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Numerical modeling of tidal current of LNG terminal in Caofeidian, Bohai Sea

Liao Peng[1] Zhang Wei[2]

([1] School of Transportation, Southeast University, Nanjing 210096, China)
([2] College of Traffic, Hohai University, Nanjing 210098, China)

Abstract: In order to reasonably simulate tidal currents around small structures such as piles in a large-scale model domain, a 2-D hydrodynamic integrated model for Bohai Sea is established with the finite element method. The grid can be discretionarily refined as a non-structure triangle or quadrilateral so that piers can be treated as one or several impermeable elements with an area of 20 to 30 km^2 in a model domain over 85 700 km^2. The computational results of tidal levels and horizontal velocities are in good agreement with the field data. Based on the computed results by the model, the layout of an open 10^5 DWT liquefied natural gas (LNG) terminal in Caofeidian, Bohai Sea is effectively and reasonably optimized. It can be concluded that the model is suitable and reasonable for direct simulation of tidal currents around small structures in projects.

Key words: tidal current; numerical model; pier; Bohai Sea

In the northern part of China, with the rapid development of the economy, a deep-water port is now urgently needed for the transport of bulk cargo, such as ore, coal, crude oil and natural gas. Fortunately, a zonal sand island named Caofeidian has a superb natural condition for a large-scale deep-water port in the northwest coast of Bohai Sea. According to the geological survey, a 30-meter-deep trough is only several hundred meters away from the island, and a tidal flat with an area over 150 km^2 can be reclaimed between the island and the shoreline[1]. Since the 1950s, many investigators have studied the geological, hydrodynamic and sediment environments in Caofeidian[1–2]. Particularly, field observations as well as physical and numerical models have been carried out at the integrated planning stage in recent decades[3]. An open 2.5×10^4 DWT ore dock has operated since 2006. According to the planning, an open 10^5 DWT LNG terminal will be built along the coast near the trough, and studies on the layout should be conducted.

Numerical simulation of tidal currents has become a popular and preferred method to study hydrodynamic environment in estuarine and coastal engineering, as well as a numerical model for the terminal. However, it is difficult to simulate small structures such as piles[4–5]. Generally, there are two ways to solve the problem. One is the nested model, and high resolution will be used in a local model for the area of interest. The other is an integrated model with variable grid techniques, and the fine grid will describe the current field around small structures.

The numerical model for Bohai Sea has been performed, especially coupled with East China Sea[6]. Those studies usually focused on the characteristics of tides and tidal currents in Bohai Sea, and the horizontal resolution is not adequate enough in coastal engineering. In this paper, a 2-D hydrodynamic integrated model for Bohai Sea is developed. With the finite element method, the model simulates the piers directly in a model domain over 85 700 km^2. The optimization of the terminal's layout is carried out based on the simulations of the currents. This may offer a practical example for similar projects, such as jetties, piers, and wharfs.

1 Numerical Model

1.1 Governing Equation and Solution

The depth-averaged equations of fluid mass and momentum conservation are valid for this application due to the predominantly horizontal current flows in Bohai Sea[7]. The forms of the equations in two horizontal directions are given as

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

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

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

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

In order to accurately simulate the complicated bathymetric, flexural coastal line, and construction structures, the finite element method is used to solve Eqs. (1), (2) and (3) by the Galerkin method of weighted residuals[8]. The elements are quadrilaterals or triangles, and they may have curved sides. The shape functions are quadratic for velocity and linear for depth. Integration in space is performed by Gaussian integration and derivatives in time are replaced by a nonlinear finite different approximation. The solution is fully implicit and the set of simultaneous equations is solved by a Newton-Raphson nonlinear iteration scheme.

The complicated interaction between the tidal current and piers is mainly simplified as a horizontal eddy viscosity co-

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efficient ε around piers. For complex geometric settings around piers, taking into account the gradients of velocity to determine the appropriate turbulence coefficient to meet the conditions in the simulation, ε is determined by[9]

$$\varepsilon = \alpha A\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\right] \quad (4)$$

where α is a coefficient; A is the area of the element; $\partial u/\partial x$ and $\partial v/\partial y$ are the velocity component gradients.

1.2 Domain, grids and boundary conditions

The simulated domain, as shown in Fig. 1, is the whole area of Bohai Sea from 117°33′ to 122°18′ E and 37°06′ to 40°57′ N, which covers 85 700 km^2. The plan is discretized with quadrilateral and triangle grids in variable sizes. Horizontal resolution is 1′ to 4′ in the open sea region for the sake of saving computer time. For the area where detail is desired, the grid is refined to 3.0 m × 3.5 m so that the piers, including those of the ore dock, can be treated as one or several impermeable elements as shown in Fig. 2. The whole computation domain includes 60 965 nodes and 22 028 elements.

The initial values of water levels and velocities in each node are

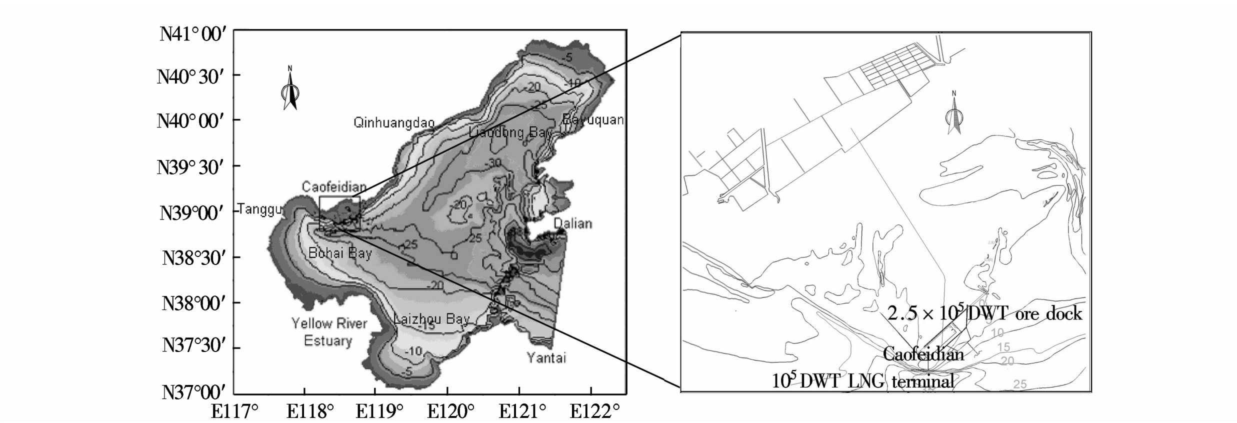
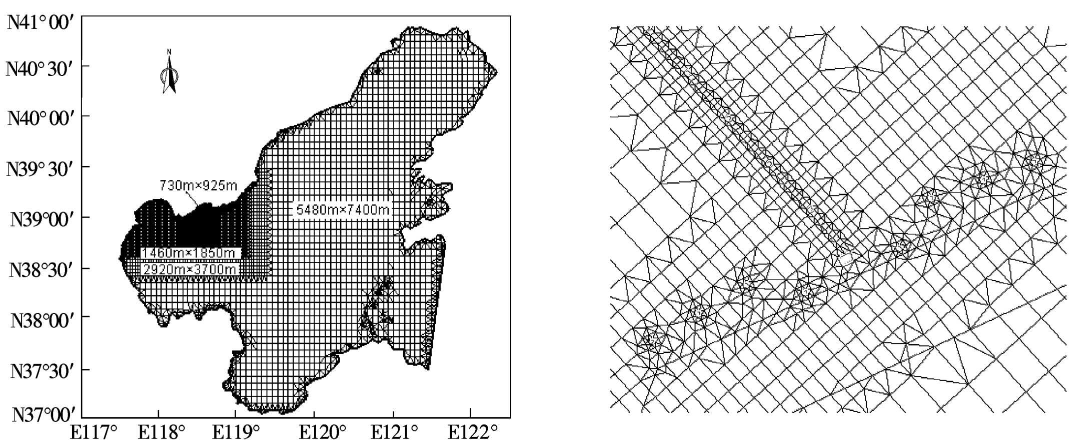


Fig. 1 Caofeidian in the model for Bohai Sea on March, 2005



(a) (b)

Fig. 2 Grid of the model. (a) Grid at the simulated domain; (b) Grid around piers

$$\left.\begin{aligned} \xi(x, y)\big|_{t=0} &= \xi_0(x, y) \\ u(x, y)\big|_{t=0} &= u_0(x, y) \\ v(x, y)\big|_{t=0} &= v_0(x, y) \end{aligned}\right\} \quad (5)$$

The open boundary of the model is the connection line of Dalian city (38°52′ N, 121°41′ E) to Yantai city (37°33′ N, 121°23′ E). The tidal stage hydrograph at the open boundary is given as

$$\xi\big|_b = \xi(x, y, t) \quad (6)$$

The tidal level processes at different points on the open boundary are offered by the forecasts of the National Marine Data and Information Service[10]. For the sandbar and lagoon in Caofeidian, the wide tidal flat alternates between wet and dry due to sea surface elevation changes. A wet-dry approach is used to deal with the moving boundary[11].

1.3 Verification

In order to inspect whether the model can accurately simulate the tidal current in Bohai Sea, calibrations and validations of the model are performed, using data synchronously measured in Caofeidian from March 13 to 15, 2005. The measuring stations and their spring tidal ellipses are shown in Fig. 3. Furthermore, within the simulated domain, two tidal gauging stations, Qinhuangdao (39°55′ N, 119°37′ E) and Caofeidian (38°56.5′

N, 118°33.5′ E), are chosen to be tested for the tidal level. Sea surface elevations (tidal levels) and the horizontal velocity field are simulated for the tidal currents. The computational results of the tidal level and horizontal velocity are in good agreement with the field data. Fig. 4 and Fig. 5 show the partial comparisons between the computational results and the field observed data of the synchronous measurement. It can be drawn that the numerical model is reasonable and can be applied to study the tidal currents in Bohai Sea.

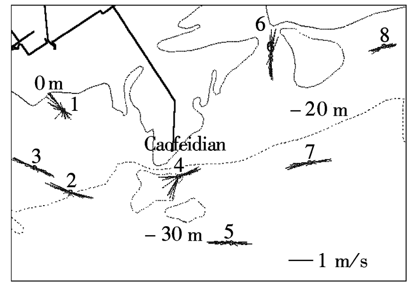


Fig. 3 Observed stations and their spring tidal ellipses in March, 2005

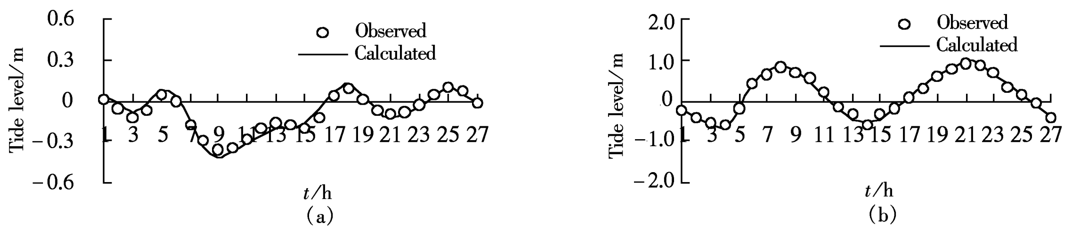


Fig. 4 Comparisons of the tidal level from observation and model in March, 2005. (a) Qinhuangdao; (b) Caofeidian

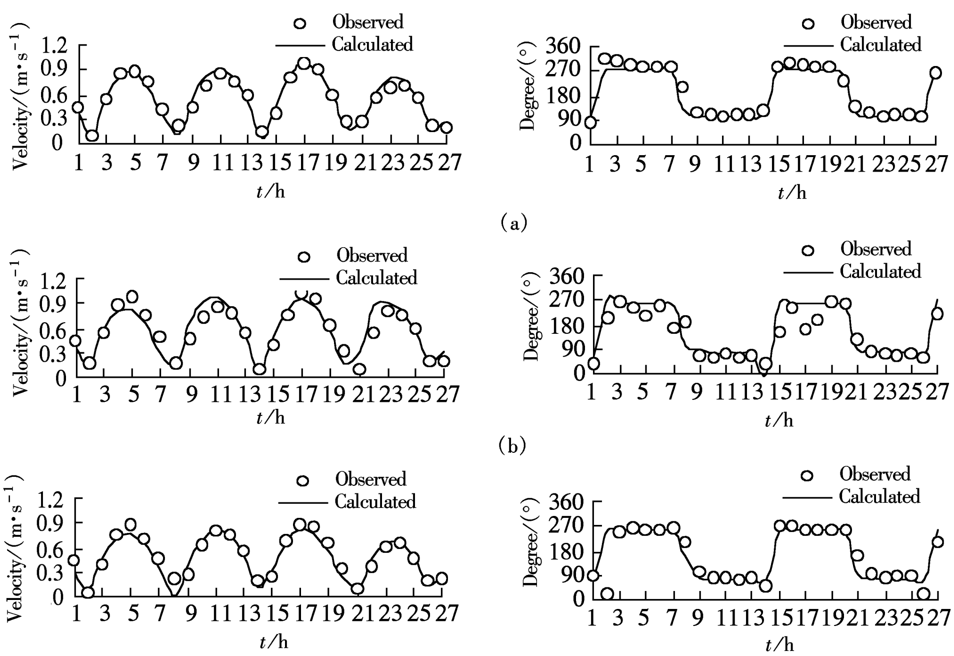


Fig. 5 Comparisons of the velocity from observation and model in March, 2005. (a) Point 2; (b) Point 4; (c) Point 7

2 Computation and Discussion

2.1 Tidal current field in Bohai Sea

The depth-averaged tidal current field distribution of Bohai Sea is shown in Fig. 6 for the flood and ebb strength in spring. The flood tidal current mainly flows northwestward through Laotieshan waterway, then divides into two branches. One of them flows slowly northward or northeastward to Liaodong Bay, the other one turns westward to Bohai Bay, and vice versa. Generally, the tidal current mainly runs clockwise in Bohai Sea, but anticlockwise in Bohai Bay and in the east of Liaodong Bay. The long axis' direction of tidal ellipse agrees with that of Bohai Bay, as well as with those in Liaodong Bay and Laizhou Bay. Just in the peak and the bottom of Bohai Bay, the tidal current turns northwestward and southwestward, respectively.

2.2 Tidal current field near piers

Generally, the tidal current near the Caofeidian is basically to-and-fro motion, and the current direction is westward in flood tide while eastward in ebb tide. Near the island and beach, it is along the shoreline or parallel to the isobath. In flood current, water fills in lagoons and tidal channels from the east and west sides of the tidal flat, and then meet in the ridge. Contrarily, with the fall in tide level, sandbars are become visible. The ebb current flows eastward and westward to the lagoons and tidal channels, and then joins the mainstream in a deep trough. The magnitude of velocity is usually related to

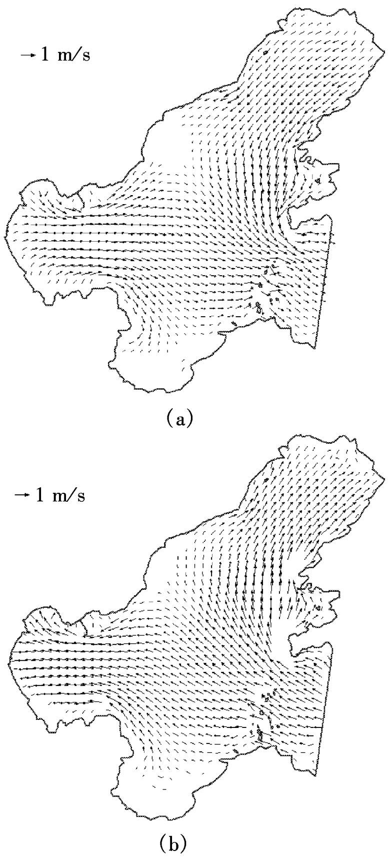


Fig. 6 Spring tidal current field in Bohai Sea on March 14, 2005. (a) Ebb strength in Caofeidian; (b) Flood strength in Caofeidian

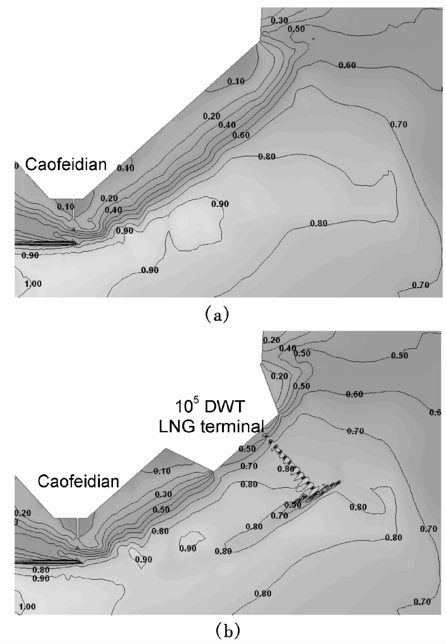


Fig. 7 Distribution of speed isobath at spring flood near the LNG terminal(unit: m/s). (a) Before construction; (b) After construction at a 12 m isobath

water depth, and the strongest velocity occurs near the deep trough in front of the island. The maximum flood speed can reach 1. 3 m/s and the ebb 1. 04 m/s. In addition, the flood current is stronger than the ebb so that the net transfer of water and sediment is from east to west in the sea area of Caofeidian.

As far as the tidal current field around the LNG pier, it flows parallel to the isobath in the deep water. The mean flood and ebb tidal current speeds are 0. 87 m/s and 0. 58 m/s at 12 m isobath , respectively (local theoretical sea level datum), while 0. 88 m/s and 0. 63 m/s at a 14 m isobath. The mean directions of flood and ebb tidal currents are 236° to 56° and 241° to 61° at a 12 m and a 14 m isobath, respectively. It means that the tidal current direction at the project area parallels neither to the shoreline (228° to 48°) nor to the isobath (245° to 65° at 12 m or 254° to 74° at 14 m).

Fig. 7 shows the distributions of the speed isobath in spring flood before and after the construction of the pier at a 12 m isobath. It can be seen that the project does not change the characteristics of the tidal current field in Caofeidian, and the impact area is limited just around piers. As far as the pier is concerned, its layout has an effect on the scope of the block area and the velocity on the pier side. Considering the operating efficiency and safety of the pier, a deflection angle between the pier axis and the flood and ebb tidal current directions should be less than 10° or as little as possible[12]. The pier's layout can be optimized according to the calculated results by the model.

3 Optimization of the Pier's Layout

According to the original planning, there are two schemes for the pier's location. One is located at the 12 m isobath, and the other at the 14 m isobath. And the pier axis' direction, α, is along the isobath or parallel to the shoreline. The cases for the optimization are listed in Tab. 1. Based on the model, comparisons among case 1, case 2 and case 3 are made to understand the impact of the pier's layout on the mean direction of flood and ebb tidal currents on the pier side, β. The optimized results are shown in case 4.

Tab. 1 List of cases calculated for the optimization

Case	Location of the pier	α/(°)
Case 1	Along 12 m isobath	245 to 65
Case 2	Parallel to the shoreline at 12 m isobath	228 to 48
Case 3	Parallel to the shoreline at 14 m isobath	228 to 48
Case 4	Optimized at 14 m isobath	238. 7 to 58. 7

Tab. 2 Mean directions of flood and ebb tidal current (°)

Case	β		γ
	Before construction	After construction	
Case 1	236 to 56	233 to 60	5 to 12
Case 2	236 to 56	233 to 60	5 to 12
Case 3	240 to 60	235 to 64	7 to 16
Case 4	240 to 60	235 to 63	3. 7 to 4. 3

For case 1, β changes from 236°- 56° to 233°- 60° after the construction of the pier(as shown in Tab. 2). If the pier is located at a 12 m isobath and parallel to the shoreline, the value of β is still 233° to 60° in case 2. It shows that β is hardly variable when α is deflected a little. The optimization just focuses on the pier axis direction or the deflection angle, $\gamma(= |\alpha - \beta|)$ in any case. For case 3, β becomes 235° to 64° after the construction of the pier while 240° to 60° before. It can be seen that the value of γ is more than 10° in the ebb current. Therefore, an 8° to 12° clockwise angular deflection for the pier axis direction is proposed based on case 3. Besides, according to the optimization of mooring force with the known β, the value of α is adjusted from 238.7° to 58.7°. The computational results show that the value of β is 235° to 63° for case 4 and the values of γ are both less than 5° in flood and ebb current. It denotes that the optimization is effective and reasonable. It can be concluded that the model is successful and suitable for direct simulation of tidal current around small structures in practical projects.

4 Conclusion

In estuarine and coastal engineering, numerical modeling of tidal current has become a popular and preferred approach to the study of hydrodynamic environments. However, it is still difficult to directly simulate small structures such as jettys, piers in large-scale domains. In order to optimize the layout of an open 10^5 DWT LNG terminal in Caofeidian, Bohai Sea, a 2-D finite element hydrodynamic model for Bohai Sea is established. The grid can be discretionarily refined as a triangle or a quadrilateral so that piers can be treated as one or several impermeable elements in a model domain over 85 700 km^2. Calibration and validation of the model are performed and the results indicate that the model is reasonable for tidal currents around piers in Bohai Sea.

The tidal current field in Caofeidian will hardly be variable after the completion of the terminal. And its layout needs to be optimized in order to decrease the impact on environments and to increase the operating efficiency and safety of the pier. The optimization is mainly based on the deflection angle between the pier axis and the flood and ebb tidal current directions on the pier side. The verification computation indicates that the optimization is effective and successful. It can be concluded that the model is suitable and reasonable for direct simulation of tidal currents around small structures in practical projects such as jetties, piers, and wharfs.

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渤海曹妃甸 LNG 码头布置的潮流数值模拟

廖 鹏[1]　　张 玮[2]

([1] 东南大学交通学院,南京 210096)
([2] 河海大学交通学院,南京 210098)

摘要:为了在大范围数学模型中合理有效地模拟码头桩基等小尺度建筑物附近的潮流场,采用非结构网格建立了渤海二维有限元潮流数学模型. 在面积达 85 700 km^2 的模型范围中将码头桩基概化为面积约 20 ~ 30 m^2 的不透水单元,用于直接模拟桩基附近的复杂潮流场. 在此基础上,对渤海曹妃甸海域 10 万吨级 LNG(液化天然气)码头布置的走向进行了优化. 结果表明:数学模型模拟的潮位和流速等水动力特征与实测结果一致,LNG 码头布置的优化结果合理可信. 表明建立的能够直接模拟小尺度建筑物的渤海二维有限元数学模型可应用于码头工程布置及优化的潮流场模拟研究.

关键词:潮流;数值模型;桩基;渤海

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