Numerical simulation on cold water discharge of Nanshan LNG project in Longkou

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Abstract. Taking Nanshan LNG project as background, a 2-D numerical model based on the hydrodynamics and advection-diffusion equation is used to simulate the tidal current field and temperature diffusion caused by the cold water discharge, the distribution of temperature diffusion is predicted, the envelope area of the maximum temperature drop and the temperature drop of water intake are counted. Calculating results show that: (1) tidal current shows a typical reciprocating characteristic in the project area, the outlet is located in the shallow reef area south of the breakwater, with the background velocity less than 0.2m/s; (2) the temperature diffusion distance along the north-south direction is longer than that in the east-west direction. The maximum envelope area of temperature drop more than 1°C is less than 0.25km²; (3) Cold water discharge has little effect on the inlet, and the maximum temperature drop at the inlet is 0.68°C, so the layout of outlet is reasonable and feasible. The conclusions can provide technical support to the local government for decision-making.

1. Introduction
In order to speed up the construction of natural gas production and supply system around Bohai Bay and alleviate the demand of clean energy for Shandong Province, CNOOC Group Co., Ltd., in cooperation with Nanshan Group, has built the Nanshan LNG receiving station project in Longkou city. The project is located in Qimu Island operating area of Longkou Port District, Yantai Port, Shandong Province. The first phase is 5 million tons LNG/year, and a 266000 square LNG special berth is constructed, with a long-term scale of 20 million tons per year. As an important part of the LNG project, intake-outlet project is directly related to the normal operation of the gasification plant. A total of 8 ORV, seawater consumption of 62400 m³/h is installed in the long-term scale of the receiving station. Based on the Nanshan LNG project in Longkou, this paper simulates the tidal current field and temperature diffusion caused by cold water discharge by means of numerical model, and the influence of the project on the surrounding waters is analyzed, conclusion can provide services for decision-making of related departments.

Numerical study of thermal discharge by domestic scholars began in the early 1980s, Li [1] (1988) used the ADI difference method to simulate the influence of temperature diffusion on the nearby sea area. Hua [2] (1995) carried out numerical simulation on the temperature diffusion of two large power plants in Yangtze estuary and predicted the influence on the tide-sensitive areas. Hu [3] (2001) simulated the temperature and salinity based on the N.S equation and k-ε turbulence model. He [4] (2008) used EFDC model to carry out 3D numerical simulation on temperature diffusion of a power plant.
plant in Shandong province. Yan [5] (2011) used unstructured mesh to simulate the temperature diffusion range of a power plant in Indonesia and predict its influence on water temperature rise. MIKE21 model is used in this paper, and the model adopts unstructured triangular mesh, which has considerable advantages in simulating complex shoreline and building boundary, and can well simulate the shoreline in the area where the project is located, so that the simulation results are more accurate.

2. Study site
The project is located in Qimu Island operating area of Longkou Port District, Yantai Port, Shandong Province. The tide in the project area is irregular semi-diurnal tide with an average tidal range of 0.91m, which belongs to the weak tidal area. Both the constant wave direction and the strong wave direction are NE direction, and the sub-constant wave direction and the sub-strong wave direction are NNE direction. The tidal current belongs to irregular semi-diurnal shallow sea current, and the average tidal velocity is 0.18~0.38 m/s during the spring tide in May 2017. The average annual temperature is about 13.4 ℃ and the annual average relative humidity is 63%. The sea water temperature is higher in July, August and September, and the water temperature is lower in December, January and February. The constant wind direction in the engineering area is S, and the annual average wind speed is 2.8~4.4 m/s.

Longkou LNG wharf is arranged in a butterfly shape. The berth length is 380m, the width is 110m, and the bottom elevation of the berth and turning basin is -15.4m. For this LNG project, ORV process is adopted for LNG gasification, and the intake-outlet project is recycled water with the same discharge. In this study, the temperature diffusion under 62400 m³/h of long-term water consumption is simulated, and the temperature drop at the outlet is set as 5 ℃. The layout of intake-outlet project is shown in figure 1.

3. Model theory
The 2D modelling of the tidal current movement is based on the MIKE21 flow model (FM module), which is developed by DHI (Danish Hydraulic Institute). The governing equations are listed as follows:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial u h}{\partial x} + \frac{\partial v h}{\partial y} = 0
\]  
(1)

\[
\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} = fu - g \frac{\partial \zeta}{\partial x} + \frac{\tau_x - \tau_y}{\rho h} + E_x \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{1}{\rho} \left( \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right)
\]  
(2)

\[
\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} = -fu - g \frac{\partial \zeta}{\partial y} + \frac{\tau_x - \tau_y}{\rho h} + E_y \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \frac{1}{\rho} \left( \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right)
\]  
(3)

Where \( h \) is the total water depth; \( x \) and \( y \) are horizontal coordinates, respectively; \( t \) is time; \( g \) is gravity acceleration; \( u \) and \( v \) are velocity components, respectively; \( f \) is the Coriolis force; \( \rho \) is the seawater density; \( E_x \) and \( E_y \) are horizontal eddy viscosity components, respectively; \( \tau_x \) and \( \tau_y \) are bed shear stress components, respectively; \( S_{xx}, S_{xy}, S_{yx} \) and \( S_{yy} \) are wave radiation stress components.

The modeling of the temperature diffusion is based on the Eulerian advection and diffusion, see equation(5):

\[
\frac{\partial (\bar{h}T)}{\partial t} + \frac{\partial (\bar{h}u \bar{T})}{\partial x} + \frac{\partial (\bar{h}v \bar{T})}{\partial y} = hF_t + h\bar{H} + hT_S S
\]  
(4)

Where \( \bar{h} \) is the depth-averaged temperature; \( \bar{u}, \bar{v} \) are the depth-averaged velocity; \( \bar{T} \) is the temperature at the source; \( \bar{H} \) is the heat exchange at the sea surface; \( S \) is the discharge of the source; \( F_t \) is the horizontal diffusion item, which can be calculated by equation(5):
Where $D_h$ is the horizontal diffusion coefficient, related to the eddy coefficient, $D_h = \frac{\nu}{\sigma_T}$, where $\sigma_T$ is Prandtl number.

### 4. Model set up and verification

The flow model is calculated by nested large and small models. The large model contains the whole Bohai Sea, the small model includes the project area with 70km in the east-west direction and 80km in the north-south direction. The open boundary is controlled by water level. There are 45683 mesh nodes in the small model, the minimum spatial step is 8m. Mesh generation about the model is shown in figure 2.

The 2-D numerical model was verified according to the observed data in both May, 2017 and April, 2014, through the comparisons, the calculated results are in good agreement with the observed data, such as tidal level, flow speed and direction, readers of interests could see Yao and Zhang [6] for more details.

![Figure 1. Layout of the project.](image1)

![Figure 2. Mesh generation of the model.](image2)

### 5. Numerical simulation of hydrodynamic and temperature diffusion

#### 5.1. Hydrodynamic simulation

Before the simulation of temperature diffusion, flow field is simulated firstly. Taking the spring tide as an example, figure 3 ~ figure 5 show the flow field under 62400 m$^3$/h of long-term water consumption. The analysis is as follows:

- After the project, due to the flow through the gap between the piers of LNG wharf, the background flow velocity near the intake is relatively large, so there is no obvious inflow around the intake. However, the outlet is located in the shade area behind the breakwater of Qimu Island. The background hydrodynamic force is weak, so it can be seen that there is obvious outflow near the outlet, and the velocity is much larger than at the intake. The discharge from the outlet will increase the flow velocity in a certain distance along the inside of the breakwater.

- According to statistics, the average velocity of LNG wharf berth and turning basin is about 0.2m/s~0.6m/s. Under the long-term scale, the average velocity near the intake is about 0.2m/s~0.5m/s, and the average velocity near the outlet is about 0.08m/s~0.95m/s.
5.2. Temperature diffusion simulation

Based on hydrodynamic simulation, temperature diffusion caused by the cold water discharge is further simulated. Two calculation conditions, typical tide and extreme water level, are considered in the model. Where, the typical tide adopts 2017 continuous spring tide, for the extreme water level, the extreme high water level 3.19m and the extreme low water level -1.68m occur simultaneously. The determination of the two calculation conditions can be detailed in the literature. Figure 6 shows the temperature diffusion range under the condition of typical tide and extreme water level. Table 1 calculates the envelope area of different temperature drop grades and the maximum temperature drop at the intake.

- After the intake-outlet project, the temperature diffuses both in east-west and north-south, and the distance in north-south is longer than that in east-west. Under the long-
term discharge, the envelope area with great temperature variation (temperature drop ≥3°C and ≥4°C) under extreme water level conditions is slightly larger than that under typical tidal conditions, and the envelope area with small temperature variation (temperature drop ≥ 0.5 °C and ≥ 1 °C) is slightly smaller than that under typical tide condition. This is related to the shallow topography where the outlet area is located, there will be a large exposed beach when the extreme low water level occurs.

- According to the statistics, under the condition of typical tide and extreme water level, the maximum temperature drop around the intake is about 0.68 °C and 0.72 °C, respectively, which can meet the requirement of temperature drop ≤ 1 °C; the envelope area of temperature drop ≥ 1 °C is 0.25 km² and 0.24 km², respectively, and the envelope area of temperature drop ≥ 4 °C is 0.001 km² and 0.01 km², respectively.
- Generally speaking, temperature diffusion caused by cold water discharge is mainly concentrated around the intake-outlet project, it has little impact on the surrounding water environment.

**Figure 5.** Local flow filed near the outlet. (a) flood and (b) ebb.

**Figure 6.** Envelope of the maximum temperature drop. (a) Typical tide and (b) Extreme water level.
Table 1. Statistics on the envelopes range of temperature diffusion.

| Discharge m$^3$/h | Tide condition          | Maximum temperature drop at intake (°C) | Envelope area (km$^2$) |
|-------------------|-------------------------|-----------------------------------------|------------------------|
| Long-term Discharge 62400 | Typical tide             | 0.68                                    | 0.46 0.25 0.06 0.01 0.001 |
|                   | Extreme water level      | 0.72                                    | 0.37 0.24 0.14 0.04 0.01 |

6. Conclusions

Based on MIKE21 numerical model, this paper carries out a numerical simulation study of cold water discharge in Longkou Nanshan LNG Wharf. The model is verified according to the measured data, the law of flow movement is simulated, the envelope range of temperature diffusion is predicted, and the influence of cold water discharge on the surrounding water environment is analyzed. The findings are as follows:

The tide in the engineering sea area is irregular semi-diurnal tide with mean tidal range of 0.91m. The large-scale flow movement shows a reciprocating state, with the flooding tide tending to the southwest and the ebbing tide tending to the northeast. After the project, the average velocity of LNG wharf berths and basin is around 0.2m/s~0.6m/s. Under the long-term discharge of 62400m$^3$/h, the average velocity near the intake is around 0.2m/s~0.5m/s, and the average velocity near the outlet is around 0.08m/s~0.95m/s.

After the intake-outlet project, the temperature diffuses both in east-west and north-south, the distance in north-south is longer than that in east-west. Under the long-term discharge, the envelope area with great temperature variation (temperature drop $\geq$3°C and $\geq$4°C) under extreme water level conditions is slightly larger than that under typical tidal conditions, and the envelope area with small temperature variation (temperature drop $\geq$0.5 °C and $\geq$1 °C) is slightly smaller than that under typical tide condition.

Under the condition of typical tide and extreme water level, the maximum temperature drop around the intake is 0.68 °C and 0.72 °C, respectively, which can meet the requirement of temperature drop $\leq$1°C; the envelope area of temperature drop $\geq$ 1 °C is 0.25 km$^2$ and 0.24 km$^2$, respectively, and the envelope area of temperature drop $\geq$ 4 °C is 0.001 km$^2$ and 0.01 km$^2$, respectively.

In summary, temperature diffusion caused by cold water discharge is mainly concentrated around the intake-outlet project, it has little impact on the surrounding water environment.

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