Numerical Simulation of Wind Waves and calculation of planning wave factors in the East Taihu Lake, Jiangsu Province, China

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Abstract. Taihu Lake is a large shallow lake in the lower Yangtze River Delta. The wave action in Taihu Lake plays an important role in coastal port construction. In this paper, based on the 10 min average wind speed at 10 m above the water surface recorded hourly from August 14 to August 17, 2014, the SWAN wave model is used to simulate the wind waves of the Taihu Lake in the corresponding period. Due to the lack of long-time series of wave observation data in the project area, the relationship between design wind speed and wind wave is used to calculate wave elements in different return periods. The results show that the strong wind direction and strong wave direction of the East Taihu Lake are NNW. The waves in the proposed Qidu harbor are mainly from the waves outside the permeable breakwater. Under the action of the most unfavorable wave direction NE, the effective wave height of most waters in the harbor is below 0.4m, which can meet the requirements of avoiding waves for fishing boats.

1. Introduction
Taihu Lake is a large shallow lake in the lower Yangtze River Delta, with an area of 2338km², a length of 68.5km from north to south, an average width of 34km from east to west, and a maximum width of 56km. The average water depth of Taihu Lake is 1.9 m, and the maximum water depth is not more than 3 m. The deepest part of Taihu Lake lies in the west of the lake center and the north of the Pingtai mountain. Taihu Lake has an open surface and flat underwater terrain, with an average slope of only 19.7 °[1]. According to the natural conditions and water environment indicators, Taihu Lake can be divided into 9 Lakes which are great Taihu Lake, Meiliangwan Lake, Gonghu Lake, Zhushan Lake, Xu lake, west coast, south coast, East Taihu Lake and Jianhu Dongjiaozui[2].
The dominant wind direction of Taihu Lake Basin is southeast wind in summer and northwest wind in winter, with an average wind speed of 3.5 ~ 5.0 m/s[^3].

East Taihu Lake is a long and narrow bay on the east side of Dongshan peninsula of Taihu Lake (Fig. 1). It starts from Dongjiaozui to Lujiagang in the South and extends to Guajingkou in the north. The total length is about 32 km and the maximum width is 9 km. The lake area surrounded by the dike is 172.1 km². The proposed Qidu port is located near the entrance of East Taihu Lake.

2. SWAN model and validation

2.1. Establishment of Swan model

The Swan model is used for wave calculation, and the basic governing equations of the model are as follows.

\[
\frac{\partial N}{\partial t} + \nabla \left[ \left( \frac{c_r}{c} + \frac{U}{c} \right) N \right] + \frac{\partial c_r}{\partial x} + \frac{\partial c_\theta}{\partial y} = \frac{S_{sw}}{\sigma^3} \tag{1}
\]

The left is the kinematics part of the equation. The first term is the change of exercise density to time. The second term represents the propagation of wave energy in the x-direction of two-dimensional space. The group velocity \(c_g = \frac{\partial \sigma}{\partial k}\) is derived from the discrete relation \(\sigma^2 = gk | \tanh(kd)|\). \(k\) is the wave number vector and \(d\) is the water depth. The third term represents the change in angular frequency due to water depth and mean current. The fourth term represents the wave refraction caused by water depth and current. \(c_r\) and \(c_\theta\) are the propagation velocities in spectral space \((\sigma, \theta)\). The source sink term \(S_{sw}\) on the right is defined as the wave energy density \(E(\sigma, \theta)\), which includes all the physical processes.

\[
S_{sw} = S_a + S_{aw} + S_{sw} + S_{bw} + S_{bw} + S_{sw} \tag{2}
\]

The source term on the right side of the equation mainly includes six parts: the wave energy term \(S_a\) converted from wind energy, the white hat dissipation term \(S_{aw}\), the nonlinear wave energy transfer \(S_{sw}\) due to four wave interaction, the energy dissipation \(S_{bw}\) due to bottom friction in shallow water, the wave breaking \(S_{bw}\) due to water depth, and the nonlinear three wave effect \(S_{sw}\).

2.2. Model setting and result verification

In this paper, Swan wave model is used to simulate the wind wave field in Taihu Lake. The calculation range of the model is the whole Taihu Lake area, and the grid resolution is 100 m × 100 m (Fig. 1). At the closed boundary, the wave energy is completely absorbed by the boundary for the wave that is about to cross and leave the shoreline. In the two-dimensional spectral space of frequency and
direction, the frequency distribution is set from 0.0418hz to 1.0Hz, there are 36 wave directions, and the resolution is 10°.

According to the 10 min average wind speed (sampling interval 30 min) at 10 m above the water surface recorded hourly from 6:10 on August 14 to 5:40 on August 17, 2014, the wind and wave field of Taihu Lake during this period is simulated by SWAN model. The results of comparison between wave simulation and measured data are shown in Figure 2. It can be seen that the significant wave height simulated by swan is in good agreement with the measured value, which indicates that the wave model can simulate the wind wave in Taihu Lake.

![Fig. 2. Comparison curve of simulated and measured wave height](image)

3. Calculation of design wind speed and design wave elements

3.1. Analysis of measured wind speed characteristics

According to the wind speed and direction observation data of the whole year from March 2015 to February 2016, the wind direction frequency rose charts of March, April to August, September, October to February of the next year and the annual maximum wind speed rose chart are drawn (Fig. 3).

From April to August, the wind direction in Taihu Lake is the most in ESE and the second in SE. From October to February of the next year, N is the most, NNE or NNW is the second. March and September are the transition periods of wind direction in winter and summer. The maximum wind direction in March is E, followed by N and NNE. In September, E-wind was the most. The main wind direction in flood season is SE. The direction of maximum wind speed is NW (Fig. 4).

According to the relevant research results (Wang et al., 2016), the monthly average wind speed of Taihu Lake is 0.5-0.6m/s higher than that of the lakeshore and 1.2 - 1.3m/s higher than that of the far lake, and the maximum monthly average wind speed is 3.8-4.3m/s.

The annual average wind speed of East Taihu Lake is 2.0-4.7m/s, the strong wind direction is NNW, and the maximum wind speed is 20.5m/s. In the northern coastal area of East Taihu Lake, the unfavorable wind direction is se, which is greatly affected by wind and waves in flood season; The unfavorable wind direction in the southern coastal area is NW, and the southern coastal area is more affected by wind and waves in winter.

![Fig. 3. Rose chart of wind direction frequency in different months](image)
3.2. Calculation of design wind speed

According to the requirements of the hydrological code for port and waterway (JTS 145-2015), the number of years should not be less than 20 years when analyzing the frequency of wave height or period. Because there is no long-term wave observation data near the East Taihu Lake, the wave parameters can only be calculated from the local return period design wind speed.

According to the comparison between the wind field data of ECMWF (European Centre for Medium-Range Weather Forecasts) and the wind speed of platform mountain buoy observation station (2019.03.01-31; 2019.08.01-31) (Fig. 5), it can be seen that the wind field of ECMWF is in good agreement with the measured wind speed. The annual extreme value of ECMWF can be used to replace the measured wind speed. Based on the wind speed data of ECMWF from 1984 to 2018, the design wind speeds of NNW (the direction of maximum wind speed) and NE (the most unfavorable direction of entrance incidence) in different return periods near the entrance of East Taihu Lake are obtained. The results are shown in Table 1.

![Fig. 5. Comparison curve between ECMWF wind speed and measured wind speed](image)

| Return period of wind speed (year) | 50 | 20 | 10 | 5 | 2 |
|-----------------------------------|----|----|----|---|---|
| NE                                | 19 | 16 | 14.2 | 12.2 | 9.6 |
| NNW                               | 20.6 | 17.6 | 14.2 | 12.3 | 9.6 |
3.3. Calculation of wave elements in front of breakwater

According to the design wind speed and water level, the front wave elements of the port without breakwater are obtained by using SWAN model (Figure 6, Table 2).

For the proposed port area, the strong wind direction and strong wave direction are NNW. For the combination of 50-year wind speed and extreme high water level (4.80m), the effective wave height in front of the breakwater is 1.08m, the corresponding H1% is 1.49m, and the wave period is 3.64s. For the combination of 2-year wind speed and design high water level (3.0m), the effective wave height in front of the dike is 0.42m, the corresponding H1% is 0.60m, and the wave period is 2.48s.

Table 2. Statistical table of design wave elements of wind wave combination corresponding to wind speed and water level in different return periods

| Wind Speed and Water Level | Wind Direction | $H_{1%}$ (m) | $H_0$ (m) | $T$ (s) |
|---------------------------|----------------|-------------|-----------|--------|
| 50-year wind speed +      | NWW            | 1.49        | 0.71      | 3.64   |
| water level (4.80m)       | NE             | 1.20        | 0.55      | 3.06   |
| 2-year wind speed +       | NWW            | 0.60        | 0.27      | 2.48   |
| water level (3.0m)        | NE             | 0.49        | 0.22      | 2.10   |

The most unfavorable direction of entrance is NE. For the combination of 50-year wind speed and extreme high water level (4.80m), the effective wave height in front of the breakwater is 0.85m, the corresponding H1% is 1.20m, and the wave period is 3.06s. For the combination of 2-year wind speed and design high water level (3.0m), the effective wave height in front of the dike is 0.34m, the corresponding H1% is 0.49m, and the wave period is 2.10s.
Fig. 6. Wave vector diagram of wind wave combination corresponding to wind speed and water level in different return periods

(a) NE (50-year wind speed and extreme high water level 4.80m); (b) NNW (50-year wind speed and extreme high water level 4.80m); (c) NE (2-year wind speed and design high water level 3.0m); (d) NNW (2-year wind speed and design high water level 3.0m).

3.4. Calculation of wave height distribution for wave diffraction in harbor

Waves consist of wave component with different frequencies and directions, which constitute directional spectrum. Each component wave in breakwater external spectrum is regarded as sine wave. It is assumed that the sine wave outside the breakwater will be diffracted into the harbor, and the diffracted wave will form a new directional spectrum in the harbor. Based on the diffraction spectrum, the wave elements in the harbor area are calculated\(^4\)-\(^5\).

According to the design scheme of breakwater section, the wave penetration coefficient of breakwater is 21.8% under the extreme high water level (4.80 m). Through the model calculation, the isopleth distribution of wave height and the wave elements of the calculation point are obtained (Table 3, Fig. 7).

| Wave direction | Calculation point | Design wave elements |
|----------------|-------------------|----------------------|
| NNW            | 6                 | 0.35 0.15 4.07       |
|                | 7                 | 0.35 0.15            |
|                | 8                 | 0.35 0.15            |
Under the strong wind direction and strong wave direction NNW with 50-year wind speed and extreme high water level (4.80m), the waves in the harbor mainly propagate through the permeable breakwater. The effective wave height in the harbor is about 0.24m. Under the action of the most unfavorable wave direction NE, the effective wave height in the harbor is basically below 0.4m, and only a small part of the area near the entrance has the effective wave height of 0.5m, which can meet the requirements of fishing boats to avoid wind.

|   |   |   |
|---|---|---|
| 9 | 0.35 | 0.15 |
| 10| 0.35| 0.15|
|   |    |   |
| 6 | 0.60| 0.26|
| 7 | 0.41| 0.18|
| 8 | 0.40| 0.17|
| 9 | 0.48| 0.21|
| 10| 0.41| 0.18|

3.06

(a) NNW (The wave height in front of the breakwater is 1.09m and the period is 4.07s); (b) NE (The wave height in front of the breakwater is 0.85m and the period is 3.06s)
4. Conclusion
In the absence of long series of measured wind field, ECMWF data can be used as the basis for wind field design when there is a good correlation between ECMWF data and measured wind speed data. Based on Swan model, the wind and wave mathematical model of Taihu Lake is established to predict and simulate the wind and wave field of Taihu Lake. For the combination of 50-year wind speed and extreme high water level (4.80m), the effective wave height in front of the breakwater is 1.08m, the corresponding H1% is 1.49m, and the wave period is 3.64s. The waves in the harbor are mainly from the waves outside the breakwater. Under the action of the most unfavorable wave direction NE, the effective wave height of most waters in the harbor is basically below 0.4m, which can meet the requirements of avoiding waves for fishing vessels.

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