Numerical simulation of oil spill transport under the effect of dredging projects in the north part of the Xiaogan Island of Zhoushan

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Abstract. In the present study, a two-dimensional tidal current and oil spill numerical model was established by using the software MIKE21 to simulate the transport and spread of the oil spill in the area of the Xiaogan Island of Zhoushan, Zhejiang Province. After validated by the field measurements, the model was applied to simulate the current and the spread of the oil spill before and after the dredging project. The results showed that: The oil particles diffused faster under the calm wind, with a spread area of 751.55 km² after 72 hours. The diffusion area and the time for the particles reached to the sensitive points were obviously different between the flood and ebb tide, and the diffusion area was larger during the flood tide. The duration of the particles reached to the sensitive points was shorter during the ebb tide. Under the wind directions of NW, NNW and N during flood tide, the oil particles adhered to the south breakwater and the surrounding area was not affected by the oil spill. The current velocities for both flood and ebb tide were decreased after the project. The decreasing of the current velocity ranged from 0.05 to 0.2 m/s during the flood tide, and 0.1 to 0.15 m/s during the ebb tide. It can be concluded that wind is beneficial for the water environment.

1. Introduction
The Xiaogan Island is located in Putuo district of Zhoushan, Zhejiang Province of China, with Mazhi Island in the east side and Shenchuanmen port area on the north side. The Xiaogan Island was composed of two parts in history, which were combined as one in the 1960s by reclamation project. The narrow island is 4.2 km from east to west and 1.2 km from north to south, covering an area of approximately 5.56 km². The land area of the island is 3.25 km², with a hilly area of 0.62 km² and a plain area of 2.63 km². The shoal area (intertidal zone) is 2.31 km². The northern waters can be affected by the dredging project in the northern part of Xiaogan Island. Therefore, it is necessary to analyze the influence of oil spilled by the engineering ship on the surrounding water environment and conduct numerical simulations to investigate the transport of the oil spill in the north part of the Xiaogan Island.

With the globalization and the continuous development of the port engineering and overseas trade, oil spilling from the ship has become a global pollution of the marine environment. When an oil spill occurs, it may destroy the local marine ecosystem, coastal resources and even may cause huge losses of lives and properties. The damage to the marine ecological environment and the local marine species are immeasurable. Therefore, it is necessary to establish oil spill models for guiding the emergency response and reducing the losses caused by the oil spill. In the past decades, many previous studies...
were conducted by using numerical models to simulate the spread of oil spill. Liao et al [1] studied the oil spill caused by the ship collision accident which occurred near Dalian Xingang area, the results were in good agreement with the field measurements. Guo et al [2] applied POM model to simulate the oil processes of spreading, advection, turbulent diffusion, evaporation, emulsification, and dissolution and shoreline deposition. Huang et al [3] studied the influence of the wind and flow conditions on the diffusion of the oil spill based on WRF and ROMS. They also studied the influence of the grid resolutions to improve the accuracy of the model. Qi et al [4] established the oil spill model of Beijing-Hangzhou grand canal based on MIKE21/SA, and the results showed that the diffusion of the oil spill in inland rivers was affected significantly by the hydrodynamic and wind conditions. Pan et al [5] established a three-dimensional unstructured triangular grid hydrodynamic model coupling wind current, tidal current and baroclinic current for Changjiang River Estuary and its adjacent sea areas based on the SELFE (Semi implicit Eulerian-Lagrangian Finite Element ) model, and the results show that at the position outside the deep channel, the spilled oil slick drifts spirally toward southeast under the influence of tidal fluctuation, northwest wind and the Changjiang diluted water, while it drifts spirally northward due to the pushing effect of the Changjiang diluted water under the southwest wind. The most part of spilled oil is concentrated at the surface layer, and the next part leaves the water through evaporation.

2. Numerical model
A two-dimensional numerical model was established based on MIKE21, which was developed by the DHI [6], to study the tide current and the diffusion of the oil spill in the project sea area. The software has the advantages of the reliable algorithm, stable, friendly interface and powerful pre- and post-processing functions. It has been applied in more than 70 countries around the world and with hundreds of successful examples. The model uses flexible unstructured triangular meshes, which can better fit the land boundary. The numerical solution of the two dimensional incompressible Reynolds averaged Navier-Stokes equations with the assumptions of Boussinesq and hydrostatic pressure is applied in the model. The spatial discretization of the governing equations is performed by using an element-centred finite volume method. The spatial domain is discretized by subdivision of the continuum into non-overlapping elements. The governing equations are shown in the manual [6].

2.1. Initial and boundary conditions
The computational domain was divided by the unstructured triangular mesh. The density and the scale of the mesh were controlled by the mesh generation module. In order to fit the underwater frontier and shoreline of the project area and ensure sufficient calculation accuracy, the mesh of the project area was refined in the small-scale model, with a minimum grid size of 20 m. In the large-scale model, the mesh was relatively sparse, with a resolution ranged from 500 to 4000 m. Smoothness process was conducted between the two different scale meshes.

The large-scale underwater terrain of the computational domain was obtained from the naval aviation insurance department and was converted through GIS digitization. The latest surveyed CAD data of the underwater terrain was used in the sea areas near the project. All the data were unified based on the averaged sea level.

2.2. Parameters of the numerical model
The harmonic constants for the open boundary of the model were obtained from the OTIS dataset of China Sea Area. The water levels of the open boundary were then predicted by these harmonic constants. 11 constituent tides were used (M2, S2, N2, K2, K1, O1, P1, Q1, MF, M4, MS4) for the hourly tidal level calculation. The tidal level of each open boundary then can be obtained by interpolation. The Manning coefficient of the model was set as 0.015-0.1 after the repeated calibration with the measured hydrological data. The time step was set as dynamically adjusted according to the CFL condition to ensure stable calculation. In the large-scale model, the time step was automatically adjusted within the range of 0.01 s to 30 s, while in the small-scale model, the time step ranged from
0.01 s to 10 s.

2.3. Validation of the model
In the present study, the model was validated and evaluated by using the tide level and current data from the field measurements in the spring of 2017. The specific locations of the stations for tide level and current observation are shown in figure 1.

Figure 1. The Xiaogan Island and location of verification stations.

2.3.1. Verification of the tide level. The hourly tide-level data obtained during the spring field measurement from March 28 to April 7, 2017, was applied for the verification. The results are shown in figure 2. From the figure, the simulated tidal levels fitted well with the field measurements at the Shenjiamen tidal station in the project area. The amplitude errors of the highest and lowest tidal levels were generally within 0.15 m, except few were around 0.20 m. The simulated tidal phases were basically consistent with the field measurements.

Figure 2. Verification of tide level at Shenjiamen.

2.3.2. Verification of the tide currents. The data obtained from the field measurements in March to April 2017 was used for the tide currents verification. The results are shown in figures 2 and 3. From the figures, the simulated flow direction was well simulated, excepting for some stations with direction difference exceeds 30° at the turning points. The averaged errors for most of the stations were within 20°. For the flow velocities, the peaks velocities during the flood and ebb tide were well simulated, which was close to the field measurements. The averaged flow velocity error ranges from 0.09 to 0.18 m/s. The specific flow velocity and errors are shown in table 1.
Figure 3. (a) Velocity flow verification (Spring tide) at SW03, (b) Velocity flow verification (Spring tide) at SW09, (c) Velocity flow verification (neap tide) at SW03 and (d) Velocity flow verification (neap tide) at SW09.

Table 1. Statistics of the flow direction errors.

| Station | Averaged error of the flow velocity (m/s) | Averaged error of the flow direction (°) |
|---------|------------------------------------------|----------------------------------------|
| SW03    | 0.12                                     | 12                                     |
| SW09    | 0.12                                     | 19                                     |

Overall, the simulated tidal levels, flow velocities and directions for a single station were satisfactory. The characteristics of the tidal current in the project area can be simulated well by the numerical model, which meet the specification requirements and can be applied to the simulation of
the tidal current of the project area.

3. Analysis of the hydrodynamic results
The changes of the flow velocities after the dredging project are shown in figure 4. During the flood tide, the flow velocity in the project sea area was generally reduced, the decreasing amplitude was 0.05-0.2 m/s. The flow velocity in the waterways on the west side of the dredging project increased, and the increasing range was 0.05-0.07 m/s. During the ebb tide, the flow velocities of the most sea areas of the Shenjiamen port and channel decreased due to the increase of the water depth, and the decrease range was 0.1-0.15 m/s. The flow velocity in the waterway near the Luqiazi also slightly decreased; Outside the dredging channel, the flow velocities in the area near to the shore slightly increased, the increasing range was 0.025-0.05 m/s. The velocities in the area on the west side of the dredging project were significantly increased, the increasing range was 0.05-0.08 m/s.

![Figure 4. (a) The changes of the distribution of the flow velocities after the project during flood and ebb tide, and (b) the changes of the distribution of the flow velocities after the project for a complete tide cycle.](image)

The averaged flow velocity of the whole tide cycle showed that the flow velocity in the dredging area was generally reduced, and the averaged decrease range was 0.12-0.14 m/s. The velocity of the waterway at the north side of Luqiazi decreased slightly. The averaged velocity in the waterway on the west side of the dredging project was increased, and the increasing range was 0.02-0.06 m/s.

4. Analysis of the diffusion of the oil spill
4.1. The distribution and intensity of the source
The tonnage of the grab dredger for the construction was approximately 500 t. According to the calculating method, if the oil carrying rate was 10%, the amount of fuel carried by the grab dredger was 50 t. Therefore, the source intensity of oil spill during the construction period was set as 50 t. In
the present model, the influence range and diffusion of the oil spill was simulated by the trajectory of Lagrangian motion of representative oil particles. In other words, the results were not sensitive to the type of oil.

One oil spill source was set in the middle of the dredging project area. The specific location of the source point is shown in figure 1. The relevant predicted sensitive points around the oil spill are shown in table 2.

Table 2. The sensitive points around the dredging project.

| Type             | No. | Orientation, the nearest distance to the project | Sensitive point                                                                 |
|------------------|-----|--------------------------------------------------|---------------------------------------------------------------------------------|
| Scenic area      | 1   | Northeast, 6.8 km                                | Putuo mountain tourist scenic area, Tourism and entertainment district of Putuo mountain |
|                  | 2   | North-southeast, 1.2 km                          | Zhuiqian scenic area                                                            |
|                  | 3   | South, 9.7 km                                     | Taohua island scenic area                                                       |
|                  | 4   | Southeast, 9.2 km                                 | The northern part of the entertainment district of Putuo                        |
| Fishing area      | 5   | South, 2.4 km                                     | Traditional fishing area                                                        |
| Uninhabited island| 6   | South, 1.5 km                                     | Laitouyuan islet                                                                |
|                  | 7   | South, 1.9 km                                     | Baimutian reef                                                                  |
|                  | 8   | South, 2.3 km                                     | Liyuan mountain islet                                                           |
|                  | 9   | South, 2.4 km                                     | Waiyuan mountain islet                                                          |

According to the statistical data of the annual wind conditions in Putuo district and the distribution of sensitive points near the project area, the wind conditions for the simulation are as follows (see table 3):

- Calm wind 0 m/s;
- Annual dominant wind direction NW, with the averaged wind speed of 4.9 m/s;
- Secondary dominant wind direction NNW, with the average wind speed of 4.7 m/s;
- Unfavorable wind direction N, with a maximum unfavorable wind speed of 10.8 m/s.

Both flood and ebb tides were selected in the simulation.

Table 3. The combination of the conditions for the oil spill simulation.

| Amount of oil spill | Representative wind direction | Wind speed | Tide time |
|---------------------|--------------------------------|------------|-----------|
| 50 t                | Calm wind                      | 0 m/s      | Flood tide                        |
|                     | Annual dominant wind direction (NW) | 4.9 m/s    | Flood tide                        |
|                     | Secondary dominant wind direction (NNW) | 4.7 m/s   | Ebb tide                           |
|                     | Unfavorable wind direction (N) | 10.8 m/s  | Flood tide                        |
|                     |                                 |            | Ebb tide                           |

4.2. Analysis of the numerical results

According to the numerical results, the time for the oil particles reaching the sensitive points and the sweeping area under the four different wind conditions during the flood and ebb were investigated. The specific analyses are as follows:

- Oil spilling during the flood tide

When the oil spill occurred under the calm wind, the oil particles began to move upstream along the
river due to the influence of the tide currents. The particles spread to the water area near the Changzhi island and then transported to the waters near the Luzhi island due to the effect of the ebb tide. During the process, part of the oil particles passed through the channel between Luzhi and Xiaogan island, and then spread to the traditional fishing areas after about 12.5 hours under the effect of the tide currents. The other part of the oil particles passed through Luzhi island, Putuo Mountain, Zhujiajian, and spread to the Zhujiajian Scenic Area after 22 hours. After that, they spread to the Taohua Island Scenic Area after 48.5 hours and continued spread eastwards to the eastern tourism and entertainment district of Putuo district under the effect of ebb tide (table 4). In this process, the oil particles spread out from the bay increased and the diffusion range kept increasing. The diffusion area was about 10.86 km$^2$ after 12 hours, and were about 76.39 km$^2$ and 336.85 km$^2$ after 24 and 48 hours, respectively. The final diffusion area (after 72 hours) can increase to 751.55 km$^2$, with a relatively large impact range (see table 5). The distribution of oil particles at the representative time is shown in figure 5.

Table 4. Duration for the oil particles reached to the sensitive points.

| Sensitive points                                      | Duration under the flood tide (h) |
|------------------------------------------------------|-----------------------------------|
| Putuo mountain scenic area                           | 70                                |
| Tourism and entertainment district of Putuo mountain | 71                                |
| Zhujiajian scenic area                                | 22                                |
| Taohua island scenic area                             | 48.5                              |
| Eastern Putuo tourism and entertainment area          | 58                                |
| Traditional fishing area                              | 12.5                              |

Table 5. The spread area of the oil spill under the calm wind during the flood tide.

| Time after the oil spilling (h) | 12  | 24  | 48  | 72  |
|----------------------------------|-----|-----|-----|-----|
| Diffusion area (km$^2$)          | 10.86 | 76.39 | 336.85 | 751.55 |
Figure 5. The spread area of the oil spill under the calm wind during the flood tide. (a) 6 h, (b) 12 h, (c) 18 h, (d) 24 h, (e) 48 h and (f) 72 h.

When the oil spill occurred under NW, NNW, and N wind during the flood tide, the particles adhered to the south breakwater due to the effect of the wind, and the surrounding area outside the breakwater was not affected by the oil spill.

Oil spilling during the ebb tide

When the oil spill occurred under calm wind during the flood tide, the oil particles began to move downstream along the river due to the influence of the tide currents. The particles spread to the water areas near the lower part of the Xiaogandao River at first and then spread to the upstream due to the effect of the flood tide. In the process, part of the oil particles passed through the channel between Luzhi and Xiaogan Islands, and spread to the traditional fishing areas after about 21.5 hours under the effect of the tide currents. The other part of the oil particles passed through the Luzhi Island, Putuo Mountain, Zhujiajian, and reached to the Zhujiajian scenic area after 34.5 hours. After that, it spread to the Taohua Island scenic area after 43.5 hours and continued spread eastwards to the eastern tourism and entertainment district of Putuo district under the effect of ebb tide (table 6). In this process, the oil particles that spread out from the bay increased and the diffusion range kept increasing. The diffusion area was about 4.04 km² after 12 hours, and were about 60.07 km² and 289.27 km² after 24 and 48 hours, respectively. The final diffusion area (after 72 hours) can increase to 568.29 km², also with an relatively large impact range (see table 7). The distributions of oil particle at the representative time are shown in figure 6. The oil particles spread to the sensitive point faster during the ebb tide.

When the oil spill occurred under NW, NNW, and N wind during the ebb tide, the particles adhered to the south breakwater due to the effect of the wind, and the surrounding area outside the breakwater was not affected by the oil spill.

Table 6. Duration for oil particles reached to sensitive points at the calm wind during ebb tide.

| Sensitive points                                      | Duration under the flood tide (h) |
|-------------------------------------------------------|-----------------------------------|
| Putuo mountain scenic area                            | 58                                |
| Tourism and entertainment district of Putuo mountain   | 63                                |
| Zhujiajian scenic area                                | 34.5                              |
| Taohua Island scenic area                             | 43.5                              |
| Eastern Putuo tourism and entertainment area           | 52                                |
| Traditional fishing area                              | 21.5                              |

Table 7. The spread area of the oil particles under the calm wind during the ebb tide.

| Time after the oil spilling (h) | 12  | 24  | 48  | 72  |
|---------------------------------|-----|-----|-----|-----|
| Diffusion area (km²)            | 4.04| 67.07| 289.27| 568.29|
5. Conclusion

A two-dimensional current and oil spill numerical model was established based on the MIKE21 software to investigate the transport and spread of the oil spill in the area of the Xiaogan island of Zhoushan, Zhejiang Province. The validated numerical model was applied to simulate the current and the spread of the oil spill before and after the designed dredging project. The transport of the oil spill and the current velocity changes were analyzed with different wind and tide conditions. The conclusions are shown as follows:

- Under the calm wind, the oil particles moved faster, and the maximum spread area of the oil spill can reach to 751.55 km² after 72 hours. The time for oil particles reached to sensitive points was significantly different between the flood and ebb tide. The particles reached to the sensitive points with a shorter time during the ebb tide;
- The spread area of the oil spill between the flood and ebb tide was also different. The spread area was larger during the flood tide.
- Under NW, NNW, and N wind, the oil particles adhered to the south breakwater quickly and the surrounding sensitive points were not affected by the oil spill.

After the project, the current velocities at the project area decreased for both flood and ebb tide. The decreasing of the current velocities ranged from 0.05-0.2 m/s during the flood tide, and 0.1-0.15 m/s during the ebb tide.
m/s during the ebb tide.

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