A Preliminary Study on Tidal Level and Water Increase during Typical Recurrence Period in Zhoushan City

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Abstract: By using numerical simulation and taking Zhoushan City as the research area, this paper conducts station analysis and field analysis of tidal level and water increase based on long-term tidal data of Dinghai and Shengshan tide stations, with the purpose to prevent and reduce storm surge disasters that influence the marine and terrestrial environment. The results show that Dinghai Station is more greatly influenced by Typhoon 1509, and its water increase based on the 26-years series is significantly larger than that based on the 20-years series. Longer time series, taking more comprehensive situations into consideration, makes the results more credible. It also suggests that more reasonable situations shall be taken into consideration, so that we can get more reliable storm surge recurrence period analysis.

1. Introduction
The storm surge disaster is the severest marine disaster, which not only threatens people's lives and property, but also causes salinization, jeopardizing the growth of crops and ecological environment. The crude oil leakage caused by storm surge endangers the marine ecology and the edible safety of seafood. Storm surges at nuclear power plants may lead to nuclear leaks as well. The research area in this paper is Zhoushan City, which is located in the northeast of Zhejiang Province. It is composed of archipelagos with developed marine industry, with oil terminals along the coast, where storm surges occur frequently. Take Dinghai District as an example, there were more than 110 storm surges from 2000 to 2011, according to Zhoushan Water Conservancy Report and the record of water increase at tide station.

The study on high tidal level and the frequency of water increase in Zhoushan City is of direct and important significance for assessing the risk of storm surge and strengthening storm surge prevention in a targeted manner. The pilot projects of storm surge risk assessment in recent years have delivered a certain analysis results of high tidal level and water increase in the recurrence period. This paper calculates the high tidal level and water increase in the recurrence period based on the observation data of at least 20 years of the two main long-term stations (Dinghai Station, Shengshan Station, as shown in Figure 1.) of Zhoushan City. Then, this paper calculates the spatial distribution of high tidal level and water increase in the typical recurrence period of 10, 20, 50, 100 and 200 years in Zhoushan City, and analyzes the influence of the length of time series on high tidal level and water increase during the...
recurrence period by combining the simulation results of storm surges in this area.

![Figure 1. Location of Dinghai station and Shengshan station](image)

2. Numerical simulation of storm surge

The numerical simulation model used in this paper is ADCIRC, which solves two-dimensional and three-dimensional free surface flow and mass transportation, outputting results of water level and flow field. Based on the finite element method, this model adopts an unstructured grid that can be flexibly encrypted locally, which is suitable for calculating tide, wind-driven circulation, typhoon and water increase. Zhoushan City boasts many islands of various sizes, deep trenches, and a complex terrain, therefore, it is suitable to use the unstructured grid terrain for faster calculation.

The model ranges from 115° to 134° east longitude and 16°~41° north latitude, covering the entire East China Sea (Figure 2.). The grids in the vicinity of the islands are encrypted, especially in the islands with dense population and economic distribution. The resolution ration of the grid along the coast is about 40-200m, and that of the 10m contour line is about 50-200m. The model uses the data of refined water depth and land elevation in Zhoushan sea area.

The model is verified by the astronomical tide and the typical storm surge. On this basis, this paper simulates the process of annual maximum tidal level and annual maximum water increase in Zhoushan sea area from 1991 to 2016 (95 cases in total). Comparison between the simulation results and the actual measurement shows that: according to the process statistics, the average error of the highest tidal level of Dinghai Station is 0.155m, while the average error of maximum water increase is 0.062m, and that of Shengshan Station is 0.123m and 0.087m, respectively, according to annual statistics, that of Dinghai Station in 20 years is 0.107m and 0.049m, and that of Shengshan Station in 20 years is 0.158m and 0.102m. Figure 3 and Figure 4 are the verification maps of the tidal level and water increase at the two stations at the occurrence of Typhoon 9711 and 0012. The model with high precision can derive the missing annual maximum values in observed data, with less error influence on fitting results in the typical recurrence period. At the same time, the 26-years annual maximum tidal level distribution and the annual maximum water increase distribution can be used to fit the spatial distribution of high tidal level and water increase in the typical recurrence period.
Figure 2. Grid design (left: East China sea area, right: Zhoushan sea area)

Figure 3. Comparison of tidal level (upper) and water increase (lower) curves during Typhoon 9711 (left: Dinghai Station, Right: Shengshan Station)

Figure 4. Comparison of tidal level (upper) and water increase (lower) curves during Typhoon 0012 (left: Dinghai Station, Right: Shengshan Station)
(Note: red dot is observed and black line is calculated by model)

3. Tidal level and water increase in typical recurrence period

3.1 Analysis method
The present method used at home and abroad for calculating the high tidal level that occurs once in many years is to combine the observed data with the actual situation, and use a certain sampling method to select the extreme high tidal level so as to form the tide height series, and then deducts high tidal level that occurs once in many years by using the appropriate theoretical frequency curve. The selection of the theoretical curve is based on the principle of data-fitting. The process of formulating the distribution curve can be divided into two steps: selecting the form of the distribution curve, and estimating the parameters contained in the distribution. In terms of adaptability, the P-III curve is more
advantageous. Therefore, it is used for the calculation of the recurrence period of the maximum sequence of water increase and high tidal level.

At first, this study collects 20 years of data concerning tidal level and water increase in Dinghai Station and Shengshan Station, and the missing 5-years data of Shengshan Station is replaced by numerical simulation results. The above data is used to analyze the high tidal level and water increase. Subsequently, this study supplements 6 years of data, thus adding up to 26 years. Then, the 26-years analysis result using the same method is compared with previous 20-years analysis results.

Only when the observed data are incomplete, failing to provide annual maximum values, and when the annual maximum values obtained using numerical simulation has no corresponding observed data do this paper uses numerical simulation results to provide the annual maximum values. The simulated annual maximum values in this paper are: water increase of Dinghai Station in 2016, tidal level of Shengshan Station from 1991 to 1994 and in 1997, water increase of Shengshan Station from 1991 to 1995, and in 1997 and 2003.

3.2 Analysis based on 20 years of data
Based on the observed data of Dinghai Station and Shengshan Station in 20 years (1991-2010) and supplemented simulation data, this paper adopts the P-III curve for analyzing high tidal level and water increase in the recurrence period of the two stations in Zhoushan City. After adjusting the ratio of Cs to Cv to optimally fit the P-III curve and the observed points, we can obtain the P-III curve distribution of the two stations (Figure 5., Figure 6.) and the respective values of the recurrence period (Table 1.).

![Figure 5. P-III Curve distribution of annual maximum water increase (20 years) at Dinghai Station (Left) and Shengshan Station (Right)](image)

![Figure 6. P-III Curve distribution of annual maximum tidal level (20 years) at Dinghai Station (Left) and Shengshan Station (Right)](image)
Table 1. Water increase (m) and tidal level (m) in each recurrence period (years) based on 20-years data analysis

| recurrence period (years) | 200   | 100   | 50    | 20    | 10     |
|---------------------------|-------|-------|-------|-------|--------|
| water increase of Dinghai station | 2.039 | 1.826 | 1.615 | 1.341 | 1.138  |
| tidal level of Dinghai station    | 3.384 | 3.241 | 3.096 | 2.897 | 2.741  |
| water increase of Shengshan station | 1.093 | 1.018 | 0.942 | 0.839 | 0.759  |
| tidal level of Shengshan station | 3.376 | 3.281 | 3.184 | 3.049 | 2.941  |

3.3 Analysis based on 26 years of data
Based on the observed data of Dinghai Station and Shengshan Station in 26 years (1991-2010) and supplemented simulation data, this paper adopts the P-III curve for analyzing the two stations in Zhoushan City again, thus obtaining the curve distribution (Figure 7., Figure 8.) and the respective values of the recurrence period (Table 2.).

Table 2. Water increase (m) and tidal level (m) in each recurrence period (years) based on 26-years data analysis

| recurrence period (years) | 200   | 100   | 50    | 20    | 10     |
|---------------------------|-------|-------|-------|-------|--------|
| water increase of Dinghai station | 2.876 | 2.546 | 2.219 | 1.792 | 1.474  |
| tidal level of Dinghai station | 3.455 | 3.303 | 3.147 | 2.937 | 2.774  |
| water increase of Shengshan station | 1.216 | 1.135 | 1.052 | 0.938 | 0.848  |
| tidal level of Shengshan station | 3.307 | 3.218 | 3.127 | 3.002 | 2.902  |
3.4 Comparison

Table 3. Differences between 26-years and 20-years data analysis (m)

| recurrence period (years) | 200  | 100  | 50   | 20   | 10   |
|---------------------------|------|------|------|------|------|
| water increase differences of Dinghai station | 0.837| 0.720| 0.604| 0.451| 0.336|
| tidal level differences of Dinghai station | 0.071| 0.062| 0.051| 0.04 | 0.033|
| water increase differences of Shengshan station | 0.123| 0.117| 0.110| 0.099| 0.089|
| tidal level differences of Shengshan station | -0.069| -0.063| -0.057| -0.047| -0.039|

It can be seen from Table 3 that the extension of the data sequence leads to greater impact on water increase but less on high tidal level of Dinghai Station, and less on water increase and high tidal level of Shengshan Station. That is mainly because that the Typhoon 1509 (Figure 9.) is at strong typhoon level when it is close to Dinghai station, and the nearshore area is easy to accumulate water, thus leading to significant water increase. However, Typhoon 1509 affects Shengshan station less strongly, and the open sea area also weakens its impact on water increase. In addition, the maximum water increase at Dinghai Station is not superimposed on the high astronomical tidal level, so the high tidal level only receives a limited impact. The analysis of the 26-years sequence is more reliable since it takes into consideration Typhoon 1509.

3.5 Spatial distribution

Based on the spatial distribution of 26-years annual maximum values (tidal level and water increase), this paper adopts the P-III curve to analyze the spatial distribution of high tidal level and water increase in the typical recurrence period in Zhoushan City. The ratio of Cs to Cv in spatial distribution refers to the common or intermediate values of the two stations. Due to space limitations, this paper only shows the spatial distribution of typical recurrence period of 100 years (Figure 10.). We can see that the tidal level that occurs once in 100 years is relatively larger near shore, while the storm surge water increase that occurs once in 100 years is relatively larger in the gulf.

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Figure 9. Path of Typhoon 1509

Figure 10. Distribution for typical recurrence period of tidal level (left) and water increase (right) in Zhoushan City (once in 100 years)
4. Further discussions

The typical recurrence period data of water increase and tidal level obtained from 26-years sequence is more credible than that obtained from 20-years sequence. However, this paper is based only on the actual occurrence without any expansion. Therefore, the results are regarded as the preliminary discussion results of the typical recurrence period. Since the storm surge has a huge impact on the marine ecology and safety, more advanced analytical tools should be in place. Some issues about it need to be discussed further.

(1) Although the Typhoon 1509 did not cause a severe storm surge disaster to Zhoushan City, yet if it was superimposed on high astronomical tide level, the highest tide level at Dinghai Stations would be very large, thus resulting in significant rise of typical recurrence period tide level. If the biggest water increase of each historical storm surge case was superimposed on various astronomical tide levels, while the possibility of each astronomical tide level was calculated, then more credible results might be obtained.

(2) Typhoon 1509 influenced Dinghai Station more strongly in terms of water increase than Shengshan Station. However, if the typhoon maintained strong when passing near Shengshan Station, then the water increase at Shengshan Station will also be more significant. If Typhoon 1509 moved slightly westward, then both stations will have higher water increase. In analyzing the water increase of the recurrence period, how the impacts of strength change time and path position change are properly considered is worth more studying.

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Reference

[1] Marine Disaster Reduction Center of the State Oceanic Administration etc. (2015) Technical Report on Marine Disaster Risk Assessment and Zoning of Zhoushan.
[2] Marine Disaster Reduction Center of the State Oceanic Administration etc. (2015) Technical Report on Marine Disaster Risk Assessment and Zoning of Nantong.
[3] Zhejiang Marine Monitoring and Forecasting Center. (2014) Technical Report on Disaster Risk Assessment and Zoning of Typhoon Storm Surge in Yuhuan County.
[4] Ji Z, Shi Y. Sea Level Rise, (1996) Coastal Disaster and Coastal Protection. Journal of Natural Disasters, 5(2): 57-63.
[5] Wang J, Lu M, Ding J. (2010) Spatial and Temporal Distribution Characteristics of Typhoon Storm Surge in Zhejiang Coastal Area. Marine Forecasts, 27(3): 16-22.
[6] Wang X. (1989) Numerical Calculation of Storm Survey in Open Sea. Marine Science Bulletin, 8(3): 11-20.
[7] Vickery, P., Skerlj, P., and Twisdale, L. (2000) Simulation of Hurricane Risk in the U.S. Using Empirical Track Model. Struct. Eng., 126(10): 1222-1237.
[8] Takeo Ueno. (1981) Numerical Computations of the Storm Surges in Tosa Bay. Journal of the Oceanographical Society of the Japan, 37: 61-73.