Assessment on typhoon prevention capability of fishing port based on numerical model calculations

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Abstract: Storm surge combined with strong wave induced by typhoon has led to significant losses of life and properties. In order to mitigate the impacts of typhoon disasters and provide early warning, the typhoon prevention capability of Shenjiamen fishing port was evaluated by using the coupled Advanced Circulation model (ADCIRC) and Simulating Waves Near shore model (SWAN). Various numerical experiments were carried out to determine the most dangerous typhoon path. The model result shows that the protection grade of seawall on the side of Xiaoqan Island is relatively low. However seawall on the Lujiazi Island is capable of withstanding category 17 typhoons. Through the comparison of external force on ship and holding force of anchor, the typhoon prevention ability of anchorage was also investigated. The protection grades of anchorage in Shenjiamen fishing port show significant spatial variation. The anchorage between Lujiazi Island and Zhoushan Island has higher grades, reaching level 16. But the protection grade of anchorage does not exceed 13 at the gate of Shenjiamen fishing port and intersection area of waterway. This study could provide scientific basis for the protection of fishing port and the dispatch of fishing boats during typhoon.

Key words: Shenjiamen fishing port; typhoon prevention grade; seawalls; anchorage

1. Introduction

In the estuary area, when the storm surge superimposes the high tide level, it will exceed the design height of the coastal seawall, causing severe economic losses and casualties [1]. There are hundreds of fishing ports around the coast of Zhejiang Province. A large number of docks, anchorages and seawalls have been built in these fishing ports, which not only guarantee the safe berthing of fishing boats, but also protect the residential areas behind the fishing ports. Due to aging facilities and surface subsidence, fishing ports are vulnerable to flooding caused by typhoon. Zhejiang Province is one of
the areas most seriously affected by typhoon disasters in China. Fishing port has become a weak point of coastal disaster protection in recent years. With the frequent occurrence of extreme weather, the protection capability of the fishing port needs to be evaluated to reduce disaster risk.

Numerical simulation method is widely used in the study of storm surge [2]. At first, storm surge was usually calculated forcing by a specified wind field and then added to predicted astronomical tide linearly for predicting the total water level [3]. However, such superposition was not accurate because of nonlinear interactions between tide and storm surges and led to great errors [4]. Thus, many scholars started to consider the nonlinear effects between storm surge and tide [5]. Tide-surge interaction induced by typhoon was investigated through numerical model and observation, highly improving the accuracy of the prediction storm surge model. In recent year, the wave effect in storm surge was also investigated [6]. Some study showed that including a wave-dependent drag coefficient in the calculation of wind stress improved storm surge prediction significantly [7]. In coastal area, inclusion of wave radiation stress gradients increased the surge height and changes in water level by storm surge also affected the wave field. Many scenario simulation experiments were carried out to assess the inundation risk of coastal plains [8].

Shenjiamen fishing port is located in the southeast of Zhoushan Islands in Zhejiang Province, which is the largest natural fishing port in China and important fishery production base. The fishing port location is shown as Figure 1. Due to the construction of reclamation projects, the topography and hydrodynamic conditions have changed significantly. In this paper, our work is focused on the typhoon prevention capability of Shenjiamen fishing port. The assessment of typhoon prevention capability includes two parts, the protection capacity of seawall and anchorage. Because the fishing port is characterized by complex geometry, unstructured grids are used for resolving the fine-scale coastline. By establishing high-resolution coupled storm surge and wave model, the typhoon prevention ability of seawall and anchorage is evaluated quantitatively, providing a scientific basis for the protection of fishing ports.

![Figure 1. The location of Shenjiamen fishing port and its extent (red dotted line)](image)

2. Data and Method

2.1 Model description

Two-dimensional Advanced Circulation Model (ADCIRC) is used to simulate storm surge in this
ADCIRC have been formulated using the traditional hydrostatic pressure and Boussinesq approximations and discretized in space using the finite element method and in time using the finite difference method [9]. The model based on depth-averaged continuity and momentum equations in the Cartesian coordinates can be written as follows:

\[
\frac{\partial H}{\partial t} + \frac{\partial}{\partial x} (UH) + \frac{\partial}{\partial y} (VH) = 0
\]

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = -g \frac{\partial \zeta}{\partial x} + \frac{\tau_{x, wind} + \tau_{x, waves}}{H \rho_0} + \frac{D_x}{H}
\]

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU = -g \frac{\partial \zeta}{\partial y} + \frac{\tau_{y, wind} + \tau_{y, waves}}{H \rho_0} + \frac{D_y}{H}
\]

Where \((U, V)\) are the x and y depth-averaged velocity components; \(\zeta\) is free surface elevation; \(h\) is the still water depth; \(H = h + \zeta\) is the total water level; \(f\) is the Coriolis force parameter; \(g\) is acceleration due to gravity; \(P_s\) is sea surface atmospheric pressure; \(\rho_0\) is sea water density; \(\tau_{x, wind}, \tau_{y, wind}\) are the x and y components of surface wind stress, \(\tau_{x, waves}, \tau_{y, waves}\) are the x and y components of wave radiation stress gradients, \((\tau_{xa}, \tau_{ya})\) are the x and y components of bottom stress, \((D_x, D_y)\) are the horizontal momentum diffusion terms.

The Simulating Waves Near shore model (SWAN) was often used for numerical simulations of typhoon waves [10]. Basic action balance equation used in SWAN is given by

\[
\frac{\partial N}{\partial t} + \frac{\partial C_x N}{\partial x} + \frac{\partial C_y N}{\partial y} + \frac{\partial C_\sigma N}{\partial \sigma} + \frac{\partial C_\theta N}{\partial \theta} = \frac{S}{\sigma}
\]

Where \(N\) is the wave action spectrum; \(\sigma\) is the relative frequency and \(\theta\) is the wave direction; \(C_x\) and \(C_y\) are velocities in x and y direction, respectively; \(C_\sigma\) and \(C_\theta\) are propagation velocities in \(\sigma\)-space and \(\theta\)-space. The first term in the left-hand of equation represents the local change of action density in time, the second and third term represent propagation of action in x and y directions. The fourth term represents shifting of the relative frequency due to variations in depths and currents with the propagation speed \(C_\sigma\). The fifth term represents depth-induced and current-induced refraction. The term \(S\) at the right hand side of Equation is the source term representing the effects of wind energy input, dissipation and nonlinear wave-wave interaction. It includes the linear and exponential growth of wind input, energy dissipation by white capping, bottom friction and depth-induced breaking, quadruplet wave-wave interactions and triad wave-wave interactions.

The wind model from Holland is applied to reconstruct the wind field for calculating storm surge and wave [11]. The data of central pressure and position were obtained from the China Meteorological Administration tropical cyclone database [12].

2.2 Model Settings
As shown Figure 2, the model domain in this study covers Bohai Sea, Yellow Sea and East China Sea. There are 190062 triangular cells and 99950 nodes with resolution varying from 0.1km to 20 km. In the full-domain, the GEBCO’s gridded dataset is used as the water depth data. In the subdomain and fishing port area, the data comes from sea chart published by China Navy Hydrographic Office. The model is forced at open boundary by 9 tidal constituents extracted from OSU Tidal Prediction Software, including M2, S2, N2, K2, K1, O1, P1, Q1 and M4 tidal constituents. The typhoon wind field is generated by Holland wind model and imposed through surface boundary condition. The ADCIRC model runs with a cold start, in which the currents and water level at the initial time setting to 0. Both storm surge model and wave model use the same computational grid. The coupling process
between ADCIRC and SWAN is as follow: SWAN computes wave heights by using wind speed from Holland wind model, as well as sea level and currents from ADCIRC. Meanwhile, wave stresses obtained from SWAN are used for ADCIRC storm surge simulation.

2.3 Model verification

Measured hourly tidal data at Zhoushan tidal gauge during typhoon Haikui in 2012 and typhoon Chan-hom in 2015 are collected for storm surge model validation. Wave height data from Dachen wave buoy during typhoon Haikui in 2012 are used to validate SWAN model. Figure 3 shows the comparison between the observed and modeled storm surge level. The model results are in good agreement with observations for the two typhoon cases. The time series curves of modeled and observed significant wave height are shown on Figure 4. As seen from the Figure 4, the model succeeds to reproduce satisfactorily wave height induced by typhoon Haikui. The verification results indicated the model parameters are reliable and satisfied the accuracy for storm surge and wave calculation.
3. Result and Discussion

3.1 Determination of the most dangerous typhoon path

In order to assess typhoon protection level of Shenniamen fishing port, different typhoon intensity is characterized by typhoon central pressure. The typhoon intensity grades corresponding to central air pressure are shown in Table 1. According to historical data, the typhoon paths that affected Shenniamen fishing port usually came from four directions. Similar to the wind direction definition, the four typhoon moving directions are E, SSE, SE, and S. Two hypothetical typhoon paths that move along the north and south sides of fishing port are designed for each direction respectively. The distance between each hypothetical typhoon path and the center of the fishing port is $R$ (maximum wind radius), and positive $R$ represents the path on the right side while negative $R$ represents the path on the left side of the fishing port (Facing the direction of typhoon movement). Typhoon moving speed is set to be 25km/h based on multi-year average data. The typhoon paths in all direction are shown on the Figure 5.

Figure 4. Comparison of time series between measured and modeled significant wave height at (a) Typhoon Haikui and (b) Typhoon Chan-hom

Figure 5. The hypothetical typhoon paths for each direction (a is E direction; b is SE direction; c is SSE direction; d is S direction)
Table 1. Typhoon intensity classification

| Typhoon intensity grade | 12 | 13 | 14 | 15 | 16 | 17 |
|-------------------------|----|----|----|----|----|----|
| Central pressure (hPa)  | 965| 955| 945| 935| 925| 915|

Firstly, the typhoon path that causes the highest level should be identified. Typhoon intensity grade 13 (central pressure at 955 hPa) is chosen to calculate storm surge. As seen from the figure 6, the storm surge level induced by typhoon landing on the left side of Shenjiamen fishing port is higher than that on the right side. By comparing the results of different paths, the typhoon path landing on the left side of Shenjiamen fishing port from the SE direction causes the most serious storm surge.

![Figure 6. The storm surge level for each hypothetical typhoon path](image)

3.2 Assesment on typhoon prevention capability of seawalls

The storm surge and wave height from various typhoon intensity grades are calculated in the path of landing on the left side of the SE direction. It should be emphasized that mean high tide level (1.6m) is used as constant water level boundary. Seawall height data are collected to compare with the sum of storm surge level and wave height. The formula to assess the risk of seawall at various typhoon intensity grades is as follows:

\[ H_W = H_{\text{Total level}} + 0.5 \times H_S \]  

(5)

\( H_{\text{Total level}} \) is the sum of mean high tidal level and storm surge, \( H_S \) is modeled significant wave height. \( H_W \) is the sum of the two terms. The protection grade of each seawall around Shenjiamen fishing port is determined by comparing the \( H_W \) and height of seawall. The latest seawall height data are collected for evaluation in our work, making our conclusions more reliable and robust.

As seen from Figure 7, the protection grade of seawall on the side of Xiaogan Island is relatively low, most of areas no more than level 15. However, because seawalls on the Lujiazhi Island were newly built and reinforced, most of seawalls are capable of withstanding category 17 typhoons. The protection grades of seawalls along Zhoushan Island are complicated. In the eastern part of Zhoushan Island, the typhoon protection grade can reach level 17. However, in the central region, due to the direct impact of the typhoon, the typhoon protection grade can only reach level 15. Because of the island shielding, the typhoon grade can reach level 16 in the western region of Zhoushan Island. The areas in Shenjiamen fishing port with the serious risk are mainly located on the north sides of Xiaogan Island, which needs to be paid more attention.
3.3 Assessment on typhoon prevention capability of anchorage

Through the comparison of external force on ship and holding force of anchor, the typhoon prevention ability of anchorage in fishing port can be analyzed. The calculation formula of holding force of anchor is as follows:

\[ P_a = \lambda_a W_a + \lambda_c W_c \]  

(6)

Where \( \lambda_a \) is holding force coefficient of anchor; \( W_a \) is anchor weight; \( \lambda_c \) represents holding force coefficient of anchor chain; \( W_c \) is the weight of chain. The external force on ship includes wind and flow forces, which can be expressed as follows:

\[ F_{\text{external}} = F_{\text{wind}} + F_{\text{current}} = kA W_k^2 \zeta + C \frac{\rho}{2} V^2 M \]  

(7)

Where \( k \) is empirical constant; \( A \) is windward area; \( \zeta \) represents wind speed correction factor; \( C \) is coefficient of flow force; \( M \) is boat projected area below waterline.

The 30m-length fishing boats with standardized ship type parameters is chosen to calculate external force on ship and holding force of anchor. The protection grades of anchorage in Shenjiamen fishing port are determined by comparing \( P_a \) and \( F_{\text{external}} \). As seen from Figure 8, the protection grades of anchorage in Shenjiamen fishing port show significant spatial variation. At the gate of Shenjiamen fishing port and intersection of waterway, due to strong current velocity, the protection grade of anchorage does not exceed level 13. The area between Lujiazhi Island and Zhoushan Island has higher grade, reaching level 16. The protection grades of the anchorage in the west part of fishing port are between level 14 and 15.

**Figure 8.** The protection grades of anchorage in the Shenjiamen fishing port
4. Conclusions
Based on ADCIRC and SWAN, high-resolution coupled storm surge and wave model was established to assess typhoon prevention capability of Shenjiamen fishing port. Seawall height data were collected to compare with the sum of mean high tide, modeled storm surge and wave heights to assess the risk of seawall at different typhoon intensity level. The protection grade of seawall on the side of Xiaogan Island is relatively low, but seawalls on the Lujiazhi Island are capable of withstanding category 17 typhoons. The protection grades of seawalls along Zhoushan Island are complicated. In the eastern part of Zhoushan Island, the typhoon protection grade can reach 17 due to the island shielding. But the typhoon protection grade is much lower in the central region. Through the comparison of external force on ship and holding force of anchor, the typhoon prevention ability of anchorage was investigated. Because of strong current velocity, the protection grade of anchorage does not exceed level 13 at the gate of Shenjiamen fishing port and intersection area of waterway. The area between Lujiazhi Island and Zhoushan Island has higher grade, reaching level 16. The protection grades of the anchorage in the west part of fishing port are between level 14 and 15. Our work could provide a scientific basis for the typhoon protection of Shenjiamen fishing ports.

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