

Preliminary study on the sediment transportation under the second phases of the reclamation and training projects in the Bodaozui of Zhoushan

X J Qian¹, B Y Wang², T L Xu¹, R L Wei¹, W Chen^{1,3} and Y L Ni¹

¹School of Port and Transportation Engineering, Zhejiang Ocean University, Zhoushan, China

²Guangxi Vocational and Technical College of Communication, Nanning, China

E-mail: chenwei_112233@163.com

Abstract. A serving area which is on the east side of Shenjia bay was proposed by Shengsi country to provide construction land for the high-end resort of Bodaozui in Zhoushan. In this study, a two-dimensional tidal current and a sediment transportation model of Bodaozui waters were established based MIKE21, and it was verified by the measured tide data. The validated model was then applied to simulate sediment transport caused by the second phase reclamation and training projects. The results showed that: Due to the influence of source, the spread range of suspended sediment for bordering and rock dumping project was larger than that in the filling and drainage project. The outfall was located on the west side of the island, where the space was relatively narrow, which was difficult for the transportation of the suspended sediment. In the bordering and rock dumping project (spring tide), the area of concentration exceeding 100 mg/L is about $11.49 \times 10^{-3} \text{ km}^2$, and is much smaller than that in the filling and drainage project with $84.61 \times 10^{-3} \text{ km}^2$. The reclamation project was affected by the two breakwaters and the impact range of SSC caused by rock dumping and filling projects maybe controlled unlikely to affect the outside hydro-environment.

1. Introduction

With the accelerated pace of modern construction in China, the population density of the eastern coastal areas has become increasingly prominent, while the development of coastal areas is restricted by land resources. This situation has also led to coastal areas look to the ocean. In recent years, there have been a lot of land reclamation projects, which have alleviated the pressure caused by the shortage of land for production and economic development. However, the offshore engineering has a certain influence on the hydrodynamic, topography and boundary condition of water movement and so on in the surrounding area, which would change the environment of sediment transport, thus affecting water environment evolution and the suspended sediment distribution. Therefore, accurate prediction of the sediment transport and analysis of the influence on suspended sediment diffusion will greatly help the theory and technology of coastal engineering, and will have a profound impact on the development of coastal structures and the construction of new ports, which is of great significance to the development of marine economy and ocean transportation.



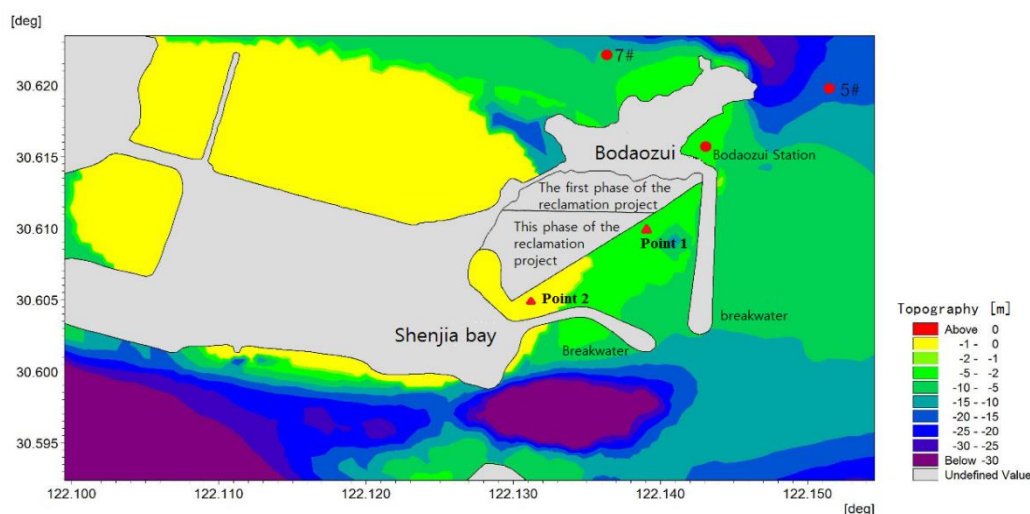


Figure 1. Location map of the project area and verification site.

In recent years, scholars have carried out many numerical simulations of suspended sediment diffusion caused by project. Li *et al* [1] predicted the increment distribution of suspended solids concentration in seawater caused by cable trench excavation of Sheyang wind farm in Jiangsu province by establishing suspended sediment diffusion model. Ke *et al* [2] on the basis of the two dimensional mathematical model for tidal currents and sediment transport, the changes of tidal current field, sediment concentration field and the seabed erosion and deposition caused by the Gouqi breakwaters were analyzed and predicted. Yao *et al* [3] took a power plant project as background and a 2D numerical model for tidal current and sediment was used to evaluate the influence on water intake caused by sediment diffusion during the period of construction. The results show that: short term construction will not produce great deposition to affect the safety of intake water during the high temperature reactor operation. Qi *et al* [4] established a 2D numerical model of flow and sediment to quantitatively study the impact of the dredged-in basin construction on the hydrodynamic sediment within the sea area around Dafeng port. The results show that the optimization of harbor basin area can reduce the total amount of sediment deposition. Some scholars have also simulated the sediment transport caused by the reclamation project construction process. Guo *et al* [5] carried out a numerical simulation of transport diffusion of suspended sediment during the construction of Fengwei reclamation project at the Meizhou bay, and the results showed that the diffusion range of suspended sediment was mainly controlled by tidal current. Shi *et al* [6] based on 2D tidal current and sediment numerical model, simulated and verified the movement of tidal current and the sediment concentration in reclamation project of Tongzhou Bay. Then calculated and analyzed the movement of tidal current and sediment by the harbor basin surrounding sea with two projects. The results show the flow rate and erosion intensity increase of the reclamation area to the south. However, there is no report on sediment transport research near the Bodaozui of Zhoushan. Bodaozui Island is located in the operation area of Shenjia bay on the eastern Xiaoyangshan. It faces Shenjia bay across the water in the southwest and runs from northeast to southwest. The land area is about 0.61 km² with the coastline about 4.84 km long and the highest point about 95.9 m above sea level. Shengsi County plans on reclamation in the south sea area of Bodaozui Island (to the breakwater of Shenjia bay passenger terminal), forming into 138 hectares of land for the construction of the comprehensive supporting park of Bodaozui, taking into account the functions of business, leisure and residence. This project provides construction land for the high-end resort of Bodaozui in Shengsi County. The construction scale is to construct a dike 1388 m long, and to form a land area of 252200 m² by hydraulic filling with dredging soil. The elevation of hydraulic fills in the land area is 6.2 m (see figure 1 for the project area).

On the basis of the topographic and shoreline data before and after the project, a two-dimensional

tidal current and sediment transport model of Bodaozui waters was established by MIKE21. The model was verified by the measured tidal level and current. The validated model was then applied to simulate sediment transportation caused by the bordering and rock dumping as well as hydraulic filling and drainage projects.

2. The establishment of two- dimensional mathematical model

2.1. Model description

MIKE 21, a two-dimensional numerical model developed by Danish hydraulics research institute, is used to study the tidal current field movement towards project sea area. The model adopts unstructured triangular mesh to divide the calculation domain. The triangular mesh can fit the land boundary well. The mesh design is flexible and the mesh density can be controlled freely. The software has the advantages of reliable algorithm, stable calculation, friendly interface and strong processing power. The result is reliable and is recognized internationally. MIKE21 adopts the standard finite volume method of horizontal space discretization. The first-order explicit Eulerian difference scheme is used to separate the momentum equation and transport equation [7].

2.2. Model range and grid size

The calculation range of the model including the sea areas of Hangzhou bay and Zhoushan Islands start from Yanguan in the west, north to the northern Luchao, south to southern Xiangshan, and to the 124°E. The horizontal width of the calculation range is about 378 km, and the longitudinal length is 216 km, and the calculation area is about 81648 km. In order to portray the underwater terrain and shoreline of the project frontier, the grid of the project area is encrypted by the 10 m in size at least to ensure sufficient calculation accuracy. In the offshore area, the relatively sparse grid resolution is between 200 to 4000 m and the smooth transitions can be achieved by setting the grid between different scales.

Many islands in Zhoushan caused the coastline to be particularly meandering, and the triangular grid is more close to the coastline. Therefore, SMS was used to construct a triangular grid. The model has a total of 30546 nodes and 58192 units before the project. After the project, there are 29776 nodes and 56669 units and the grid after the project is shown in figure 2.

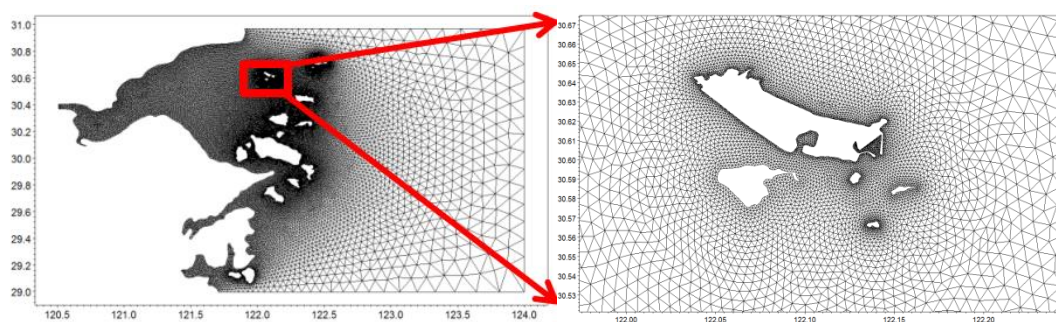


Figure 2. Model area and grid after engineering.

2.3. Boundary condition and parameter settings

The model's roughness is based on the Manning's coefficient with the range of 0.012~0.014. The time step used for 2D hydrodynamic nesting sediment model is automatically adjusted by the model with the range of 0.0001~30s. The cold start is used for the model calculation. The stability criterion is expressed in CFL (courant number), which is stable when the CFL is less than 1, and the CFL less than 0.8 is applied in this model. The effect of current circulation is uniformly considered and the wind curl is also evenly considered at the time of verification. The ocean boundaries are calculated using the East China Sea Model.

The model adopts the dynamic boundary treatment technology. The critical depth of the dry point in the model is 0.005 m, and the critical depth of the wet point is 0.05 m. The open boundary of the Mathematical Model of China Sea only considers the open boundary of the open sea, and the open boundary condition of the open sea is the tidal level process derived from the global tidal model of MIKE 21 software package. The tidal model is the TOPEX/ POSEIDON for a total of 10 years from 1992 to 2002. On the basis of the satellite altimeter data, the resolution is 0.125°, and the sub-waves considered by the model include M_2 , S_2 , K_2 , N_2 , K_1 , O_1 , P_1 , Q_1 and M_4 , totaling 9 tidal components.

3. Establishment of sediment transportation model

The suspension and sediment calculation for this project adopts the MT module in MIKE21. The two-dimensional diffusion equation of the point source emission of the module is as follows:

$$\frac{\partial C}{\partial x} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = \frac{1}{H} \frac{\partial}{\partial x} (H D_x \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y} (H D_y \frac{\partial C}{\partial y}) + Q_L C_L \frac{1}{H} - S \quad (1)$$

In the formula, C represents the averaged suspended sediment concentration (SSC), Q_L is flow rate per unit area, C_L for point source release concentration, S includes the sedimentation and soil erosion.

$$S = S_D + S_E \quad (2)$$

S_D is a sedimentation term and the calculation formula is

$$S_D = \omega_s c_b \left(1 - \frac{\tau_b}{\tau_{cd}}\right) \quad (3)$$

ω_s is the sedimentation velocity, c_b is the concentration near the bottom, τ_b is the bottom shear stress, τ_{cd} is the critical shear stress.

The calculation formula of c_b is as follows:

$$\beta = \frac{c_b}{c} \quad (4)$$

$$\beta = 1 + \frac{P_e}{1.25 + 4.75 P_d^{2.5}} \quad (5)$$

$$P_e = \frac{6\omega_s}{\kappa U_f} \quad (6)$$

$$\kappa = 0.4; U_f = \sqrt{\tau_b / \rho}$$

The calculation formula of the bottom shear stress is as follows:

$$\tau_b = \frac{1}{2} \rho f_c v^2 \quad (7)$$

$$f_c = 2 \left(2.5 \left(\ln \left(\frac{30h}{k} \right) - 1 \right) \right)^{-2} \quad (8)$$

S_E is the soil erosion term;

$$S_E = E \exp[\alpha(\tau_b - \tau_{ce})^{0.5}], \tau_b > \tau_{ce} \quad (9)$$

E is the coefficient of erosion, which is typically in the range of 5×10^{-6} to 2×10^{-5} ; α is a fixed coefficient with a value of 8; specific parameters are shown in table 1.

Table 1. Values of suspended sediment calculation parameters.

Name of the parameter	Value selection
Time step	0.0001-30 s
Sedimentation velocity	0.0005 m/s
Critical shear stress	0.06 N/m ²
Roughness coefficient of the bottom	0.001 m
Karman constant	0.4
Coefficient of erosion	1×10^{-5}
α	8

4. Model validation

The verification data of tide level was selected from the observation data obtained during the hydrology test of the spring of 2015. The data of flow was selected from the data obtained in the May 2015 hydrology test of the two tidal flow stations.

Based on the location and peculiar current characteristics which belong to this project, we selected the measured data as model validation data and evaluating the reliability of the model through validation. The specific measured time is as follows: May 4, 2015- May 5, 2015 (lunar March 16- 17, spring tide); May 7, 2015- May 8, 2015 (lunar March 19- 20, medium tide); May 12, 2015- May 13, 2015 (lunar March 24- 25, neap tide). Tide level observation time started from 0:00 on May 3, 2015, until the end of 23:00 on May 18, continuous observation for half a month. The above tidal information covers spring, medium and neap tides. The verification stations are shown in figure 1, and the tidal level and flow velocity verification results are shown in figures 3 and 4, respectively.

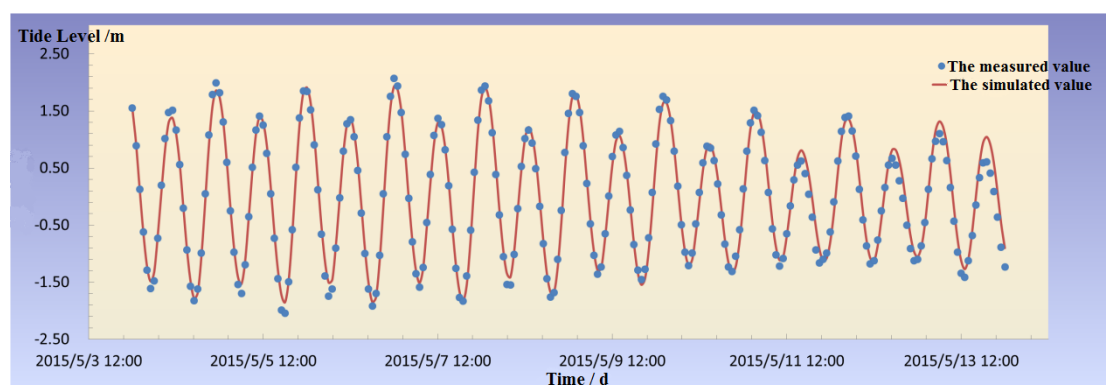
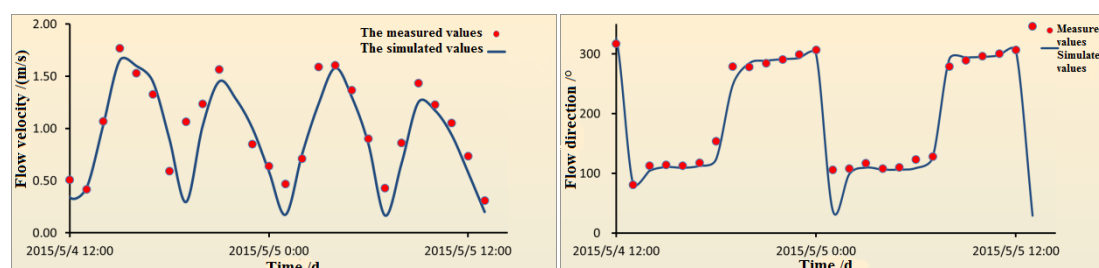


Figure 3. Verification of tide level at the Bodaozui station.



(a)

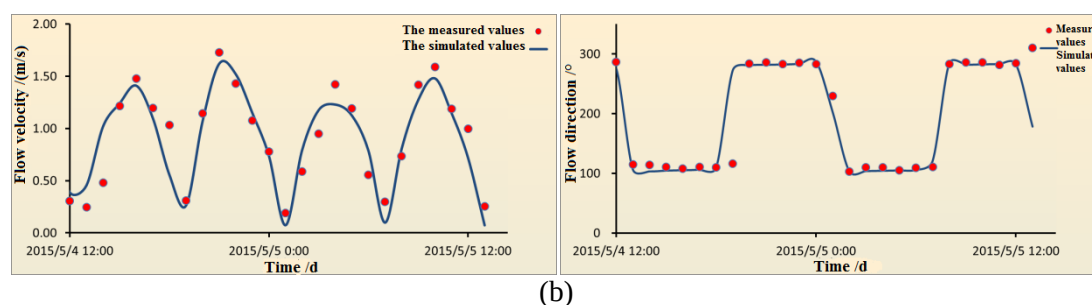


Figure 4. Flow velocity verification process. (a) site 5# and (b) site 7#.

It can be seen from the figure that the measured values and the simulated values of the engineering sea area are well fitted. The amplitude error of the highest and lowest tide level generally within 0.2 m, and the individual at about 0.25 m. So the simulated results of tidal phase agree with the measured basically. The fitting of the flow direction is better, except that the maximum error of individual points at the moment of flow turning exceed 30 degrees, and the maximum error of most stations is within 20 degrees and averaged error is about 10 degrees. The main peaks of the rising and falling current fit well with measured data, the velocity error of peak is small, the maximum velocity error is 0.15 m/s, and the average error is within 0.10m/s. There are two possible reasons for these errors: (1) the measured reasons for instrument; (2) the errors caused by the process of vertically weighted average of the measured flow velocity. The simulation results accurately reflect the current characteristics of the project area and are in line with the specification requirements. The model can be applied to the post-project prediction simulation.

The main limitations of this study are that the impact of wind was taken into account in model validation, but it was not in diffusion prediction of the suspended sediment, and this model didn't consider the vertical changes of velocity.

5. Calculation conditions of sediment transportation

5.1. Suspended sediment source intensity of the bordering and rock dumping project

In the process of dike construction of this project, drainage plate striking and rock cushion layer should be required. Among them, a small amount of suspended solids will be produced during the process of drainage plate striking. But the disturbance of the sludge during the insertion of the draining board is small and the suspended soils are generated. The amount is very small and does not have a significant impact on the marine environment. Rock dumping is carried out on the dike body after the foundation treatment of the dike body, and suspended matters are generated in the rock dumping process. On the one hand, fine particles will enter the water to increase the concentration of suspended sediment in the water. On the other hand, the suspended sediment also generated in the sediment removal process of rock extrusion.

For the sediment carried by the rock, and the amount of suspended sediment produced in the projects can be calculated according to the following formula:

$$Q = E \times c \times \alpha \times p$$

Where:

Q — Suspended sediment production during bordering and rock dumping operation, kg/s;

E — Operation efficiency of bordering and rock dumping, m³/h;

c — soil content in stone, % (volume), in 3 %;

α — The coefficient of suspended sediment generation after soil enters seawater is 20 %;

ρ — Soil density, 1310 kg/m³.

According to the design of the project, the project has two rock dumping ship, and the dumping capacity of each rock dumping ship is about 30000 m³ per month. The project rock dumping strength

of dike body is 2000 m³/d and the daily work is calculated by 10 subtotals, 3 % of the soil content in stone. According to the above calculation results, suspended sediment source intensity of bordering and rock dumping construction is about:

$$Q_1 = 200 \times 0.03 \times 0.2 \times 1310 / 3600 = 0.44 \text{ kg/s}$$

For rock squeeze silt sand, rubble subsidence will cause the bottom sediment suspension during rock dumping period. According to construction scheme and dike body structure, dike construction intensity is same as above, and dike body width is 44 m and its cross-sectional area is about 484 m². The sediment disturbance depth is 1 m, and surface sediment dry weight is 780 kg/m³ (refer to Shengsi bottom sediment dry weight), sediment buoyancy ratio is 20%, sediment source intensity = laying intensity/dike body cross-sectional area × sand bag bottom width × sediment disturbance depth × sediment density × buoyancy ratio, namely $Q_2 = 200 / 484 / 3600 \times 44 \times 1 \times 0.2 \times 780 = 0.79 \text{ kg/s}$.

Integrate the effects of both, suspended solids source strength in the project of dike construction $Q = Q_1 + Q_2$ is 1.23 kg/s.

5.2. *Suspended sediment source intensity of hydraulic filling and drainage projects*

There are two characteristic points on the outside of the dike, one of which is the mouth (see figure 1 for location). During the hydraulic filling process, an outfall is arranged at the south dike near Shenjia bay. According to the field test results of Tianjin port reclamation project conducted by Tianjin water transport engineering research institute of the Ministry of communications. The concentration of suspended sediment in hydraulic filling and drainage is about 2000 mg/L, and there are two dredgers in the project. The working capacity of each dredger is 1000 m³/h. According to the water content of hydraulic filling in the project, the source intensity of suspended sediment in hydraulic filling and drainage is $2 \times 1000 \times 54.5\%$ (maximum water content is considered) / $3600 \times 2000 / 1000 = 0.61 \text{ kg/s}$.

6. Analysis of sediment transportation calculation results

6.1. *Calculation of Suspended Sediment on bordering and rock dumping*

The calculation of suspended sediment diffusion includes the prediction of suspended sediment diffusion under three working conditions: spring tide, neap tide and one tide. The calculation of suspended sediment diffusion includes the prediction of suspended sediment diffusion under three working conditions: spring tide, neap tide and one tide. Figure 5 predicts the distribution area of suspended sediments at the characteristic point (Suspended sediment Point 1 in figure 1) under typical tidal conditions and then the range of the maximum possible SSC on three working conditions statistically obtained is listed in table 2.

It can be seen from the chart that the SSC generated in bordering and rock dumping is relatively concentrated, and the high-concentration suspended sediment is basically distributed westward along the reclamation area.

During the spring tide, the maximum concentration greater than 100 mg / L in the range is about $11.49 \times 10^{-3} \text{ km}^2$. It is concentrated near the rock dumping point and the SSC gradually decreases outward. The area with the maximum concentration (50-100 mg/L) is about $108.61 \times 10^{-3} \text{ km}^2$, and the area with maximum concentration (20-50 mg/L) is approximately $219.10 \times 10^{-3} \text{ km}^2$. In the neap tidal period, the suspended sediments with the same concentration have a larger diffusion range than those with spring tides. While the suspended sediments with the same concentration have the largest diffusion range during the one tide.

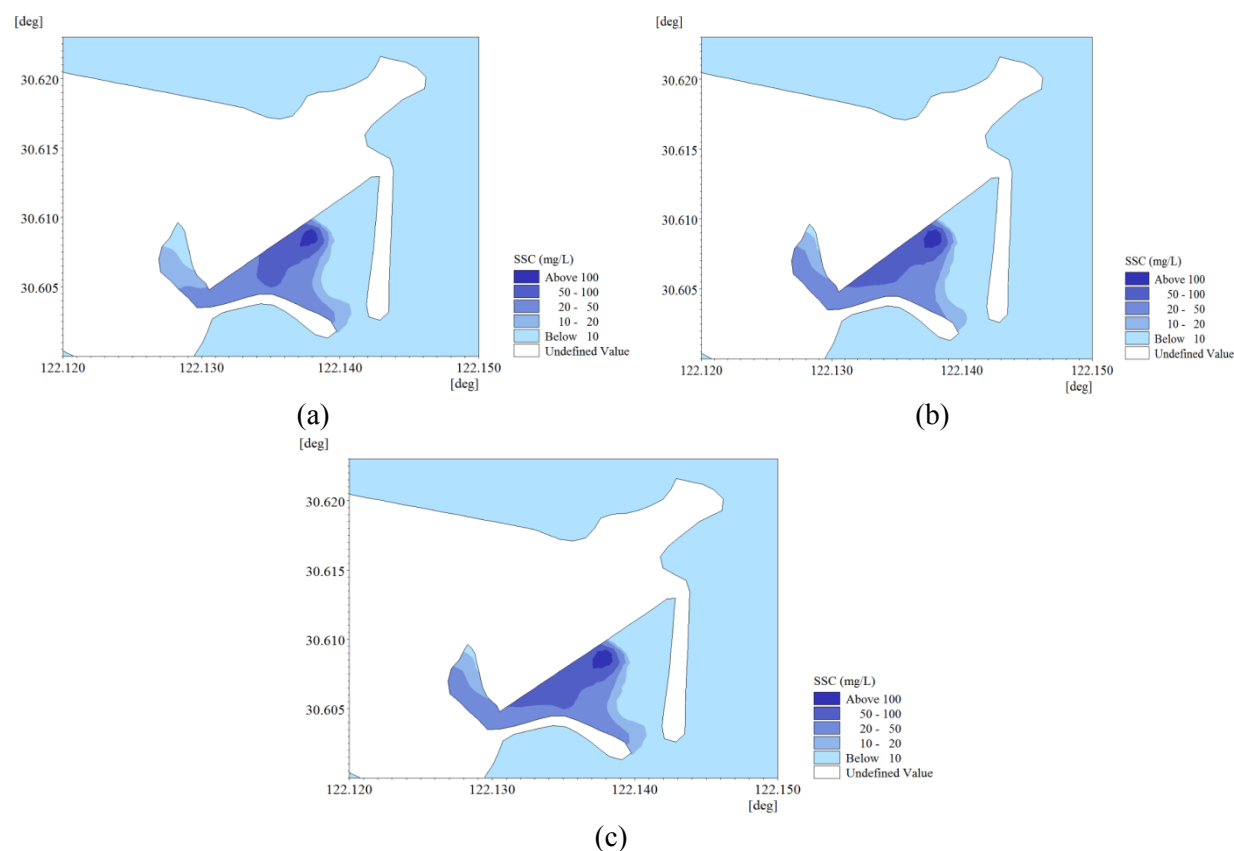


Figure 5. The distribution area of suspended sediments at the point 1 under typical tidal conditions in bordering and rock dumping. (a) The range of the maximum SSC (spring), (b) The range of the maximum SSC (neap) and (c) The range of the maximum SSC (one tide).

Table 2. Prediction of suspended sediment diffusion area (unit: $\times 10^{-3} \text{ km}^2$).

Project	Sort	The range			
		10-20 (mg/L)	20-50 (mg/L)	50-100 (mg/L)	>100 (mg/L)
Bordering and rock dumping	The range of the maximum SSC (spring)	116.80	219.10	108.61	11.49
	The range of the maximum SSC (neap)	91.70	241.80	126.14	14.66
	The range of the maximum SSC (one tide)	92.10	239.20	142.11	15.09
Hydraulic filling and drainage	The range of the maximum SSC (spring)	31.27	52.82	122.30	84.61
	The range of the maximum SSC (neap)	30.30	54.50	145.24	66.16
	The range of the maximum SSC (one tide)	28.80	50.70	123.82	91.98

Due to the breakwater built on the south side and the east side, a relatively closed area is formed in the reclamation construction area. There is only one entrance, and there was less exchange of water inside and outside the port. Due to the breakwater built on the south side and the east side, a relatively closed area is formed in the reclamation construction area. There is only one entrance and exit beside less exchange with water inside and outside the port. Therefore, the suspended sediment diffusion

caused by the bordering and rock dumping project is limited by the mouth which formed by tow breakwaters are difficult to spread outward, so that the impact on the outside of the mouth is small, but the SSC in the mouth is high.

6.2. Calculation of Suspended Sediment on hydraulic filling and drainage

The calculation of suspended sediment diffusion includes the prediction of suspended sediment diffusion under three working conditions: spring tide, neap tide and one tide. Figure 6 predicts the distribution area of suspended sediments at the characteristic point (Suspended Sand Point 2 in figure 1) under typical tidal conditions and then the range of the maximum possible SSC on three working conditions statistically obtained is listed in table 2.

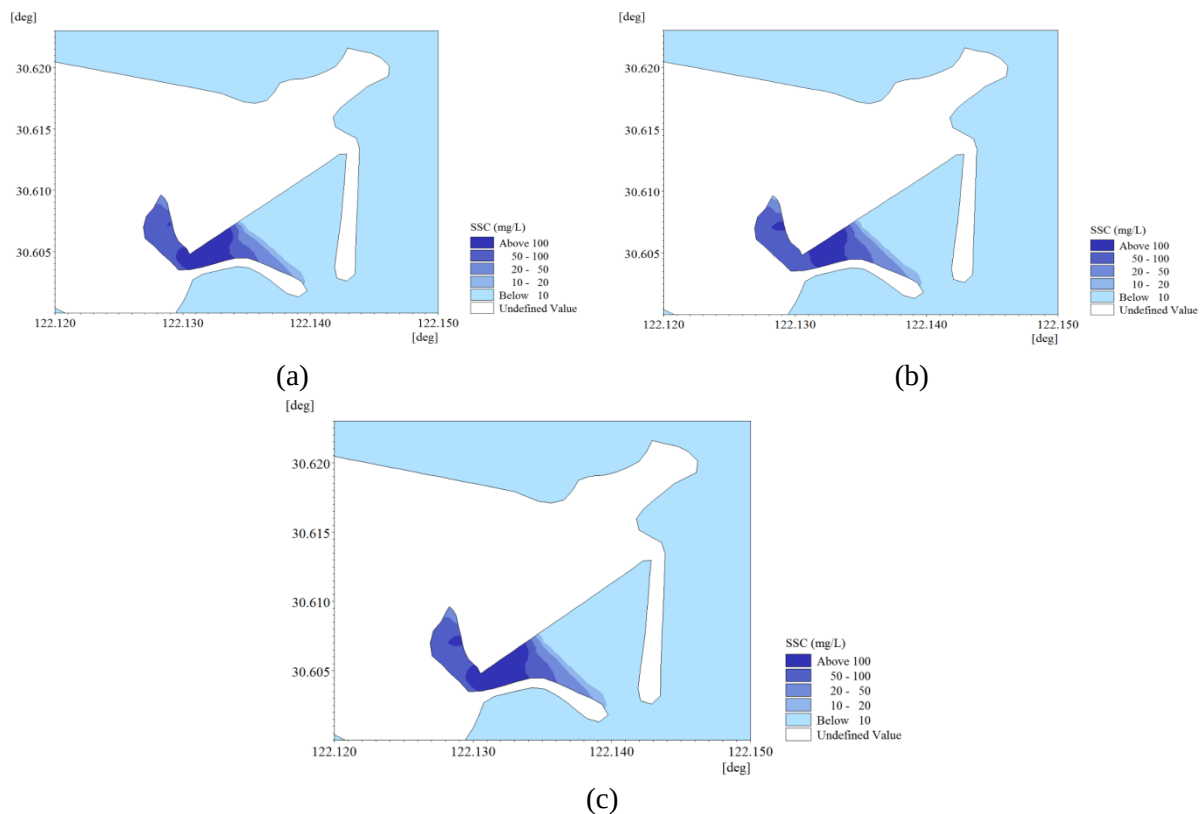


Figure 6. The distribution area of suspended sediments at the point 1 under typical tidal conditions in hydraulic filling and drainage. (a) The range of the maximum SSC (spring), (b) The range of the maximum SSC (neap) and (c) The range of the maximum SSC (one tide).

It can be seen from the chart that Since the source intensity of hydraulic filling and drainage is much smaller than the source intensity of bordering and rock dumping, the diffusion range of suspended sediment caused by hydraulic filling and drainage is obviously smaller, but the range of the suspended sediment with high concentration is significantly higher than that of bordering and rock dumping project, and the high concentration suspended sediment is concentrated near the outfall and on the west side of the bay. During the spring tide, the maximum concentration greater than 100 mg/L in the range is about $84.61 \times 10^{-3} \text{ km}^2$. It is concentrated near the rock dumping point and the SSC gradually decreases outward. The area with the maximum concentration (50-100 mg/L) is about $122.30 \times 10^{-3} \text{ km}^2$, and the area with the maximum concentration (20-50 mg/L) is approximately $52.82 \times 10^{-3} \text{ km}^2$.

Similar to the bordering and rock dumping project, the suspended sediments with the same

concentration have a larger diffusion range than those with spring tides in the neap tidal period. However, unlike that under the bordering and rock dumping project, the maximum range of concentrations greater than 100 mg/L is significantly larger than that under the bordering and rock dumping, because the filling and drainage outfall is located in the southern side of the breakwater and is jointly restricted by the cofferdam area and the breakwaters. The movement distance of suspended sediment discharged by the drainage outfall is extremely limited compared to the bordering and rock dumping, and it is difficult to diffuse in the mouth in time. The suspended sediment concentrates in a limited and relatively small range, resulting in a high concentration, but the concentration on the mouth is still less than 10 mg/L, making it difficult to spread outward.

7. Conclusion

A two-dimensional current and sediment transportation model was established based on the MIKE21 software to investigate the transport and spread of the suspended sediment in the area of the Bodaozui of Zhoushan, Zhejiang Province. The model was verified by the measured tide level and current. The validated model was then applied to simulate sediment transportation caused by the bordering and rock dumping as well as the filling and drainage projects. The transport of the suspended sediment was analyzed with different tide conditions. In addition, the results would provide assistance in studying on the water environment of Bodaozui and Xiaoyangshan islands. The conclusions are shown as follows:

- The second phase of Bodaozui island reclamation project was affected by the two breakwaters on the south and east sides. The impact range of SSC caused by rock dumping and filling projects can be controlled within the mouth formed by the two breakwaters, and the suspended sediment is unlikely to affect the outside hydro-environment.
- Due to the influence of source, the spread range of suspended sediment for bordering and rock dumping project was larger than that in the hydraulic filling and drainage project.
- The range of the high SSC of hydraulic filling and drainage project is significantly higher than that of bordering and rock dumping project and the sediment with high SSC is concentrated near the outfall and on the west side of the bay. The outfall was located on the west side of the island, where the space was relatively narrow, which was difficult for the transportation of the suspended sediment.
- The area of concentration exceeding 100 mg/L is much larger than that under the bordering and rock dumping project.

Acknowledgments

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Appendices

Appendix A. The table of tidal components.

Tidal components	Period (hours)	Nature of tide
M ₂	12.42	semi-diurnal tide
S ₂	12.00	semi-diurnal tide
K ₂	11.97	semi-diurnal tide
N ₂	12.66	semi-diurnal tide
K ₁	23.93	diurnal tide
O ₁	25.82	diurnal tide
P ₁	24.07	diurnal tide
Q ₁	26.87	diurnal tide
M ₄	6.21	quarter-diurnal tide

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