November 2005 ( $M=5.5$ ), July 1960 ( $M=5.1$ ), and August 2005 ( $M=5.2$ ) have the tectonic origin, due to the release of the accumulated strain in between different plates, moving in different directions.

In the area north of the Paracel Islands, from the longitude of  $109^{\circ}30'$ E to  $114^{\circ}$ E, during the period from 1900 to 2003, there were 12 earthquakes recorded with  $M \leq 5.6$ ,  $H \leq 25-30$  km. The predicted maximum earthquake (Nguyen Van Luong, 2007) has  $M_{\max} = 6.0$ , and  $H(M_{\max}) = 33$  km, with the return period of 476 years. In the area south of Paracel Islands, from the longitude  $110^{\circ}30'$  E to northeast of submerged rock field Macklesfield, during the period from 1900 to 2003, there were 8 earthquakes recorded with  $M \leq 5.6$  and  $H \leq 33$  km. The predicted maximum earthquake (Nguyen Van Luong et al, 2007) has  $M_{\max} = 6.2$  and  $H(M_{\max}) = 33$  km, with the return period of 625 years. In the area east of Paracel Islands, from the longitude of  $114^{\circ}$ E to  $118^{\circ}$ E, northeast of submerged rock Macklesfield, during the period from 1900 to 2003, there were 14 earthquakes recorded with  $M \leq 6.0$  and  $H \leq 33$  km. The predicted maximum earthquake (Nguyen Van Luong et al, 2007) has  $M_{\max} = 6.2$  and  $H(M_{\max}) = 33$  km, with the return period of 400 years.

In the area of Central SCS, from longitude of  $113^{\circ}$ E to the west of Luzon island, during the period from 1900 to 2003, there were 22 earthquakes with  $M \leq 5.9$  and  $H \leq 68$  km. The

predicted maximum earthquake (Nguyen Van Luong et al, 2007) has  $M_{max}= 6.4$  and  $H(M_{max})= 33$  km, with the return period of 526 years.

Contradicts to other parts of the SCS, where there are very few studies, the tectonophysics and seismic activities in the area of North Luzon has been investigated by many authors

(Seno and Kurita, 1978; Hamburger et al, 1983; Yang et al, 1996; and Bautista and Koike, 2000; Bautista et al, 2001; Bautista et al, 2006; Chew and Kuenza, 2007; Chen et al, 2007, Yen et al, 2007, Kirby et al, 2005). The authors investigated earthquake characteristics, thrust mechanisms, tectonic stress etc. of Manila Trench and the area in between Taiwan and Luzon Island. Especially, in September 12-21, 2005, an ad hoc working group of USGS geophysicists and geologists, led by S. Kirby, convened a series of meetings to characterize western Pacific subduction zones relevant to potential tsunami sources (Kirby et al, 2005). The effort was in support of ongoing NOAA efforts to optimize the deployment of Deep-Ocean Assessment of Reporting of Tsunamis (DART) stations in the Pacific. The working group's study region extended from the western Aleutian Islands south to New Zealand and from the Philippines in the west to approximate 190°E. Even the purpose of the working group is intended only for the DART network optimization and is not intended to represent a comprehensive seismic hazard assessment for these subduction zones, results of the investigation are very useful for tsunami generation modeling.

A model of Chen et al (2007), based on the statistical and tectonic dynamic analysis, estimated that the probability of an earthquake with  $M_s \geq 7.9$  to occur within the Manila – Taiwan subduction zone in the next 30 years is 88%. Last such earthquake occurred in 1934. However, the magnitude of the maximum possible tsunamigenic earthquake in this area is still unknown and needs further investigation.

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#### 4. Evaluation of tsunami risk in Vietnam based on numerical model

##### 4.1 Tsunamigenic earthquake scenarios in SCS

To evaluate the tsunami risk and forecast the tsunami at Vietnamese coastal and island areas using numerical model, it is necessary to establish tsunamigenic earthquake scenarios. As mentioned in the previous section, tentatively, there are four zones of earthquake sources in the SCS. However, according to preliminary evaluation, the

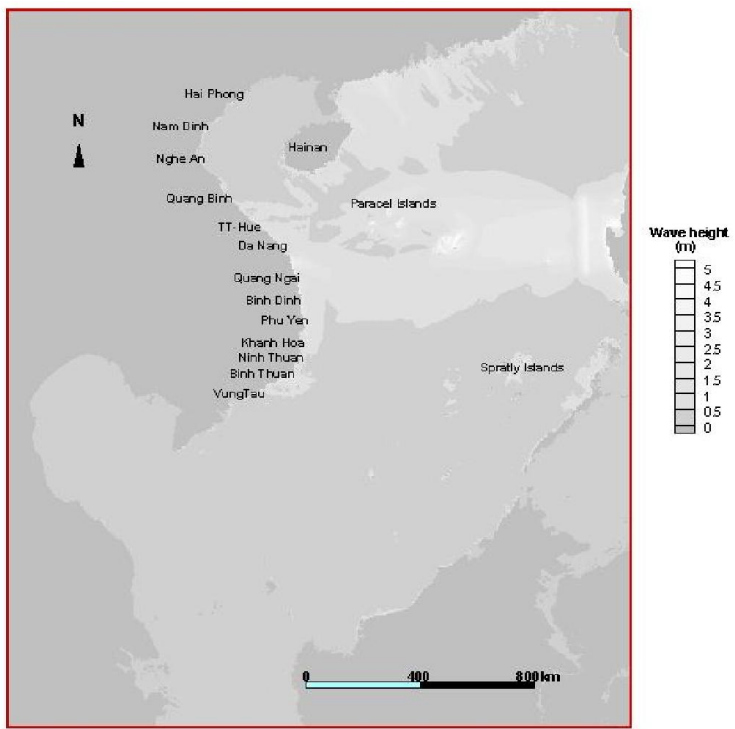


Figure 3. Tsunami height at Vietnamese coastal area with earthquake

maximum earthquake in the Central SCS has the magnitude of 6.8, and a strike slip mechanism. Results of numerical experiments with verified models of tsunami generation and propagation in SCS (not shown) show that earthquakes in this zone do not generate significant tsunami. Thus, the source zone of Central South China Sea is excluded from the consideration. Then, several earthquake scenarios with corresponding earthquake parameters, as shown in Table 1, have been used for the evaluation of tsunami risk in Vietnam. The parameters of the earthquakes were determined from results of tectonic, statistic analysis, and empirical relations (such as that of Wells and Coppersmith, 1994). Details of the analysis were referred to Vu Thanh Ca (2008). In Table 1,  $L$  is the rupture length,  $W$  the rupture width,  $H$  the depth of the source,  $\delta$  dip angle,  $\lambda$  slip angle, and  $\theta$  the strike angle.

The scenarios 1 to 3 correspond to earthquakes in Manila Trench, the scenario 4 corresponds to an extreme earthquake in Ryukyu Trench, and scenarios 9 and 10 correspond to earthquake at offshore North Central Vietnam, south of Hainan Island.

#### 4.2 Numerical model for tsunami generation, propagation and inundation

The tsunami generation model of Okada (1985, 1992) has been employed to forecast the tsunami generation by earthquake. A numerical model, similar to MOST (Titov and Gonzalez, 1997) has been developed and used for simulation of tsunami propagation in the SCS. The present model solves the same equations as MOST, but uses a leaf frog scheme for time discretization. The scheme enables an accurate discretization of the time differentiation, and at the same time, easy coding and efficient computation. The algorithm is especially efficient for parallel computation, when the computations of the values of model variables are carried out simultaneously. The numerical model for tsunami inundation onshore was developed by Vu Thanh Ca et al (2005).

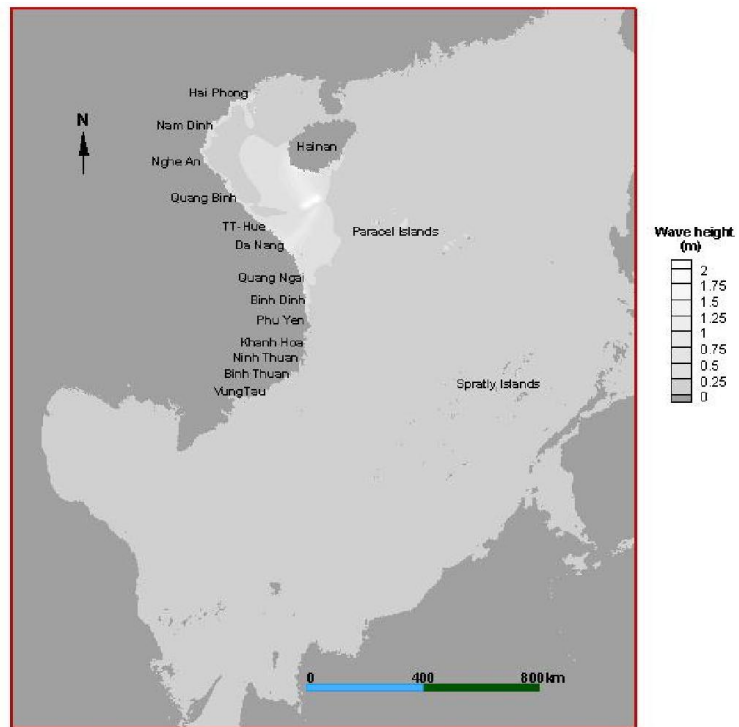


Figure 4. Tsunami height at Vietnamese coastal area with earthquake scenario 2

All above mentioned models had been validated before using for the computation. Details of the model validation are referred in Vu Thanh Ca (2008).

The digitized marine chart, adjusted to Vietnamese National Datum, in combination with onshore high resolution topographic data were used for the computation of tsunami propagation in the sea and onshore inundation. A finite volume scheme is used to discretize spatial differential terms. The scheme has a high stability and ensure the

conservation of momentum and mass. The grid mesh size is 1' for entire SCS, and 50 m for nearshore tsunami propagation and inundation computation. With fine grid mesh, the computation of the nearshore tsunami propagation and inundation can be carried out only for very narrow nearshore regions. Then, the water level and flow velocity, computed by numerical model for tsunami propagation in entire SCS, are provided at the boundary of nearshore and inundation computation regions.

Table 1 Parameters of tsunamigenic earthquake scenarios in SCS

No.	Mw	Long. (°E)	Lat. (°N)	L (km)	W (km)	H (km)	$\delta$ (degree)	$\lambda$ (degree)	$\theta$ (degree)	$u_0$ (m)
1	8.0	119.30	17.50	151	47	12	24	90	177	5.28
2	8.5	119.30	17.50	313	70	18	24	90	177	9.61
3	9.0	119.30	17.50	646	101	27	24	90	177	17.49
4	9.0	121.80	23.53	501	141	24	15	90	87	16.71
5	7.5	110.46	17.13	89	25	17	78	-45	57	2.97
6	7.5	108.52	16.91	89	25	17	78	-45	172	2.97

### 4.3 Computational results

Figure 3 shows the tsunami height distribution in SCS and near Vietnamese coast corresponding to earthquake scenario 1, when an earthquake with magnitude 8 happens at Manila Trench. As seen in the figure, with this scenario, the tsunami height at the coast of Central Vietnamese is significant. From Da Nang to Quang Ngai, the tsunami height is more than 1m, with the maximum tsunami height of more than 2m. Maximum tsunami height at the Paracel island is also more than 2m. Then, with computational results, it is necessary to issue a tsunami warning when an earthquake of magnitude 8 occurs at Manila Trench.

With the earthquake of magnitude 8.5 occurring at Manila Trench, large tsunami height can be seen at the coast of Vietnam, especially Central Vietnam, as shown in Figure 4. As can be seen in the figure, the area with tsunami height of more than 1m at the coast stretches from Binh Thuan to Quang Binh. Maximum tsunami height at Da Nang is more than 4m. Especially, at some places, it is more than 5m. Thus, this is a dangerous tsunami scenario and should be considered carefully when evaluating the tsunami risk at Vietnamese coast.

It is commonly believed that it is almost impossible for an earthquake of magnitude 9 occurs at the Manila Trench. However, this scenario is included for the consideration of an extreme case. Results of computation (not shown) show that if this earthquake occurs, almost all Vietnamese coast is under the attack of strong tsunami. The area of tsunami height of more than 1m stretches from Hai Phong in the North to Ca Mau in the South. The coast with tsunami height of more than 2m stretches from Quang Tri to Phan Thiet. Especially, at Quang Ngai, the maximum tsunami height is more than 10m.

Computational results also show that when an earthquake of magnitude 9 occurs at Ryukyu Trench, the coast with tsunami height of more than 1m stretches from Hue to Ninh Thuan. At some places, the tsunami height at the coast is more than 2m. Thus, this scenario is also a dangerous tsunami scenario and should be considered when evaluating the tsunami risk at Vietnamese coast. On the other hand, if an earthquake of magnitude 8.6 at the Ryukyu Trench cause only weak tsunami (with height less than 1m) at the Central Vietnam coast.

The tsunami height along the Vietnamese coast when earthquakes with magnitude of 7.5 occurs offshore of central Viet Nam, south of Hainan Island are shown in Figs. 5. For scenario 5, the coast with tsunami height of more than 1m stretches from Hue to Da Nang. The maximum tsunami height is about 1,5m. Comparing with tsunami scenario 5, the tsunami scenario 6 (not shown) is more dangerous since the earthquake source in this case is parallel to the coast. The tsunami height of about 2m at the coast stretches from Quang Tri to Danang. Thus, the near field tsunami scenarios 5 and 6 are also dangerous, and should be considered.

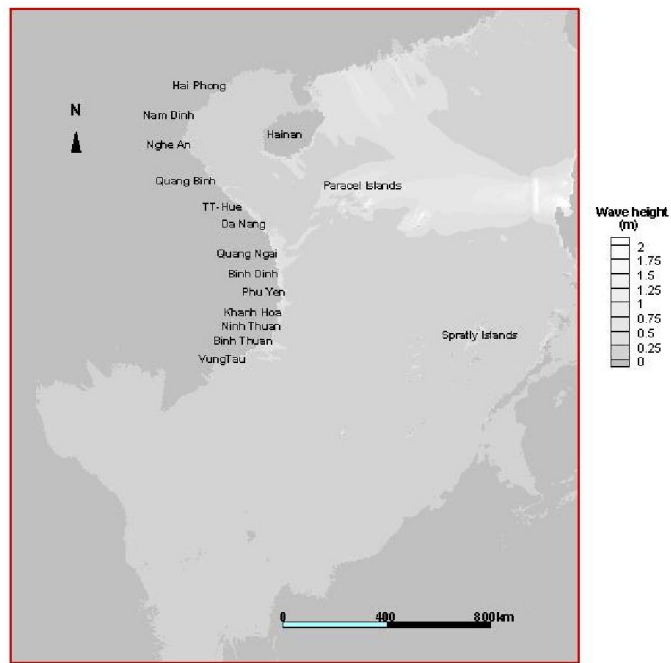


Figure 5. Tsunami height at Vietnamese coastal area with earthquake scenario 5

The computational results (not shown) reveal that due to strike slip mechanism, an earthquake of magnitude 7 offshore South Central Vietnam does not generate significant tsunami at Vietnamese coast.

Besides the risk of tsunami generated by earthquake, tsunami risk due to other mechanisms, such as terrestrial or submarine land slide, or volcanic eruption, should be considered when evaluating the risk of tsunami at Vietnamese coast. However, since lack of data, it is not considered in this study.

## 5. Conclusion

From the analysis of collected data at Vietnamese coast and computational results, it can be remarked that the risk of tsunami at Vietnamese coast is relatively low, but does exist. Therefore, with social and economic development of the coast of Vietnam, the damage due to tsunami, once it happens, may be very large. Thus, the risk of tsunami should be carefully investigated and considered to properly prepare for the disaster.

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