

Storm surge risk assessment for Yuhuan County in Taizhou City

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Abstract Using an ADCIRC model with 26 coastal sea walls and assuming that not all coastal sea walls are damaged during a storm surge, we simulated the county of Yuhuan's maximum possible inundation depth and performed a hazard assessment. Additionally, we assessed the vulnerability of Yuhuan County based on land use. Then, based on these assessments, we evaluated the overall storm surge risk for Yuhuan County. The results show that Yuhuan County can be divided into three areas. The first area includes the town of Shamen, the Damaiyu sub-district, etc., and is occupied by people and typically an active area. Although the hazard grade of a part of this area is not high, its risk grade is significant, and most areas belong to the extremely high-risk grade. The second area consists of the sea walls of Jiaomen, Puzhu, Xiaopuzhu-Xitan, Taiping, etc., and includes bare lands, farmlands, shoals, small villages and storage areas. Although the hazard grade for this area is extremely high hazard or high hazard, its risk grade is moderate risk. The third area includes the remaining area in Yuhuan County, where there is no submerged area; this area includes low-lying areas but also has two layers of sea walls. In this area, the surroundings of Xuanmen Bay are only partially used for aquaculture.

Keywords Maximum possible inundation depth · Storm surge hazard · Vulnerability · Risk assessment · Yuhuan County

1 Introduction

Yuhuan County is located on the southeast coast of Zhejiang province and is also the midpoint of the gold coastline (121°E, 28°N). The county is connected to the mainland via Xuanmen Dam; to the east lies the East China Sea, and to the west lies Yueqing Bay

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(Fig. 1). The elevations of the coastal areas of Yuhuan County are generally low (3.0–5.0 m, 1985 National Height Datum Plane), and the main towns and villages are situated at lower elevations. Due to its unique geographical position and climatic conditions, Yuhuan County experiences some of the most frequent and serious storm surge disasters throughout China. Therefore, it is necessary to study the storm surge risk in Yuhuan County to take appropriate measures to minimize storm surge losses and to provide technical support.

Different scholars have different opinions on the composition of disaster systems. Okada believes that the risk of natural disasters is formed by the interaction of hazard, exposure and vulnerability (Okada et al. 2004). Based on this theory, the factor of disaster prevention and mitigation capacity is taken into account; this capacity is also added to the compositions of natural disasters' risk (Zhang and Li 2007). Other scholars argue that

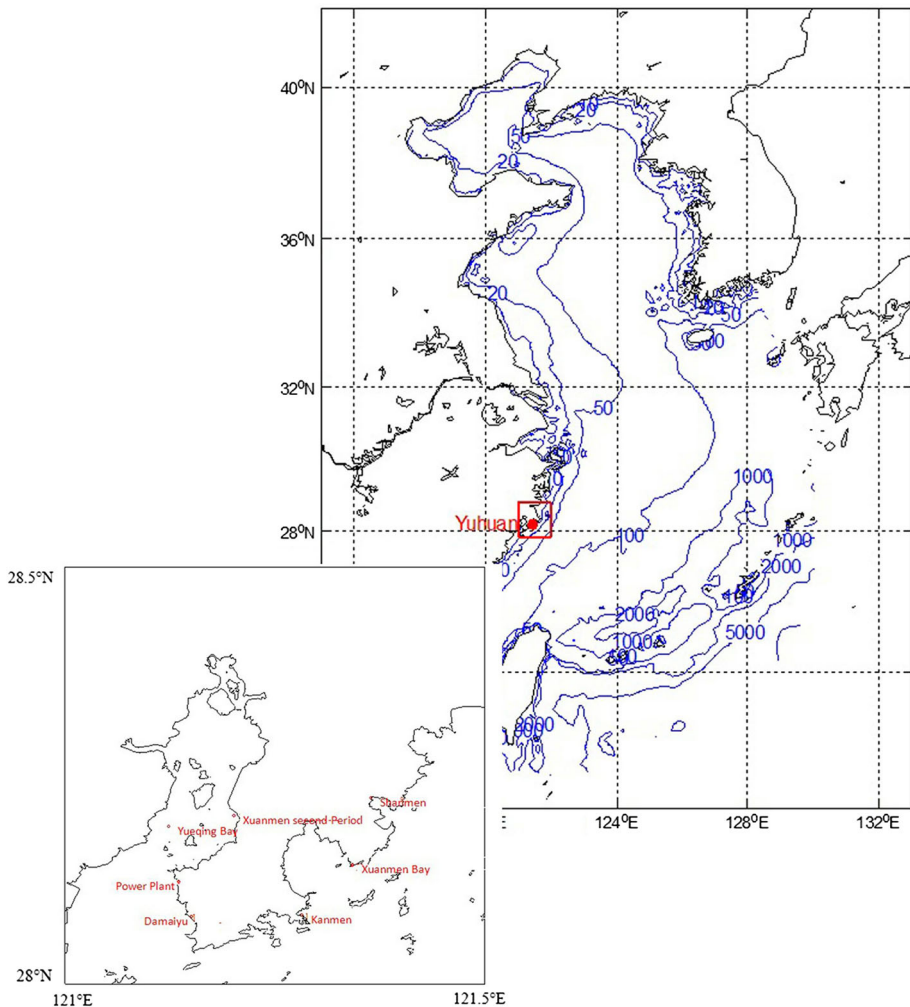


Fig. 1 Study area and the depth distribution

natural disasters are affected synthetically by disaster factors, disaster-pregnant environments and vulnerability (Shi 2002). The United Nations Development Program believes that natural disasters are the result of disaster factors combined with human vulnerability (UN/ISDR 2004). This paper argues that the storm surge disaster system has three conditions based on previous research results: (1) The disaster factors that can induce storm surge disaster exist. (2) Humans or human habitats that include society, economy and environment withstand the disasters. (3) The results of disasters include the harm of human health, life conditions, activities, possessions, resources and environment. The storm surge risk assessment is achieved by analyzing the risk of the disaster factors and the vulnerability. Storm surge risk assessment in coastal areas has been a pressing issue and a scientific problem of common concern to the international community and academia for a very long time; the theory and approach of storm surge risk assessment are more popular in developed countries (The Cabinet Office 2003; Scheffner and Mark 1996; Scheffner et al. 1999; Shook 1997; Benavente et al. 2006; Zerger 2002; Zerger et al. 2002; Aerts et al. 2014; Hall et al. 2006; Kron 2005).

The disaster factor's hazard research of storm surge starts early. The calculation of storm surge with different return period is mainly based on mathematical statistics method. The intensity of storm surge disaster which a specific region may face is evaluated in this way under long time series and thus can provide scientific basis when making planning of disaster prevention and mitigation for the government planning department. When storm surge disaster comes, the damage scope, submerged depth should be known during personnel emergency evacuation, but storm surge with different return period is not involved specific storm surge process. Based on the results of precedent researches, we use numerical model to carry out the calculation of probable maximum storm surge (PMSS) under different typhoon intensity. At home and abroad, researchers carried out a series of work on PMSS using numerical model. Among them, the study of PMSS in America is systematic and has a long history. Typhoon intensity is classified, and moving speed is supposed to be the average of historical typhoon moving speed. Using SLOSH model to calculate the probable maximum inundated area under different typhoon intensity. Usually, PMSS is the storm surge caused by the probable maximum typhoon (Wang 2002). Japan translated the path of Typhoon 5912 which assumed as the basic parameter of probable maximum typhoon to set up key parameters of PMSS in different regions (The Cabinet Office 2003). PMSS in Zhenhai was determined by calculating 13 typhoon paths within three types, and different moving speeds of the imaginary landing typhoon which caused PMSS on the basis of the probably maximum typhoon had been decided (Yin et al. 1995). Expert established a storm surge numerical model for Shanghai, and they revised the PMSS and gave the highest water level of Wusong station (Ying and Yang 1986). The high-resolution numerical model ECOM-Si was also used to calculate PMSS in Shanghai, and comprehensive factors like changeable typhoon track, intensity, speed and astronomical tidal flood were considered (Duan et al. 2004). Ensemble forecast techniques of storm surge were introduced by considering uncertainty in projections of typhoon path, and PMSS in the offshore of Ningbo was calculated based on typhoon 9711 (Hu et al. 2013). This article also takes a similar approach, and the different is that sea walls are added when calculating. Except for some hills, the coastal areas of Yuhuan County typically have elevations below 5.0 m. The socioeconomic development of the region greatly depends on the protection provided by the sea walls. To describe the actual situation in Yuhuan County, 26 sea walls were added to the mesh as one-dimensional barriers.

Index systems and stage-damage curves are common methods for vulnerability assessments of natural disasters. An index system is also used for the vulnerability

assessment in provincials, cities or on a large scale. Society, economy, environment and anti-disaster ability are considered in the research of vulnerability assessment in Taizhou and Wenzhou where the paper selected 16 evaluation factors to reflect the vulnerability and easy accessibility to build the index systems and conducted the vulnerability assessment at the city level (Zhang 2015; Zhang et al. 2015). However, because the statistical data are currently published by county or city within the administrative division and acquiring sufficient amounts of data is often difficult, an index system is not appropriate for counties or smaller areas. In addition, some studies focus on building a quantitative evaluation approach between damage and intensity for precise vulnerability assessment. Fragility curve was created based on wind speed and the average loss rate of the buildings according to the different structure types (Khanduri and Morrow 2003). Researchers built a logarithmic distribution function of housing fragility, and factors as the roof of building shape and geographical location were considered (Lee and Rosowsky 2005). Fragility curve of flood population was built through studying assessment method of population vulnerability based on historical flood data in the USA, Britain and other countries (Jonkman 2007). But disaster investigation and evaluation systems, codes and standards are not established in our country. Building a mature and practical vulnerability curve is difficult due to lack of disaster data sharing. Therefore, this method was not suitable for the current national conditions although it has been widely applied overseas. The State Oceanic Administration People's Republic of China organized experts to write the technology guideline of storm surge risk assessment (trial) in 2012, which provides a standard for risk assessment in China. The method to define the vulnerability in this article refers to the guideline which recommends using the land use type as a basis. The guideline also defines the ranges of hazard grades and risk grades, and Tables 1, 2, 3 and 4 refer to the guideline (Zhang 2015).

2 Data and methods

2.1 Data

The primary data used in this study included the following. 1. Coastline and bathymetry data were used in the storm surge model. A wide range of these data came from <http://www.ngdc.noaa.gov/>, and the Zhejiang coastal data came from the Zhejiang “908” offshore special investigation, which accurately described the area's key geomorphic features. 2. Elevation and sea wall data for Yuhuan County were obtained from the “Marine Disaster Risk Investigation and Hidden Danger Investigation Project,” which is supported by a special fund for disaster prevention and mitigation in Zhejiang Province. 3. Typhoon and tidal data were used to validate the storm surge model. The typhoon data were obtained

Table 1 Five ranks of typhoon parameters

	Fifth Rank	Fourth Rank	Third rank	Second rank	First rank
Grade of typhoon	TY	STY	SuperTY	SuperTY	SuperTY
Central pressure (hpa)	965	945	935	925	915
Maximum wind (m/s)	35	50	55	60	65
The radius of maximum wind (km)	56	42	38	36	36

Table 2 Vulnerability classification table of the typhoon storm surge in Yuhuan County

First class of land use status			Second class of land use status					
Number	Name	Grade	Number	Name	Grade			
01	Farmland	III	011	Paddy fields	III			
			012	Dry land	III			
02	Field	III	021	Orchard	III			
			022	Tea garden	III			
			023	Other field	III			
03	Woodland	IV	031	Closed forest land	IV			
			032	Bush forest land	IV			
			033	Other woodland	IV			
04	Grassland	IV	041	Other grassland	IV			
05	Land for industrial and mining storage	II	051	Mining lease	II			
06	Residential land	I	061	City	I			
			062	Town	I			
			063	Designate town	I			
			064	Village	I			
07	Land for public management and service	I	071	Land for scenic spot facilities	II			
08	Land for special use	I			I			
09	Land for traffic	II	091	Highway land (expressway, first-class highway)	I			
				Highway land (under second-class highway)	II			
			092	Country road	II			
			093	Land for harbor and wharf	II			
			10	Water and land for water facilities	IV	101	River	IV
						102	Reservoir	IV
						103	Pond	IV
104	Coastal beach (Not include farmland)	IV						
105	Inland beach	IV						
			106	Ditch	IV			
			107	Irrigation and water conservancy land	III			
			108	Hydraulic building land	III			
11	Other lands	IV	111	Facility agricultural land (Include farmland)	III			
			112	Ridge	IV			
			113	Salt pan	II			
			114	Shoal and marsh	IV			
			115	Nature reserve	IV			
			116	Bare land	IV			
			117	Independent construction land	IV			

Remark: (1) land for special use includes military installation, supervision and teaching place, religious and funeral land; the grade of vulnerability of the first three is I, and that of the funeral land is III. (2) Independent construction land refers to the energy, transportation, water conservancy, environmental governance land outside the city, town and village construction land defined in the general plans for land use

Table 3 Corresponding relationship between the hazardous grade and the submergence depth

The grade of storm surge hazard	The submergence depth (m)
IV	(0.0, 0.5]
III	(0.5, 1.2]
II	(1.2, 3.0]
I	>3.0

Table 4 Corresponding relationship between the risk grade and risk

The risk grade	Risk
IV	≥ 12
III	[7,12)
II	[4,7)
I	<4

from TYPHOON YEAR (i.e., the Tropical Cyclone Yearbook after 1989). The tidal data were obtained from the water conservancy department of Zhejiang Province. 4. The data regarding the storm surge hazard in the region were extracted from Yuhuan's Digital Orthophoto Maps in 2012; these maps had an image resolution of 0.5 m.

2.2 Model and validation

The ADCIRC is an unstructured grid finite-element hydrodynamic model that provides high grid resolution where solution gradients are large and low grid resolution where solution gradients are small. This model has been widely used to simulate the hydrology of shelves, coasts, and estuaries (Bacopoulos et al. 2012; Bai et al. 2012; Balzano 1998; Byung et al. 2013; Cao et al. 2005; Du 2012; Wu et al. 2005; Zhang 2004). More detailed information is available in the ADCIRC User Manual (Luettich et al. 1992; Luettich and Westerrink 2000).

To reduce the boundary effect on the simulation results, we chose the line from Korea Lishui to Guangdong Shanwei to be an open boundary and the model domain to include the Bohai Sea, the Yellow Sea and most of the East China Sea (Fig. 1); this simulation area is large enough to accurately simulate a storm surge in Yuhuan County. Additionally, considering computational costs and quality, the unstructured triangular grids used have a horizontal resolution varying from 40 km near the open boundary to 60 m along the coast of Yuhuan County. In total, there are 414,005 nodes and 806,107 triangular elements in the model mesh. Nearly 80 % of the grid is distributed along the coastal area of Zhejiang Province, and the model can thus accurately describe the key geomorphic features of the area with significantly lower computational costs. And, to describe the actual situation in Yuhuan County, 26 sea walls were added to the mesh as one-dimensional barriers (Fig. 2).

Using the fully nonlinear, two-dimensional, depth-integrated option of the model (ADCIRC-2DDI), wind force is applied as a surface stress using the quadratic drag law, as proposed by Garratt (1977), to convert wind speeds into wind stresses. The bottom friction is represented by a quadratic relationship and a depth-dependent drag coefficient (Luettich et al. 1992). The model begins by assuming that the sea is static, and the initial conditions

of all of the elements' elevations and flows are zero; thus, $\zeta = 0$ and $u = v = 0$. For the land and island boundary conditions, the normal flow velocity is zero ($V_n = 0$). For the tidal elevation on the open boundary, the amplitudes and phases of the tide constituents (K1, O1, P1, Q1, M2, S2, N2, K2) are interpolated from the global tide model FES (Le Provost et al. 1998). The time step is 2 s.

To examine the feasibility of simulating storm surges with the proposed ADCIRC model, this study simulated the water elevation caused by Typhoons 7504, 9417, 9608, 9711, 0216, 0414, 0505, 0515 and 1323. During these typhoon influence periods, we compared the highest water level between Haimen, Kanmen, Ruian and Aojiang stations, and found that the simulated water elevations were in good agreement with the observed results. The mean absolute error in the maximum water elevations was 33.4 cm, and the mean relative error was 8.0 %. The relative errors between the highest water level and measured value in Haimen, Kanmen, Ruian and Aojiang stations are 8.13, 4.16, 13.94 and 0.80 %, respectively, during typhoon 1323 (Fig. 3).

2.3 Typical typhoon track and probable maximum tropical cyclone (PMTC)

After analyzing the typhoon data, we chose three typhoons that caused serious damage in Yuhuan County: Typhoons 9417, 0414 and 1323. We also chose to investigate Typhoon 0608, which was the typhoon with the lowest atmospheric pressure in Zhejiang Province since 1949, because this typhoon had the potential to cause serious damage in Yuhuan County if it had landed directly in that region; in reality, this typhoon did not have significant effects on Yuhuan County due to its smaller radius and lower maximum wind speed in that region. To compare the four typhoon paths under the same conditions, we translated the path of Typhoons 0414, 0608 and 1323 to the same landfall position as that of Typhoon 9417 and adjusted them to have the same intensity. The results show that the

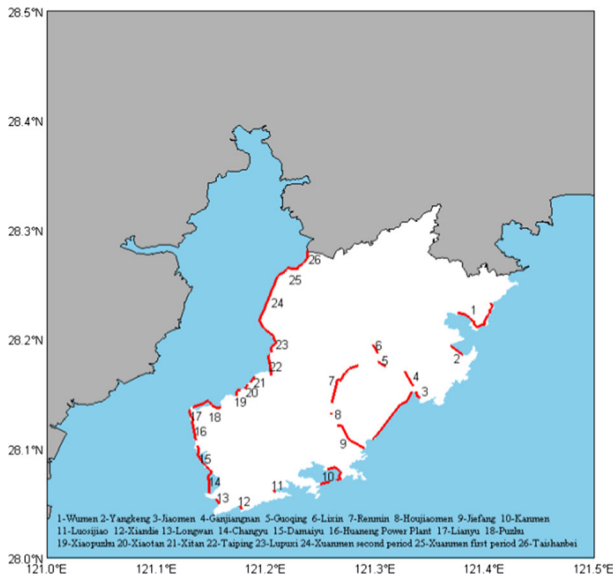


Fig. 2 Distribution of sea walls in Yuhuan

surge elevations induced by Typhoon 0608 were higher at the Haimen and Kanmen stations, which were located north of the landfall position; therefore, we chose the path of Typhoon 0608 for further analysis.

In this study, the proposed shifted tracks of Typhoon 0608 were expected to cause potentially higher surge. A total of 32 other typhoon tracks can be proposed by shifting the original track of Typhoon 0608 5 km south or north, but only two paths result from the translation south. The chosen tracks of these typhoons are shown in Fig. 4. Model simulations were performed for these different typhoon tracks under the same atmospheric conditions. Six representative points from the coastal area of Yuhuan County were selected to act as representative locations for the results. Moreover, Kanmen station is an ocean station that has already been established among these points. The principles for selecting other points include no obvious islands obstructed in the area, low altitude and high degree of land use in the area.

The results show that the surges induced by these paths are similar, and the maximum surge at the 6 representative points is created by the typhoons on the northern paths. The maximum surges at the Damaiyu station and the Huaneng Power Plant are found to be caused by the path created by shifting the original track of Typhoon 0608 10 km northward. The maximum surge at the Xuanmen Second Period station is shown to be caused by the path obtained by shifting the original track 20 km northward. The maximum surge at the Kanmen station and the Xuanmen Bay station are found to be caused by the path obtained by shifting the original track 30 km northward. Finally, the maximum surge at the Shamen station is found to be caused by the path obtained by shifting the original track 50 km northward.

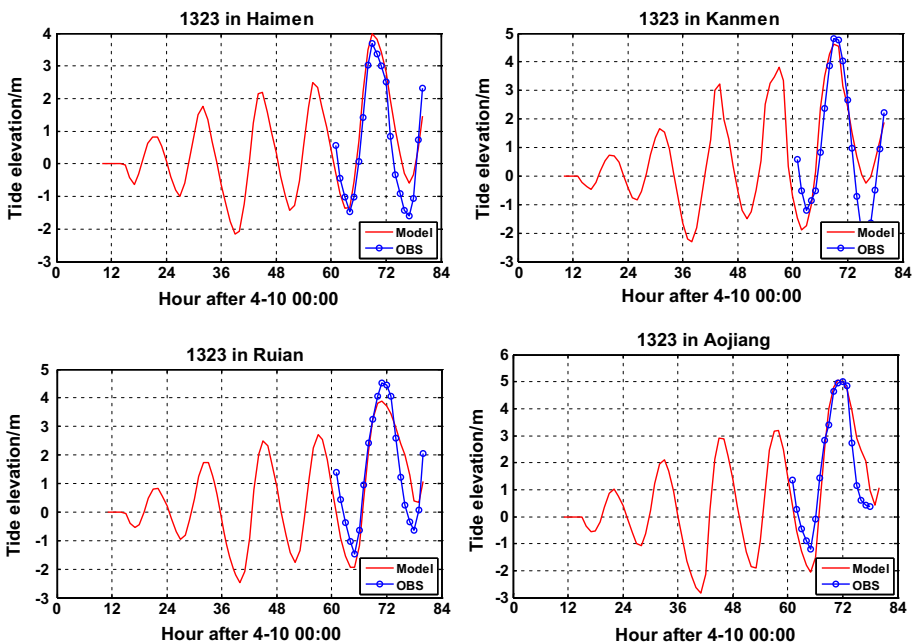


Fig. 3 Comparison of observations and predictions of tide elevation during Typhoon 1323

2.4 Typhoon intensity

The radius of the maximum wind is calculated using Eq. (1). The calculated radius of the maximum wind is consistent with that of Typhoon 5612 and 9417 but is greater than that of Typhoon 0608. Therefore, the calculated radius is safe for the calculation of the real storm surge:

$$R = R_c - 0.4(P_0 - 900) + 0.01(P_0 - 900)^2 \tag{1}$$

where P_0 is the central pressure of the typhoon and R_c is the empirical constant, which has a recommended value of 40.

The maximum wind is calculated by:

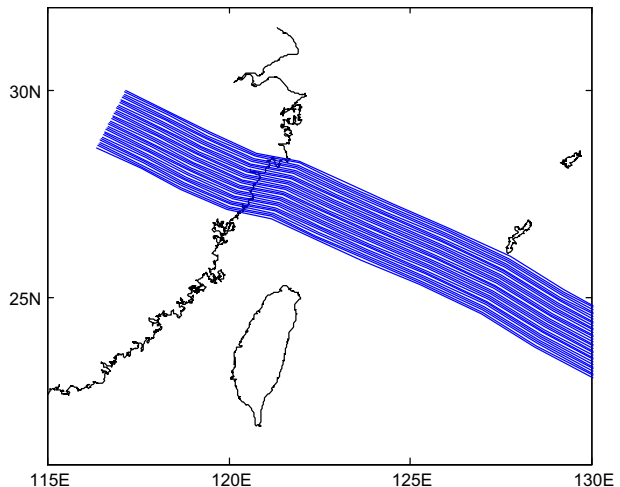
$$W_R = 3.447(P_\infty - P_0)^{0.644} \tag{2}$$

where P_0 is the central pressure of the typhoon and P_∞ is the atmospheric pressure far from the typhoon, which is equal to 1010 hpa in this study. The relationship between the central pressure and the maximum wind speed is based on an analysis of 28 years of maximum wind speed measurements made at the coastal and island stations in the northwestern Pacific (Atkinson and Holliday 1977). The calculated maximum wind speeds are 40, 51, 56, 60 and 65 m/s. The results with other historical observation data are shown in Table 1.

2.5 Vulnerability analysis of storm surge

Index system is to choose the index data which come from Bureau of Statistics' yearbook. The statistical unit is usually the whole county or township within the administrative division. For fine areas, the spacial scale may be only hundred meters. There are no authoritative index data, and data cannot be collected. So the method of vulnerability analysis is based on the land use type which data can obtain from the survey departments. Vulnerability grade can be identified through the certain correlation of the technology guideline of storm surge risk assessment.

Fig. 4 Thirty-two tracks proposed from shifting the original track of Typhoon 0608



In this study, we used a set of vulnerability assessment methods recommended by the guideline based on land use type for typhoon storm surge disaster assessment. The primary method included finding the corresponding relation between land use and the vulnerability grade, referring to the GB/T21010-2007 Current Land Use Classification, which is applicable to the standard of land use. Vulnerability can be divided into four grades (I, II, III and IV), where IV is the lowest grade and I is the highest grade. This is a simple method and can be applicable to counties or smaller areas. The vulnerability classification table of the typhoon storm surge combined with the practical land use of Yuhuan is shown in Table 2 (State Oceanic Administration People's Republic of China (2015)).

2.6 Calculation of storm surge risk assessment

In 1989, Maskrey proposed that the natural disaster risk is the sum of the hazard and the vulnerability (Maskrey 1989). However, in 1991, UNDHA proposed that the natural disaster risk is the product of the hazard and the vulnerability (UNDHA 1991). This updated view has been accepted by many scholars and is applied in risk assessment. The technology guideline of storm surge risk assessment (trial) also recommended Eq. (3) to assess the storm surge risk in 2012. Therefore, we also use it in this paper:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \quad (3)$$

3 Results and discussion

3.1 Estimates of storm surge hazards

We calculated the astronomical tide elevation at the Kanmen station from 2001 to 2019, chose the average spring high tide in June, July, August, September and October and found the statistical average tide elevation to be 2.9 m in Yuhuan County. The points' amplitudes of the eight tidal constituents on the open boundary were adjusted to ensure that the maximum storm surge and the astronomical high tide added together. Using the ADCIRC model and PMTC, we simulated the different areas' maximum possible inundation extents and depths in Yuhuan County for five different typhoon intensities. We then divided the different hazard areas based on their submergence depth (Table 3) (State Oceanic Administration People's Republic of China 2012) and performed an assessment of the storm surge hazards. The final results are shown in Fig. 5.

In this paper, we assumed that all of the sea walls were undamaged during a storm surge. Using a storm surge floodplain model, we computed the hazard grade of Yuhuan County with regard to five typhoons with different intensities (Fig. 5). The results show that the areas with a high hazard of storm surge are mainly distributed in the western area of Yuhuan County. The elevation of western Yuhuan County is relatively low; also, compared to eastern Yuhuan County, the sea wall construction standard in the west is relatively low. The area can be divided into three categories. The first category includes areas where the grade of the storm surge hazard is at level I; these areas include the protected areas of the sea walls of Wumen, Jiaomen, Damaiyu-Changyu, Puzhu, Xiaopuzhu-xitang, Taiping-Lupuxi, and Xuanmen second period-Taishanbei. These regions have an extremely high hazard to storm surge during a first-rank typhoon with a central pressure of 915 hpa. These areas lie along the coast and are at lower elevations. The second

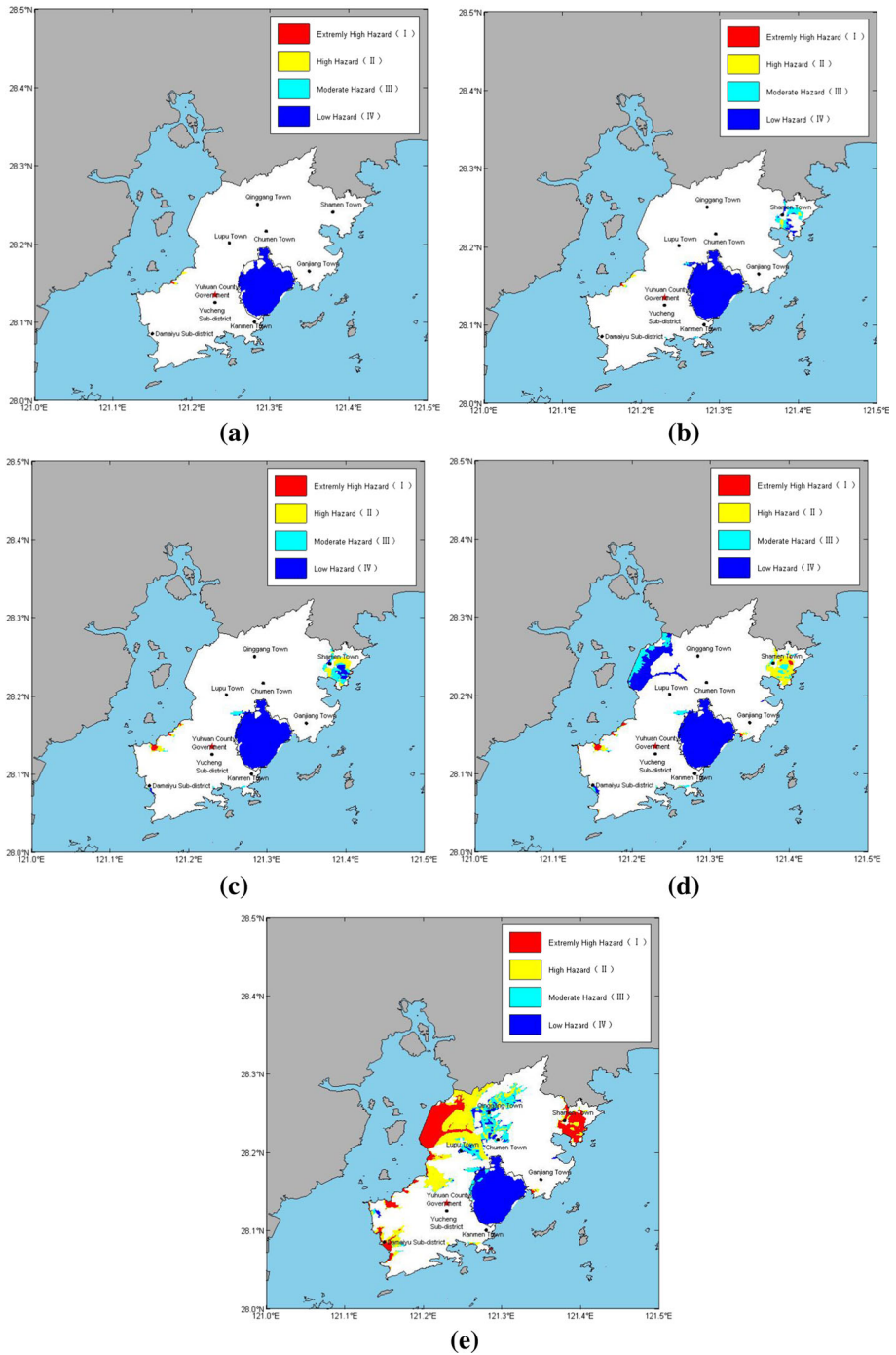


Fig. 5 Grade of storm surge hazard under five different intensity of typhoon (a –965 hpa, b –945 hpa, c –935 hpa, d –925 hpa, e –915 hpa)

category includes areas where the grade of the storm surge hazard is at level III or IV; these areas include the surrounding areas of southeast of Lupu Town, north of Chumeng Town, south and northeast of Qinggang Town, the sea wall of Renmin, Kamen fishing port and Huaneng Power Plant. Among these areas, the areas of southeastern Lupu Town, north of Chumeng Town, and south and northeast of Qinggang Town, where storm surge hazard is less serious than the coastal areas, are susceptible to submergence due to high water flow over the sea wall of Xuanmen second period, which results in a water level rise in Xuanmen Cove. The remaining areas have less serious hazard risks because their local sea wall protection measures are more effective. For example, the sea wall of Renmin is a backset sea wall, and its periphery is defended by another sea wall with a height of 9.0 m. The elevation of the Kamen fishing port area is relatively high, and its periphery is also defended by another sea wall with a height of 8.0 m. The construction standard of the sea wall near the Huaneng Power Plant has a 1-in-200-year return period. The areas of the last category, such as Ganjiang Town and Yuhuan County Town, are not susceptible to submergence. These areas have low elevation but are protected by two layers of sea walls.

3.2 Vulnerability assessment

Based on digital orthophoto maps with an image resolution of 0.5 m and the corresponding relationship between land use and the vulnerability grade (Table 2), the vulnerabilities were calculated, as shown in Fig. 6.

From Fig. 6, it is shown that for human-occupied areas, such as the center of Yuhuan County, Qinggang Town, Chumen Town and Lupu Town, the vulnerability grade is level I, which is the highest vulnerability. These areas would be most affected and suffer the most significant socioeconomic losses during a storm surge disaster. Although the area occupied by roads is small, it plays an important role in disaster preparedness and response during

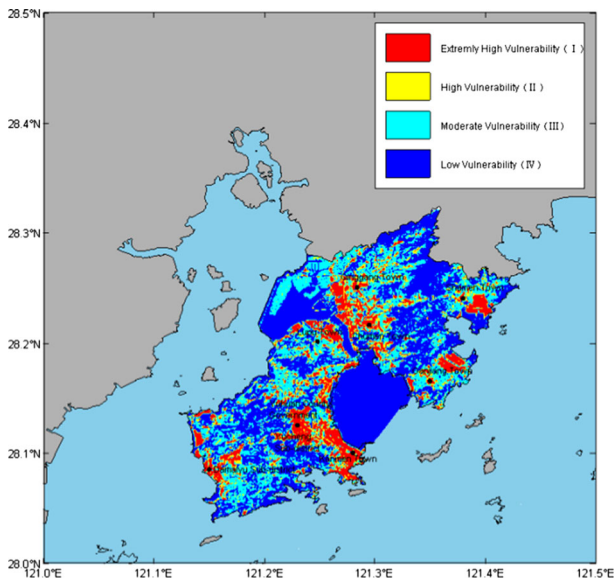


Fig. 6 Vulnerability of typhoon storm surge in Yuhuan County

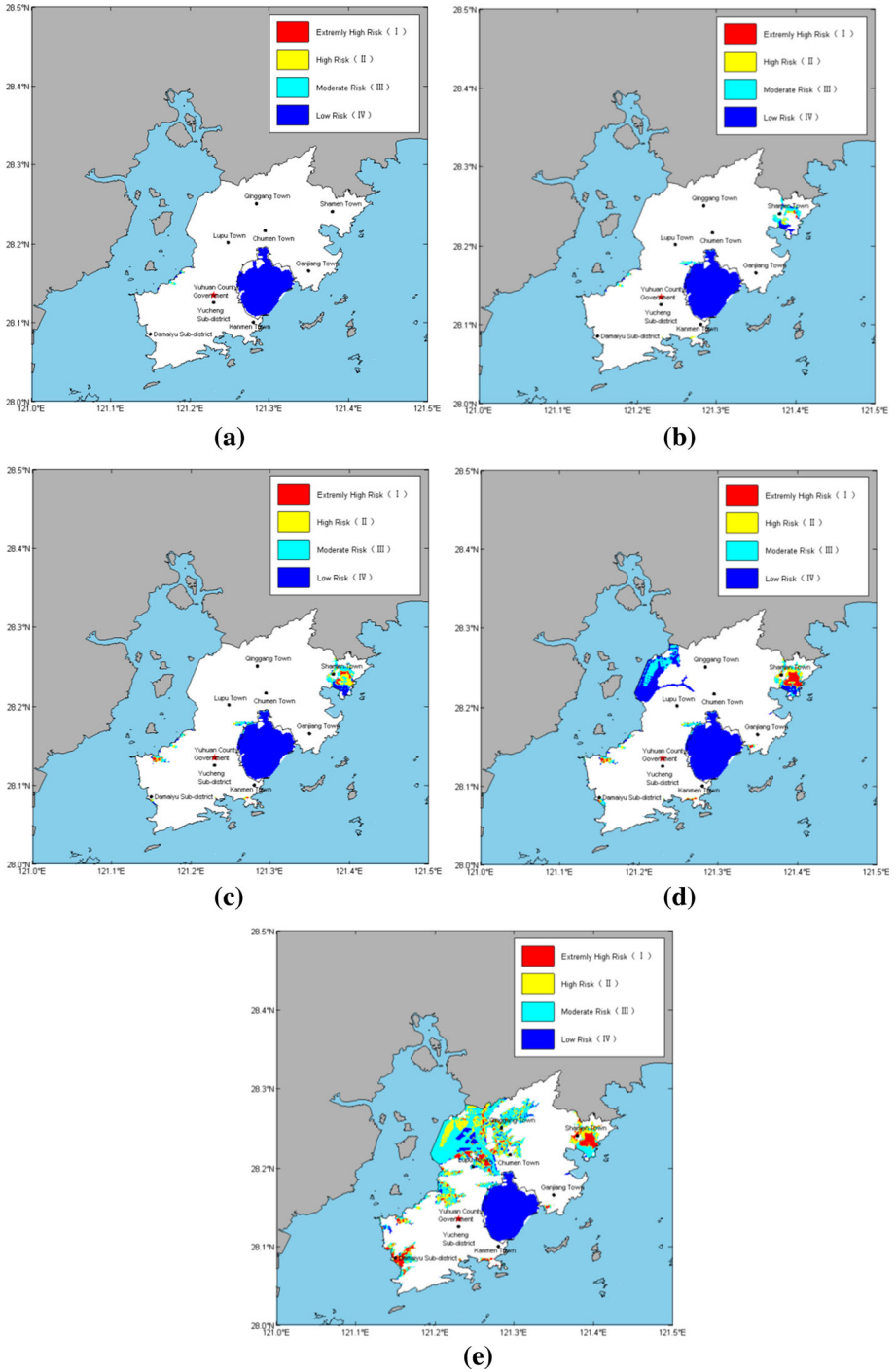


Fig. 7 Risk grade under five different intensity of typhoon (a -965 hpa, b -945 hpa, c -935 hpa, d -925 hpa, e -915 hpa)

rescues. Therefore, the vulnerability grade of the roads is determined to be level II (i.e., high vulnerability). The main areas where the grade is at level III (i.e., moderate vulnerability) include fields and coastal sea walls. These areas are sensitive to storm surge hazards due to their exposure to the elements; however, based on the potential socio-economic losses, they still belong to the moderate vulnerability category. Finally, the areas of Xuanmen, shoals, marshes and bare lands along the coastal sea walls, and forests, belong to level IV (i.e., low vulnerability). These areas are undeveloped and remain least affected by storm surges.

Due to the real conditions, the land use type is adopted as the judgment basis for vulnerability. This evaluation method is simple and feasible, and the results of the vulnerability assessment are objective and true. However, with the development of technology, the trend of the vulnerability assessment moving from qualitative to quantitative is not changed.

3.3 Risk assessment

According to the corresponding risk range (Table 4) (State Oceanic Administration People's Republic of China 2012), the coastal region of Yuhuan County was divided into four grades, as shown in Fig. 7.

According to the risk grade of Yuhuan County (Fig. 7), we divided the entire region into three classes. The first class includes the areas in Shamen Town, Damaiyu Sub-district, Lupu Town and north of Chumen Town, and south and northeast of Qinggang Town. These regions are occupied by humans and particularly active; thus, their vulnerability grade is level I (i.e., extremely high vulnerability); therefore, the risk grade of these areas is high. Among these areas, the storm surge hazard and the vulnerability are high in Shamen Town and Damaiyu sub-district; thus, they are typical high-risk areas. However, the areas of Lupu Town near Xumen Bay, north of Chumen Town, and south and northeast of Qinggang Town are less affected by storm surges than coastal areas because they are far from the coastline. Their hazard grade is thus level III, but their vulnerability is high; as a result, they are still high-risk areas.

The areas along the sea wall of Jiaomen, Puzhu, Xiaopuzhu-Xitan, Taiping, Xuanmen second period, and Taishanbei, area of north of Kanmen fishing port, and Xuanmen third period are now considered. These areas include bare land, farmland, shoals, small villages and storage areas. Although their hazard grade is level I or II, their risk grade is level III (i.e., moderate risk).

The third class includes the remaining area of Yuhuan County, where the risk grade is near zero even when faced with a 915-hpa super typhoon. This area of Yuhuan County is low-lying but has two layers of sea walls.

4 Conclusions

In this study, a high-resolution unstructured triangular grid was established, and coastal sea walls were added to the grid as one-dimensional barriers to accurately model the real-world situation. Using a two-dimensional (parallel) Advanced Circulation Model (ADCIRC), we built a storm surge floodplain model and applied it to Yuhuan County, in which 26 coastal sea walls were considered. Supposing that all of the coastal sea walls were not damaged during a storm surge, we simulated Yuhuan County's maximum possible inundation extent

and depth for five different typhoon intensities and performed an assessment of the associated storm surge hazards. Based on land use, the corresponding relation between land use and vulnerability grade was determined by referring to GB/T21010-2007 Current Land Use Classification; the vulnerabilities of Yuhuan County were also assessed. Finally, we used Eq. (3) to assess the storm surge risk by considering the storm surge hazard and the vulnerability of the county. This paper provides an important case study and demonstrates the risk analysis of storm surges.

However, wave overtopping and sea wall damaged were not considered when we computed the maximum possible inundated area. The basis for vulnerability is land use type. This evaluation method is simple and feasible, but the trend of the vulnerability assessment moving from qualitative to quantitative is not changed with the development of technology. These limitations need to be improved in future.

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References

- Aerts JCJH, Botzen W, Emanuel KA, Lin N, Moel HD (2014) Evaluating flood resilience strategies for coastal megacities. *Science* 344(80):473–475
- Atkinson GD, Holliday CR (1977) Tropical cyclone minimum sea level pressure-maximum sustained wind relationship for western north pacific. *Mon Weather Rev* 105:421–427
- Bacopoulos P, Dally WR, Hagen SC, Cox AT (2012) Observations and simulation of winds, surge, and currents on florida's east coast during hurricane jeanne (2004). *Coast Eng* 60:84–94
- Bai ZG, Pei L, Yang L (2012) Hydrodynamic numerical simulation for wind farm in intertidal zone. *Port Eng Technol* 49(3):1–4
- Balzano A (1998) Evaluation of methods for numerical simulation of wetting and drying in shallow water flow models. *Coastal Eng* 34:83–107
- Benavente J J, Rio LD, Gracia FJ (2006) Coastal flooding hazard related to storms and coastal evolution in Valdelagrana Spit (Cadiz Bay Natural Park, SW Spain). *Cont Shelf Res* 26(9):1061–1076
- Byung HC, Byung M, Kyeong OK, Jin HY (2013) Wave-tide-surge coupled simulation for typhoon maemi. *Chin Ocean Eng Soc* 27(2):141–158
- Cao YH, Zhang QH, Yan SW, Ji ZZ, Yang H (2005) Two dimensional current field analysis of Huanghua Port. *China Harb Eng* 3:1–4
- Du BR (2012) Research of the changes of storm surge before and after construction of the coastal engineering. master thesis. South China University of Technology, Guangzhou
- Duan YH, Gao QP, Zhu JR (2004) Research on probably maximum water level calculation in Changjiang Estuary. *Acta Oceanol Sin* 26(5):45–54
- Garratt JR (1977) Review of drag coefficients over oceans and continents. *Mon Weather Rev* 105:915–929
- Hall JW, Sayers PB, Walkden MJA, Panzeri M (2006) Impacts of climate change on coastal flood risk in England and Wales: 2030–2100. *Philos Trans A Math Phys Eng Sci* 364:1027–1049
- Hu RF, Wang YH, Zhang H, Shan HJ (2013) Numerical simulation on probably maximum storm surge in Ningbo. *J Appl Oceanogr* 32:340–348
- Jonkman SN (2007) Loss of life estimation in flood risk assessment, theory and applications, Ph.D. thesis. Delft University of Technology
- Khanduri AC, Morrow GC (2003) Vulnerability of buildings to wind-storms and insurance loss estimation. *J Wind Eng Ind Aerodyn* 91(4):455–467
- Kron W (2005) Flood risk = hazard · values · vulnerability. *Water Int* 30:58–68
- Le Provost C, Lyard F, Molines JM, Genco ML, Rabilloud F (1998) A hydrodynamic ocean tide model improved by assimilating a satellite altimeter-derived data set. *J Geophys Res* 103(C3):5513–5529
- Lee KH, Rosowsky DV (2005) Fragile assessment for roof sheathing failure in high wind regions. *Eng Struct* 27:857–868

- Luettich RA, Westerrink JJ (2000) ADCIRC user manual: a(parallel) advanced circulation model for oceanic, coastal and estuarine waters. <http://www.unc.edu/ims/adcirc>
- Luettich RA, Westerink JJ, Scheffner NW (1992) ADCIRC: an advanced three-dimensional circulation model for shelves, coasts, and estuaries, I: theory and methodology of ADCIRC-2DDI and ADCIRC-3DL. Technical report DRP-92-6, U.S. Army Corps of Engineers
- Maskrey A (1989) Disaster mitigation: a community based approach. Oxford, Oxford
- Okada N, Tatano H, Hagihara Y (2004) Integrated research on methodological development of urbandiagnosis for disaster risk and its applications. *Annals of Disas. Prev. Res. Inst. Kyoto Unit*, p 47
- Scheffner NW, Mark DJ (1996) Empirical simulation technique based storm surge frequency analyses. *J Waterw Port Coast Ocean Eng* 122(2):93–101
- Scheffner NW, Clausner JF, Militello A (1999) Use and application of the empirical simulation technique: user's guide. US Army Corps of Engineers Engineer Research and Development Center, Washington, DC
- Shi PJ (2002) Theory on disaster science and disaster dynamics. *J Nat Disasters* 11(3):1–9
- Shook G (1997) An assessment of disaster risk and its management in Thailand. *Disasters* 21(1):77–88
- State Oceanic Administration People's Republic of China (2012) Guideline for risk assessment and zoning of storm surge disaster, p7
- The Cabinet Office (2003) Tsunami and storm surge research association, Tokyo
- UNISDR (2004) Living with risk: a global review of disaster reduction initiatives. United Nations Publication
- United Nations Department of Humanitarian Affairs (UNDHA) (1991) Mitigating natural disasters: phenomena, effects and options: a manual for policy makers and planners. United Nations, New York, pp 1–164
- Wang XN (2002) Risk analysis and calculation of storm surge. *Marine forecasts*. 19(4):73–76
- Wu XZ, Zhang QH, Zhang N, Yang H (2005) Numerical simulation of three-dimensional velocity field in sea waters around Huanghua Harbor. *Hydro Sci Eng* 3:13–19
- Yin QJ, Wang XN, Wu SH (1995) Probably maximum storm surge calculation in Zhenhai. *Acta Oceanol Sin* 17(6):21–26
- Ying RF, Yang TZ (1986) Analysis of storm surge calculation and probably maximum water level in the study of flood control water level in Shanghai. *Acta Oceanol Sin* 7(4):423–428
- Zerger A (2002) Examining GIS decision utility for natural hazard risk modeling. *Environ Model Softw* 17:287–294
- Zerger A, Smith DI, Hunter GJ (2002) Riding the storm: a comparison of uncertainty modeling techniques for storm surge risk management. *Appl Geogr* 22:307–330
- Zhang N (2004) 3D numerical simulation of cohesive sediment transport under winds and waves, master thesis. Tianjin University, Tianjin
- Zhang YX (2015) Risk assessment method and application of typhoon storm surge on ADCIRC—A case study of Taizhou, Ph.D. thesis. Ocean University of China
- Zhang JQ, Li N (2007) Quantitative methods and applications of risk assessment and management on main meteorological disasters. Beijing Normal University Press, Beijing
- Zhang YX, Guo J, Che ZM (2015) Discussion on evaluating the vulnerability of storm surge hazard bearing bodies in the coastal areas of Wenzhou. *Front Earth Sci* 9(2):300–307