Risk Assessment of Marine Hydrodynamics for Coastal Engineering

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Abstract: Risk assessment in marine hydrodynamics is an important part of ocean disaster and risk analysis. Its key scope lies in the identification of hydrodynamic risk factors and the forecast of their severity which is one of the most effective approaches to improve disaster protection capability, control risk and reduce damage and loss during a disaster. Haikou Bay is located off the north coast of Hainan Island, within Qiongzhou Strait, and close to the South China Sea. The most significant marine hydrodynamic disasters in the waters of Haikou Bay include storm surge, extreme waves and tsunami. The Holland wind and Monte Carlo method were integrated to predict storm surge elevation, and the SWAN model with the Pearson method was used to calculate the extreme waves and using USGS source parameters to predict tsunami waves. High water surface elevations are 3.75m, 3.02m and 2.68m with a return period of 500, 100 and 50 year respectively at Xiuying; an extreme water surge up to 4.42m from the Probable Maximum Storm Surge analysis; significant wave heights present with different return periods and wave directions; the maximum tsunami wave amplitude reaches 2.25m in case of all fault plates under a 9.0 earthquake.

1. INTRODUCTION

Surrounded by sea, Hainan Province is the most vulnerable region to marine disasters in China. Located in the forefront of economic development in Hainan Province, its largest city Haikou City is close to the Haikou Bay water area facing a grim situation of marine disasters. Super typhoon, storm surge, extreme waves, tsunamis, sea level rise, increasing erosion of the beach and coastal ecological environment deterioration, etc. all pose a serious threat to the coastal economics and have become one of the constraints on coastal development planning and economic construction. The risk assessment of a project with sea area usage is mainly about the types of ocean disaster risk threatening the project, the risk to the sea water area functions around the project, and the risk of the sea usage to nearby stakeholders [1], and presenting schemes for avoidance of the occurrence of disaster or contingency measures after disasters. Therefore, it is of great significance to carry out an analysis of marine disaster risk assessment in coastal engineering, which is one of the key technical methods to improve disaster protection capability, control risk and reduce subsequent damage and loss. Haikou Bay is located off the northern coast of Hainan Island and opposite to the mainland Leizhou Peninsula across the Qiongzhou Strait. Marine hydrodynamic disasters in the sea area include storm surge, wave, tsunami etc. In this paper, the severity and hazards associated with the major risk factors are determined using historical record data, and an analysis method combined with the numerical simulation of the shallow water wave model,
SWAN wave model and the Holland wind model.

2. ASSESSMENT CONTENT AND RESULTS ANALYSIS

2.1. STORM SURGE ELEVATION
The northern part of Hainan Island is more frequently affected by storm surge tropical cyclones. According to historic records, 136 storm surges have occurred in Haikou since 1953, with an annual average about 3 instances and in which serious or disastrous storms occurred once every two years[3]. Storm surges are likely to occur in Haikou Bay from June to December every year, concentrated in the period from July to October, and most happen in October. Based on the collection of historical storm surge data, possible typhoon storm surges are studied by analyzing existing measured typhoon data, combined using the Monte Carlo method and hydrodynamic model, in order to predict the extreme high water level with a return period of 50, 100 and 500 years.

2.1.1. METHOD AND MODEL
A depth-averaged two-dimensional storm surge model is used as the hydrodynamic model of the typhoon storm surge in the offshore area. The storm tide elevation is the most important variable in the hydrodynamic model, which is also the core variable of the extreme high water elevation in storm surge prediction. A large area numerical model domain is adopted in the study, which can make it possible to simulate a typhoon process over its full path, model scope is shown in Figure 1. To obtain local simulation data in detail, a fine mesh domain with small overlaid area is adopted. To match meshes between the large domain and small domain, a medium domain model is adopted to ensure the local fine mesh model presents accurate results in the simulation. The north and the west boundaries of the large model are the continental coastline; the south boundary is the line of 15.0 ° north latitude, and the east is that of 117.9 ° east longitude. The domain covers the Northern Bay, Qiongzhou Strait, east area of Qiongzhou Strait and part of the South China Sea.

The Holland model is adopted in the air pressure distribution simulation, in which the gradient wind speed formula is adopted for the circulation wind modeling; the wind speed is modeled by the Miyazaki model. The typhoon wind field simulation scheme combining air pressure distribution simulation and the wind speed formula is referred to the Holl model [4]. The simulating circle method is adopted to analyze a typical measured typhoon, which is the data processing method based on the analysis of US FEMA typhoon historical data recordings. In the method, all the typhoon records passing the circle with the center located at the studied city and a setting radius are analyzed[5, 6].

During the period from 1949 to 2015, there were 151 typhoons passing the circle with a radius of 200km centered on Haikou Bay, of which 60 typhoons with their minimum pressure in the center of the landing point falling into the range of 0 to 980 hPa. Most of the selected typhoons landed in the eastern or southeastern part of Hainan Island and left from the island’s west or northwest, and six of them left from the island’s northeast. In all the 60 measured typhoons, the strongest intensity one is the typhoon
Rammasun on July 18, 2014. Therefore, the typhoon wind field has been verified by the No. 1409 typhoon Rammasun which caused the largest storm surge in 2014. Figure 2 shows the wind field simulated at 18:00 on 18 July 2014 after Typhoon Rammasun landed. Then, the Monte Carlo model was used to generate simulated typhoon data that may occur with return period of 100 years. Because the typhoon historical data used 60 typical typhoons, the number of typhoons with a return period of 500 years should be 448. According to the parameters analyzed, typhoon data were simulated. The water level is obtained by combining the stochastic model (Monte Carlo) and the hydrodynamic model, and then the extreme water level can be obtained. In detail, the Monte Carlo stochastic model was used to obtain 448 reconstituted typhoons by a random combination of 60 typhoon’s air pressure and pathways as independent elements over 67 years. Those typhoon elements were collected into the verified storm surge model. Furthermore, the typhoon process was randomly combined with the astronomical tide elevation. Finally, 448 water level process lines were obtained, and the maximum water level in each water level process line was calculated in the extreme water level analysis.

2.1.2. CALCULATED RESULTS

Through the above procedure, the maximum water elevation value in each water elevation process line was counted, and part of the larger water elevation process line is shown in Fig. 3 (a). The maximum values of all the 448 maximum water elevations are ranked in descending order, and the maximum value is 3.75 m from the maximum water level sequence at Xiuying Station. The return period TR of the extreme water elevation is estimated by the order series of the water elevation: \( TR = \frac{500}{M} \), where M is the order series among the descending 448 highest water elevations and TR is the return period. For example, when \( M = 1 \) (corresponding to the maximum of 448 extreme water elevations), the corresponding return period is \( TR_1 = \frac{500}{1} = 500 \) years. The graph of extreme water elevation versus corresponding return period can be plotted, and then the extreme water elevation value can be determined for any of corresponding period. The fifth highest water elevation of 3.02m corresponds to a return period of 100 years, and the extreme high water levels corresponding to return periods of 500 years, 100 years and 50 years at Xiuying station are 3.75m, 3.02m and 2.68m respectively. In addition, the Probable Maximum Storm Surge (PMSS)\(^7\) is calculated using the imaginary path, with air pressure \( P_0 \) of 883hPa, the maximum wind speed radius \( R \) of 33 km and the typhoon movement speed of 35 km/h in the case of a return period of 100 years. The results show that the maximum water surge is up to 4.42m, and the corresponding water surface elevation increase process is shown in Fig. 3 (b).

2.2. EFFECTS OF EXTREME WAVES

There are more wind waves and less swells at Haikou Bay annually. The wind wave frequency is from 76% to 85%, the swell frequency is from 14% to 23%, the most frequent wave direction is ENE with a frequency of 30.1%, and the second most frequent wave direction is NE with a frequency of 22.9%. The least frequent wave direction is from S to WSW. Due to monsoon, the most frequent wave direction at the local sea water area often changes with the seasonal wind. During the northeast monsoon period (From November to next March), the most frequent wave direction is ENE, and the second most frequent wave direction is NE. During the monsoon transition period (From April to May, September to October), the most frequent wave direction and the second most frequent wave direction are the same as those during the northeast monsoon period, while the frequency of the most frequent wave is slightly lower in

![Figure 3](image-url)
winter, the frequency of the second frequent wave is slightly higher in winter. During the southwest monsoon period (from June to August), the most frequent wave direction is NE. Currently the maximum known wave was caused by the No. 1409 Typhoon Rammasun. It passed over the northeast side of Haikou Bay, which was very conducive to the growth of NW waves, during which the largest significant wave height in the bay was 6.8m and the period was about 7.8s. The wave height is the anomalous large value of that trend to west wave direction. The maximum significant wave height was 3.9m in the N-E-S direction with a period of about 6.3s.

2.2.1. METHOD

There are two main causes of wind formation in the region, i.e. monsoon and typhoon. Therefore, the wave field is calculated mainly by using the wind field simulation, in which both the monsoon and typhoon effects are taken into account for the wind field data simulation. Research methods are as follows in detail: (1) The wind field is analyzed based on the typhoon path published by China Meteorological Data Network (www.data.cma.cn), combined with European hind-casting wind field data in medium and long term in the southern China Sea area, affecting the project sea area were selected every year. (2) According to the long-term wind field data, the SWAN model was used to simulate the large-area wave data, and the annual extreme wave in the deep sea water area near the project area was obtained. Then the Pearson-III curve was used to calculate the wave condition for different return periods. (3) According to the deep sea wave condition of different return periods, the SWAN model was used to simulate the small-area wave data under the natural terrain condition before any project construction, and the wave condition at the engineering area was analyzed.

The typhoon path data of Chinese Meteorological Data Network (www.data.cma.cn) were adopted in this study, the data contains the typhoon center warp/weft value, maximum wind speed (2 min average maximum wind speed), central pressure and so on elements, extracted the typhoon kai-tak (1213) and path information of typhoon Swallow (1309). The correlation coefficient of the calculated value and the measured value sequence is 0.95, the mean square error is 0.29 m, and the comparison analysis indicates that the verification is good.

2.2.2. RESULTS AND DISCUSSION

According to the typhoon and monsoon data of the last 30 years (1986-2015) in the engineering sea water area, the typhoon field model and the monsoon field data were used to simulate the wind moving in the engineering sea area, and then the wind wave field was calculated by using the large-scale wind and wave model. Annual extreme waves in the ENE, NE, NNE, N, NNW and NW directions were calculated in order to analyze the waves of different return periods in the deep sea water area. The results for different wave return periods at the offshore calculation point (water depth of about -70m) on the north side of the Haikou Bay are shown in Table 1.

| Wave Direction Return Period (a) | ENE | NE | NNE | N | NNW | NW |
|----------------------------------|-----|----|-----|---|-----|----|
| 200a                             | 7.58| 6.30| 6.03| 4.07| 4.76| 5.26|
| 100a                             | 7.14| 6.02| 5.78| 3.82| 4.42| 4.88|
| 50a                              | 6.80| 5.53| 5.52| 3.53| 4.07| 4.48|
| 25a                              | 6.20| 5.28| 5.23| 3.07| 3.70| 4.07|
| 10a                              | 5.51| 4.92| 4.82| 2.89| 3.17| 3.48|
| 5a                               | 4.90| 4.52| 4.45| 2.55| 2.71| 2.97|
| 2a                               | 3.90| 3.82| 3.80| 1.99| 1.97| 2.15|

Fig.4 shows the significant wave height distribution of the typhoon No. 1117 passing Qiongzhou Strait, in which the significant wave height for a return period of 100 years is 7.14m and that for a return period of 50 years is 6.80m.
In addition, according to the above wave height, the Hudson formula can be used to estimate the weight of an armor block on the slope revetment or the breakwater in the coastal area of Haikou Bay. For example, the artificial islands in Haikou Bay generally apply 30t armor blocks with a corresponding damage wave height being up to 8.78m. If the design life cycle of the protection is 100 years, the 30t armor block stability guarantee rate is up to 93%. At the same time, according to an analysis of wave run-up and overtopping, the significant wave height excess is over 7.9m at extreme high water level which would incur destructive overtopping water volumes over the top structure of the revetment or the breakwater. This wave condition corresponds to a return period of about 400 years, which means that the annual occurrence frequency is 0.25%. As waves propagate from offshore to the shore, the wave distribution in this area will be affected by the natural water depth of the bay. The SWAN model is used to simulate the wave distribution in the project sea water area. The simulated wave direction includes the ENE, NE, NNE, N, NNW and NW in the case of high water level, the design high water level and design low water level with a return period 100 years. The maximum significant wave height of the ENE is 6.7m, NE 5.8m, NNE 5.5m, N 3.8m, NNW 4.4m, and NW 4.9m respectively. Two wave directions ENE and NE have great influence on the coastal area. The H_{13\%} wave height distribution for high water level with return period 100 years is shown in Fig. 5.

2.3. TSUNAMI WAVE
According to the risk survey of a potential tsunami earthquake fault zone provided by the USGS \[8\], there are three subduction zones near the South China Sea that are considered to have the potential risk of earthquake-induced tsunami, namely, the Manila subduction zone, the Ryukyu Islands subduction zone and north Sulawesi subduction zone, in which the Manila subduction zone (also known as Manila Trench) would bring a great tsunami threat to the countries and regions around the South China Sea. The Manila subduction zone is located at the junction of the Asia-Europe continental plate and the Philippine Sea plate extending from the northern tip of Palawan Island, along the western edge of Luzon Island, northward to Taiwan Island, with a total length of about 1000km (Liu & Wang, 2009). The USGS divides it into six fault zones (Kirby, 2006) according to the azimuthal characteristics and fault geometry of the Manila trench.

A tsunami wave triggered by the above-mentioned regional earthquakes would make the southern
sea water area of China exposed to a major tsunami threat. Although historical statistics show that several large transpacific tsunami have had limited impact on the southeastern coastal areas of China, the South China Sea and Manila trench tsunami would still cause varying degrees of impact to Taiwan, Hainan, Guangdong, Fujian and other coastal areas. The South China Sea has experienced about 15 local tsunami, resulting in impact on coastal areas\(^9\),\(^10\). In recent years, the global geological movement is more active and the frequency of devastating tsunami is higher, and the Manila trench is considered to be the most likely potential source of tsunami. Based on the analysis, the potential threat of tsunami waves cannot be ignored.

2.3.1. TSUNAMI SIMULATION
The shallow water wave numerical model, GeoClaw is used to numerically simulate a tsunami wave by solving the nonlinear shallow water equations based on the finite volume method. The high nonlinear effects of the tsunami wave considered in its nearshore propagation, with an automatic adaptive grid technique to track the tsunami wave crest. In the numerical simulations, the earthquake fault zone source parameters were obtained by the Liu et al. (2009) method and the USGS source parameters. According to an analysis of the characteristics of the Manila trench fault, Liu et al. (2009) determined the complete parameters of each plate at a 8.0 magnitude earthquake based on the seismic and empirical relational formula that had historically occurred in the vicinity. The USGS source parameters are given based on the Nguyen et al. (2014) parameters which applied for a 9.3 magnitude earthquake\(^{10}\). Based on the Okada elastic half-space dislocation theory model\(^{11}\), submarine deformation can be calculated according to the above-mentioned six fault zone parameters, with which a tsunami wave can be generated. It is shown that the E1, E2 and E3 submarine plates bring greater impact to Hainan Island. The tsunami waves generated by 7.0 and 8.0 earthquakes are simulated numerically to estimate its influence on the sea water area of Haikou Bay. The large earthquakes formed by the rupture of the whole fault zone are also taken into account. The domain of the simulation extends from 99\(^\circ\) east to 130\(^\circ\) west, 1\(^\circ\) south to 33\(^\circ\) north, covering China's southeast, South China Sea, the Philippines, Vietnam and other countries.

2.3.2. RESULTS AND DISCUSSION
Some of numerical simulation results are shown in Figure. 6, and the tsunami waves generated by earthquakes on the Richter scale at 7.0 and 8.0 arising from the three sections of the northern Manila trench (E1, E2, E3) are given respectively. The characteristic values of the tsunami wave in the engineering area are shown in Table 2.
Figure 6. Tsunami wave propagation pattern and wave time history generated under 7.0 and 8.0 magnitude earthquakes

From the tsunami wave propagation pattern it can be seen that the tsunami wave travels for about 4 to 5 hours to reach the sea water area of Haikou Bay. For the general magnitude earthquake of a single fault plate, the tsunami wave that arrives in the vicinity of Haikou has an amplitude less than 4cm with a wavelength about 50km, a period of 1.6-2hr, a tsunami wave lasting duration (the first big wave amplitude) of about 0.7-1.1hr, and a moving speed of 8.1m/s. For the extreme tsunami caused by the 9.0 magnitude earthquake, the tsunami wave reaches an amplitude of 2.25m, a wavelength of 115km, a period of 3.4hr, a lasting duration of 1.3hr and a moving speed of 9.4m/s, which will have a great impact on Haikou Bay, especially the Cape Bay area of Haikou Bay near the coast, where it is more likely to achieve wave energy concentration. This should cause much concern for stake holders.

Table 2. Characteristic values of tsunami waves in Haikou Bay

| Fault plate | E1-7.0 | E1-8.0 | E2-7.0 | E2-8.0 | E3-7.0 | E3-8.0 | 9.0 |
|-------------|--------|--------|--------|--------|--------|--------|-----|
| Wave amplitude (m) | 0.0007 | 0.0165 | 0.0009 | 0.0227 | 0.0013 | 0.0375 | 2.25 |
| Wave length (km) | 47     | 47     | 53     | 53     | 58     | 58     | 115 |
| Wave period (hrs) | 1.6    | 1.6    | 1.8    | 1.8    | 2.0    | 2.0    | 3.4 |
| Lasting time (hrs) | 0.7    | 0.7    | 0.8    | 0.8    | 1.1    | 1.1    | 1.3 |
| Moving speed (m/s) | 8.1    | 8.1    | 8.1    | 8.1    | 8.1    | 8.1    | 9.4 |

3. CONCLUSION
Marine hydrodynamic risk is an important part of sea area utilization and its key lies in risk identification and risk estimation. In this study, the possible storm surge, extreme wave and tsunami in Haikou Bay were studied, and the hydrodynamic risk factors related to the sea area were analyzed, and the storm surge water levels in different return periods were obtained. The results of the simulation reflect the hydrodynamic conditions of different intensity caused by Marine disasters in Haikou Bay, and provide important reference parameters for the design and management of coastal engineering projects and
disaster prevention planning in coastal areas.

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