NUMERICAL CALCULATION OF THE IMPACT OF OFFSHORE WIND POWER STATIONS ON HYDRODYNAMIC CONDITIONS

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Abstract In the estuarine and coastal engineering, numerical modeling of tidal current has become a popular and preferred approach to study the hydrodynamic environment. However, it is still difficult for direct simulation of small structures such as jetty, pier, offshore platform in a large-scale domain among the 2-D numerical models for calculating tidal current. The traditional method to deal with the problem mainly adjusted the friction coefficient and local topography in a local model, but these coefficients are difficult to be determined. In this paper, to study the impact of the foundation structures of offshore wind energy plant on hydrodynamic conditions, a 2-D hydrodynamic numerical model was developed, including the Yangtze Estuary and the Hangzhou Bay. The grid can be discretionary refined as a non-structure triangle or regular rectangle so that those piers can be described as impermeable elements. The verified computation indicates that the influence is related with the characteristics of tidal current and the arrangement of foundation structures. As far as the Shanghai Offshore wind power stations are concerned, the impact on the tidal currents is limited in the region around the structures.

Key words offshore wind power station; pier group; hydrodynamic condition; numerical calculation

1 INTRODUCTION

As one kind of clean and reproducible resource, wind energy makes great sense to improving energy structure and protecting environment (Hu, 2006). Nowadays, the capacity of wind power all over the world has arrived about fifty million kilowatt (Xing, Chen, Wang and Cheng, 2006). Along with the development of technique of wind power, wind energy plant has extended from ground to offshore gradually. Offshore wind energy plant has many advantages, not only of high wind speed, great output power and low turbulence intensity, but also of none consuming land resources and affecting public vision. According to data from more than 900 weather observation stations, the available resources of offshore wind energy is probably 2 times richer than resources of wind energy on land (Song, 2006). As a result, offshore wind energy will be one of main resources which are necessary to our sustainable development in the future.

Obviously, offshore wind energy plant will influence hydrodynamic conditions of the nearby region. For example, if the size of pier is between 3.5 meters and 4.5 meters, the number of piers of one wind energy station, of which capacity is one hundred thousand kilowatt, is about 50. And most of the piers will be located in the offing which is shallower than 15 meters. Consequently, the engineering will lead to changes of hydrodynamic conditions very easily in this region, such as water

surface elevation, velocity of flow, flux of tide and so on. Therefore, the layout of foundation structures of offshore wind energy plant must be optimized and reasonable. And it becomes a very important index of estimating the impact of offshore wind energy plant on hydrodynamic environment (Zhang, 2006).

Presently, it's very difficult to simulate small structures in a large-scale domain due to the different scales (Chen et al, 2003). Usually, there are two methods to simulate small structures: simulating indirectly or directly. The former includes adjusting the friction coefficient, adding an additional roughness around the pier foundation, coinciding permeable rate and so on (Tang and Li, 2001; Tang, 2002; Han and Chen, 2004). But, these coefficients are difficult to be determined and the local current may be distorted. The other way is simulating piers as impermeable elements directly in the numerical model, which results in relatively vivid effect. Yet it's rigorous for the size of the elements near piers (Lou et al, 1994). Generally, it's difficult to carry out this method by structure grids and coupled computations. In order to accurately simulate the piers and complicated topography, the finite elements may be employed to solve the problem in this paper. In the finite element method, small elements may be used in areas where detail is desired, and larger elements in areas of less interest, allowed some efficiency in computer usage(Liao, Zhang and Wang, 2006). The non-structure grid can be discretionary refined so that those piers can be described as impermeable elements. And the tidal current around piers can be directly simulated in the model. Based on the simulation, the impact of offshore wind energy plant on hydrodynamic conditions will be discussed when the wind energy plants are located in different sea area or under different layout.

As in East Asian monsoon region, there is abundant wind energy resource in Shanghai, especially in the area near Donghai Bridge, Fengxian Bay, east of Nanhui tidal flat, and east of Hengsha tidal flat. Therefore, the government plans to build five offshore wind power stations in these areas according to the principle of adjusting measures to local conditions. The capacity of offshore wind power in Shanghai will exceed a billion kilowatt by 2020.

2 NUMERICAL MODEL

2.1 GOVERNING EQUATION

The depth-integrated equations of fluid mass and momentum conservation are valid for this application due to the predominantly horizontal current flows in Yangtze Estuary and the Hangzhou Bay. The forms of the equations in two horizontal directions are following as:

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\left(\frac{\partial h}{\partial x}+\frac{\partial \alpha_0}{\partial x}\right) - fv-\frac{\varepsilon_{xx}}{\rho}\cdot\frac{\partial^2 u}{\partial x^2}-\frac{\varepsilon_{xy}}{\rho}\cdot\frac{\partial^2 u}{\partial y^2}+\frac{gu}{c^2 h}\sqrt{u^2+v^2} =0 \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\left(\frac{\partial h}{\partial y}+\frac{\partial \alpha_0}{\partial y}\right) + fu-\frac{\varepsilon_{xy}}{\rho}\cdot\frac{\partial^2 v}{\partial x^2}-\frac{\varepsilon_{yy}}{\rho}\cdot\frac{\partial^2 v}{\partial y^2}+\frac{gv}{c^2 h}\sqrt{u^2+v^2} =0 \tag{3}$$

where, x, y , t = Cartesian coordinates and time; u, v = velocities in the Cartesian directions; g = acceleration due to gravity; h = water depth; α_0 = elevation of bottom; ρ = density of fluid; f = Coriolis coefficient; ($f = 2\omega\sin\phi$, ω = rate of earth's angular rotation; ϕ = local latitude); ε_{xx}, ε_{xy}, ε_{yx}, ε_{yy} = eddy viscosity coefficient (usually treated as $\varepsilon_{xx} = \varepsilon_{xy} = \varepsilon_{yx} = \varepsilon_{yy} = \varepsilon$); c = Chezy coefficient, based on Manning's roughness n (Zhang, Xu, Cao and Cai, 2004).

2.2 DOMAIN, GRIDS AND BOUNDARY CONDITIONS

As shown in Figure 1, the simulated domain

includes Yangtze Estuary, the Hangzhou Bay and the area nearby, which cover 120°45′ to 123°20′E and 29°12′ to 32°08′N. The plan was discrete with rectangle and triangle grids in variable grids so that the piers can be simulated directly in this numerical model (Wang, Zhang and Liao, 2006; Shi and Wang, 2002). Horizontal resolution is 1′~4′ in the open sea for the sake of saving computer time. Of course, the grid size is 8m×8m near piers of wind power stations. The elements describing piers are impermeable and their four sizes are treated as fixed boundary. There are more than twenty thousand elements and about sixty thousand nodes in the whole model.

According to the equal permeable rate principle, the Donghai Bridge Pier can be simulated as 23 impermeable elements of which size are 20m×60m. The same to Donghai Bridge Pier, four foundation structures were simulated as one impermeable element, of which size was 8m×8m, in order to save computer time. As mentioned above, the finite element approach was employed to solve the governing equation using the Galerkin Method of weighted residuals (Gray, 1977). The solution is fully implicit and the set of simultaneous equations is solved by Newton-Raphson nonlinear iteration. The tidal level processes at different points on the open boundary are offered by NMDIS (NMDIS, 2003). Radiation conditions are used for the velocities in the open boundary (Orlanski, 1976). For the sandbar and lagoon in the Yangtze Estuary and the Hangzhou Bay, the wide tidal flat is wetting or drying due to sea surface elevation changes. Wet-dry approach was used to deal with the moving-boundary (Flather and Hubbert, 1990).

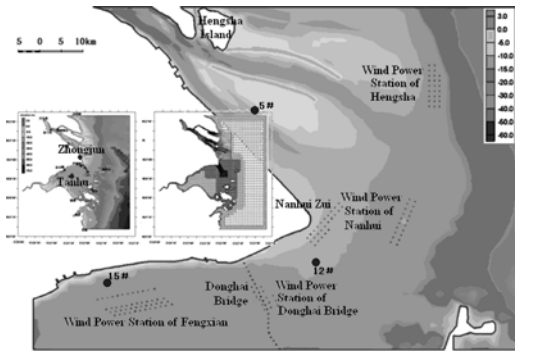

Fig. 1 Simulated domain and the layout of wind power stations

2.3 VERIFICATION

In order to inspect whether the 2-D hydrodynamic model can accurately simulate the actual tidal current in the Yangtze Estuary and the Hangzhou Bay, calibration and validation of the numerical model were performed, using data synchronous measured in the Yangtze Estuary and the Hangzhou Bay in Jan 1999, Sep 2003, Mar 2004 and Jun 2004. The curves of tidal level and velocity verification for spring tide of several points concerned are shown in Figure 2. From the comparisons, the computational results are in good agreements with the measured. It can be drawn that the numerical model is suitable for accurate simulation of tidal current field of Yangtze Estuary and Hangzhou Bay, especially in project area.

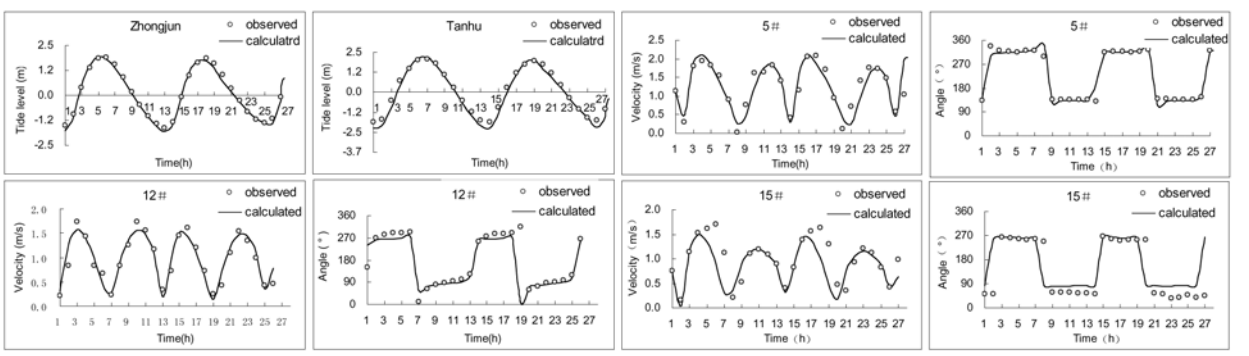

Fig. 2 Comparison of the tide level and the velocity from observation and model

3 COMPUTATION AND DISCUSSION

3.1 CHARACTERISTICS OF TIDAL CURRENT FIELD AT THE PROJECT AREA

Based on the verification, the layout of foundation structures of wind power stations were added to the model. By calculating, it can be conclude that characteristics of tidal current field at every project area are different. And their spring tidal ellipses are shown in Figure 3.

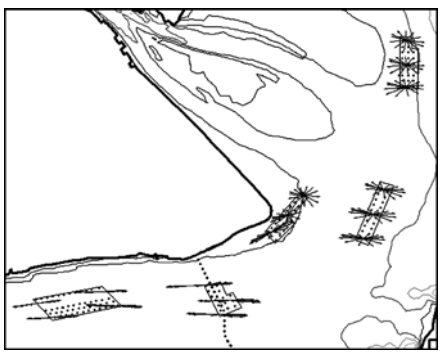

Fig. 3 Spring tidal ellipse in project area

The directions of tidal current in the area near the north coast of Hangzhou Bay are mainly east and west. The mean direction varies between 257°～277°, when the spring flood flows from west to east. And the mean velocity of the spring flood is about 1.05m/s. For the impact of shoreline, the direction of the spring flood deflects clockwise from south to north. The direction of the spring ebb is primarily contrary to the direction of the spring flood. It's mainly distributed between 80°and 91°. And its mean velocity is around 0.87m/s.

In spring flood, the tidal current mainly flows from southeast, and then divided into two branches at Nanhui Zui. One flows northwestward to Yangtze Estuary, the other turns southwestward to Hangzhou Bay. The direction of the tidal current near the shore of Nanhui Zui is parallel to the shoreline. However, with the increasing of distance to the north bank of Nanhui, the current of the area become rotary gradually. And the mean velocity is around 0.85m/s. While the current that enters into Hangzhou Bay is a reciprocating current along the shore. Its maximum velocity is about 1.8m/s, and the angle of the long axis of flood ellipse in this area is around 245°.

The east tidal flat of Hengsha Island is northeast to the Southern Branch. For the impact of the flow of Yangtze River and geological conditions, the direction of tidal current of this area is always rotating. The length of the short axis of the spring tidal ellipse is close to that of the long axis of the spring tidal ellipse. And the direction of its main axis is around 276°. The maximum velocity of the tidal current appears in the south area of the wind power station, but decreasing gradually from south to north. Averagely, the velocity is about 0.95m/s.

3.2 IMPACT ON WATER SURFACE ELEVATION AFTER PROJECTS

In order to discuss the change of water surface elevation after construction, it's necessary to place a series of points at the area concerned. The distribution of these points is shown in Figure 4, and the changes of value of water surface elevation are shown in Table 1.

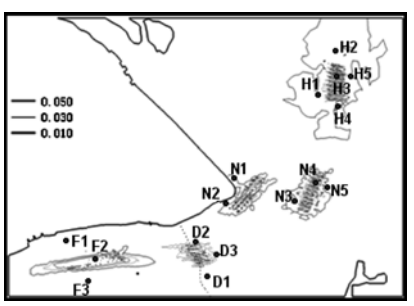

Fig. 4 Observed stations and the enveloping curves of changed velocity

From Table 1, it can be concluded that the change of high tide level and low tide level are less than 1mm. In addition, for the resistance of pier groups, the low tide level of point N1 and point H1 which are near to pier groups raise a little after projects. Generally, the tide level in Yangtze estuary and Hangzhou Bay won't be changed by the wind power stations.

Table 1 Influence on tidal level of observed points

	Point	D1	D2	D3	F1	F2	F3	N1	N2	N3	N4	N5	H1	H2	H3	H4	H5
High tide level (m)	Before projects	1.988	2.102	2.015	2.562	2.442	2.462	1.996	2.037	1.899	1.876	1.863	1.922	1.865	1.884	1.907	1.859
	After projects	1.989	2.101	2.016	2.561	2.441	2.461	1.995	2.036	1.899	1.876	1.863	1.921	1.866	1.885	1.906	1.860
	Difference	0.001	-0.001	0.001	-0.001	-0.001	-0.001	-0.001	-0.001	0	0	0	-0.001	0.001	0.001	-0.001	0.001
Low tide level (m)	Before projects	-2.194	-2.275	-2.212	-2.614	-2.529	-2.537	-2.089	-2.145	-2.047	-2.008	-1.991	-2.010	-1.916	-1.935	-1.974	-1.893
	After projects	-2.194	-2.274	-2.213	-2.613	-2.529	-2.537	-2.086	-2.144	-2.046	-2.008	-1.991	-2.007	-1.917	-1.935	-1.974	-1.894
	Difference	0	0.001	-0.001	0.001	0	0	0.003	0.001	0.001	0	0	0.003	-0.001	0	0	-0.001

3.3 IMPACT ON CURRENT VELOCITY AFTER PROJECTS

In order to analyze the impact on current velocity after projects of wind power stations, the enveloping curves of 1, 3 and 5 percent of current velocity change before and after projects are compared (shown in Figure 4 and Table 2).

Table 2 Range of influenced velocity after projects

Wind power station	1.0% (km^2)	Maximum length of the envelop curve of 1.0%(km)		3.0% (km^2)	Maximum length of the envelop curve of 3.0%(km)		5.0% (km^2)	Maximum length of the envelop curve of 5.0%(km)	
		East to west	South to north		East to west	South to north		East to west	South to north
Fengxian (30 万 kW)	143.4	35.8	4.3	83.2	27.8	3.9	58.5	22.1	3.5
Donghai Bridge (10 万 kW)	61.8	16.2	7.8	14.5	10.7	6.2	2.8	8.5	6.1
Alongshore of Nanhui (20 万 kW)	92.8	16.9	12.4	22.6	9.1	11.5	9.8	9.2	10.9
Offshore of Nanhui (20 万 kW)	119.3	13.8	14.3	32.2	7.7	12.2	11.4	6.1	11.7
Hengsha (20 万 kW)	520.6	26.8	35.7	48.2	8.2	11.6	17.5	6.0	10.9

Influen-ce on characteristics of tidal current: The tidal current in the sea area near Fengxian and Donghai Bridge is a reciprocating current in east and west. Therefore, the incidence is mainly at the western area of pier groups in spring flood. On the contrary, the effected area is mainly at the eastern area of pier groups in spring ebb. However, the tide current near Nanhui and Hengsha is mainly influenced by rotary current. Thus the impact extent of pier groups to characteristics of tide current is different with different current velocity.

Influence of different layout of pier groups: From Figure 4, it can be concluded that the influence range is nearly related to the tendency of pier groups. Take the wind power station of Fengxian for example, when the tendency of pier groups is parallel to the direction of tide current, the inter-impact between piers is obvious. And the effected area is long and narrow. Whereas, for the sea area near wind power station of Donghai Bridge, the tendency of pier groups is perpendicular to the direction of tide current. So the influence of one pier to another is evidently smaller than that of wind power station of Fengxian. And the incidence of the pier groups to the tide current is small. For the area near Nanhui Zui and Hengsha, the angle between the tendency of pier groups and tide current varies from 0°~180°. Comparatively, its influenced area of pier groups is large.

The enveloping curve area of influence district:

By and large, the affected area is mainly around the projects. The enveloping curves of 3% and 5% is distributed near piers basically. And the enveloping curves of 1% transformed with different location and different layout of pier groups. When the wind power station of Fengxian is completed, the enveloping curve of 3% and 5% of every pier foundation overlaps each other, and the area of two enveloping curves cover the wind power station nearly. The area of the enveloping curve of 1% is about 143.4km^2. Besides, the wind power station of Fengxian has no influence on tide of the area near Donghai Bridge and north coast of Hangzhou Bay. As far as the wind power station of Donghai Bridge is concerned, the velocity influenced area is mainly distributed around every pier foundation. The area of the enveloping curve of 1% is about 61.8km2. Furthermore, the layout of pier foundations is sparse, so the project has no effect on Donghai Bridge also. When the alongshore and offshore wind power stations of Nanhui are finished, the enveloping curves of 3% and 5% are mainly focused around every pier foundation. And the area of the enveloping curves of 1% of alongshore wind power station is about 92.8km^2. For the offshore wind power station, the area of the enveloping curves of 1% is around 119.3km^2. And the two enveloping curves of 1% don't overlap each other. In addition, because of the constructions, the current velocity of the area alongshore increases a little. Since the tidal current near Hengsha is rotary, the wind power station of Hengsha influences the tide current in every directions. And the area of enveloping curves of 1% is about 520.6km^2. But the enveloping curves of 3% and 5% are only around every pier foundation, therefore cross-influence between these two curves is not exist.

Furthermore, the influenced extent is mostly related to the number of piers and the distance between piers. But this problem refers to other research field. So it won't be discussed in this paper.

3.4 INFLUENCE ON TIDAL PRISM AFTER PROJECTS

Because several wind power stations are located near Yangtze Estuary and Donghai Bridge, it's probable to influence the tidal prism at the area concerned. The ratios of the tidal prism before projects to that after projects are shown in Table 3. And the cross sections are shown in Figure 5.

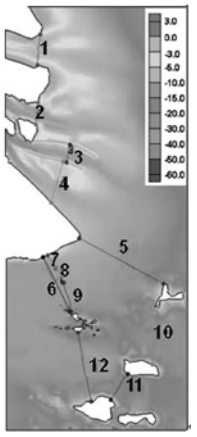

Fig. 5 Cross sections for tidal prism

Table 3 The ratios of the tidal prism before projects to that after projects

Cross section	Before projects	After projects			
		Maxima in flood	Maxima in ebb	Average in flood	Average in ebb
1、2、3、4	1.000	1.000	1.000	1.000	1.000
5	1.000	1.001	1.000	1.000	0.999
6	1.000	0.999	1.000	0.999	0.999
7	1.000	1.002	1.000	1.002	1.002
8	1.000	0.997	0.998	0.995	0.997
9	1.000	0.999	0.999	0.999	0.999
10、11、12	1.000	1.000	1.000	1.000	1.000

First of all, wind power stations won't change characteristics of tide at Yangtze Estuary. Secondly, in spring flood, for the resistance of pier foundations, the average tidal prism crossing the Cross Section 8, near to the wind power station of Donghai Bridge, will decrease by 0.3%. At the same time, the average tidal prism crossing the Cross Section 7 in spring flood will increase by 0.2%. In addition, when the projects are finished, the transform extent of tidal prism crossing the Cross Section 6 and the Cross Section 9 is less than 0.1%. Therefore, it can be concluded that the projects has no influence on tidal prism of every branch concerned, when wind power stations are completed.

4 CONCLUSION

Wind energy on the sea will be one of the main resources for our sustainable development in the future. And the impact of offshore wind energy plant on hydrodynamic environment is a very important index in layout of projects. This paper has established a 2-D numerical hydrodynamic model which based on finite element method. Taking the layout of offshore wind energy farm of Shanghai for instance, the impact aroused by wind power stations with different location or different layout of pier foundations is discussed in here. The research result shows that:

This method can simulate the small structure in a large-scale domain among the 2-D numerical models for calculating tidal current. Besides, the calibration and validation of the model showed that it's reasonable and suitable for direct simulation of tidal current field in Yangtze Estuary and Hangzhou Bay, especially in the area near projects.

The construction of wind power stations won't change characteristics of tidal current in Yangtze River estuary and Hangzhou Bay. The influenced regions after projects are just around the pier groups. But the affected extents aroused by wind power stations of different location are dissimilar with each other.

The influence extent is nearly related to many factors, such as the tendency of pier groups, the current velocity, the angle between the tendency of pier groups and the current velocity and so on. Take the wind power station of Fengxian for example, when the tendency of pier groups is parallel to the direction of tidal current, the impact of one pier to another is obvious. And the affected area is long and narrow. Whereas, as the sea area near wind power station of Donghai Bridge, the tendency of pier groups is perpendicular to the direction of tide current. So the influence of one pier to another is evidently smaller than that of wind power station of Fengxian. And the incidence of the pier groups to the tidal current is small. For the area near Nanhui Zui and Hengsha, the angle between the tendency of pier groups and tidal current varies from 0° to 180°. The influenced extent of pier groups is between that in Fengxian and Donghai Bridge.

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