Study on the Layout and Influence of Offshore Structures in Macao Waters of Pearl River Estuary

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Abstract. The coastal area is the area where human activities are most frequent. Coastal waters provide rich resources for the development of human society. The current in coastal waters is affected by shoreline, buildings in water and tidal current. The scientific location of buildings in water is of great scientific and practical significance for the sustainable development and utilization of coastal zones. In this paper, the Jiu’ao Bay is taken as the object, and mathematical and physical models are used to simulate the influence of hydrodynamic force and water exchange capacity caused by different locations of intake. The simulation results show that after the construction of the water intake, the water flow is squeezed by the water intake, and the water flow is forced to deflect eastward, while the west side water flow is deflected to the south. The flow diversion of the rising tide is advanced, and the flow convergence of the falling tide is delayed. As a result, the water exchange capacity in Jiu’ao Bay is reduced. Compared with Scheme 1, the location of Scheme 2 is less hydrodynamic, so the impact is less.

1. Background

Coastal waters are in the land-sea interaction zone. Under the joint action of the ocean and the land, they contain rich resources. Currently, approximately 60% of the world's population lives in coastal areas, while two-thirds of the cities with a population of over 2.5 million live here. For a long time, human activities and natural disasters have to some extent destroyed the coastal water environment, making the carrying capacity of the water environment gradually decrease. Due to the lack of reasonable protection, management and development of coastal waters, the research and solution of water environment problems are facing a very severe test.

Through the methods and techniques of remote sensing and GIS, Gao Yi and others analyzed the spatial-temporal changes of China's mainland coastline in the past 30 years. Overall, human development activities are the dominant factors of coastal changes, with local coastline showing natural evolution characteristics [1-2]. Chen Shudeng and others used GIS to analyze the ecological sensitivity of coastal waters, taking Tianjin as an example. It is believed that after 2006, the middle- and high-sensitive areas gradually transform into low-sensitive areas, which is a period of ecological protection [3]. It can be seen that the reasonable development of coastal waters is conducive to the protection of ecological and environmental resources along the coastal zone.

The current in coastal waters is affected by coastline, buildings in water and tidal current, and the flow pattern is complicated [4]. The location of permanent buildings not only affects the flow pattern of nearby water, but also indirectly affects the water environment of the water area. Therefore, the rationality of the site selection of permanent buildings in coastal waters has important scientific and
practical significance for the sustainable development and utilization of coastal zones. This paper takes the proposed permanent building at the mouth of Jiu’ao Bay as an object to study its site selection and its impact.

2. Research methods

2.1 Evaluation Indicators

The proposed permanent building may have an impact on the hydrodynamic force of Jiu’ao Bay and the water exchange capacity in Jiu’ao Bay. The evaluation index of hydrodynamic change is usually dominated by velocity and flow pattern. The evaluation index of water exchange capacity change is dominated by half exchange period and water exchange rate [5-6]. The half exchange period is the time required to reduce pollutants in water by half. However, the calculation of water exchange rate is relatively complicated. Water bodies and external water bodies are continuously mixed in the process of flood tide and ebb tide. The mixed water bodies are transported to the outer sea under the action of tidal current. This process is called water exchange. The definition of water exchange rate is:

\[
R(r, l, t) = \frac{C(r, l, t) - C(r, l, t_0)}{C(r, l, t_0)} \times 100\%
\]

Where \( r \) is a certain river channel, \( l \) is mileage and \( t \) is time; \( C(r, l, t_0) \) is the initial concentration field at a certain position in the river channel; \( C(r, l, t) \) is the instantaneous concentration field at a certain position in the river channel; \( C(r, l, t) \) is the instantaneous water exchange rate at a certain position in the river channel.

2.2 Research Model

In order to study the influence of the proposed permanent building on the hydrodynamic force of Jiu’ao Bay and the water exchange capacity in Jiu’ao Bay, this paper adopts the physical model and mathematical model of the waters near Jiu’ao Bay to simulate the hydrodynamic force and water exchange capacity, and studies the site selection of the permanent building and its influence.

(1) Physical model

The upper boundary of this test is about 6km (1#) from Hongwan Waterway to the upstream of Majiaozhou, from the north side of the sea area to Jiuzhou Dapai area (2#), and from the upstream of Wanchai Waterway to the vicinity of Shijiaozui Sluice (3#); The lower boundary-the south side of the sea area extends about 5km(4#) outward from the outlet of the crossgate waterway, and the east side of the sea area extends to 4km (5#) east of the airport.

According to the purpose and task of the test, combined with the site conditions and the water supply capacity of the laboratory, this model adopts a plane scale \( \lambda_z = 300 \); In order to ensure that the model water flow is in the resistance square area, the model vertical scale is taken as \( \lambda_v = 50 \), and the variation rate is taken as \( \eta = 6 \).

In the physical model water exchange capacity test, Rhodamine was used as a tracer to carry out water exchange diffusion tracer test, simulating the water transport and diffusion in Jiu’ao Bay.
Fig 1. Scope of physical model simulation

(2) Mathematical model

The mathematical model adopts Delft3D model, and its scope is larger than that of physical model. The research area is divided into 475,059 rectangular grids, and the key research area near Jiu’ao Bay is encrypted, with the minimum grid size of 5m.

① the flow mathematical model governing equation

The continuous equation of hydrodynamic integration along water depth is as follows:

\[
\begin{align*}
\frac{\partial \xi}{\partial t} + \frac{1}{\sqrt{G_{xx}G_{yy}}} \frac{\partial}{\partial \xi} \left[ (d + \xi \psi) \sqrt{G_{yy}} \right] + \frac{1}{\sqrt{G_{xx}G_{yy}}} \frac{\partial}{\partial \eta} \left[ (d + \eta \psi) \sqrt{G_{xx}} \right] = Q
\end{align*}
\]

Where \( Q \) is the flow per unit area caused by water outflow and inflow, rainfall and evaporation:

\[
Q = H \int (q_{in} - q_{out}) \, dx + P - E
\]

And \( q_{in} \) and \( q_{out} \) are respectively local water source and sink per volume unit (l/s), \( P \) is non-local source items of rainfall and \( E \) is non-local source items of evaporation.

The momentum equation in the sum \( \xi \) and \( \eta \) direction is as follows:

\[
\begin{align*}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{\partial \psi}{\partial x} + \frac{\partial v}{\partial y} + \psi = & \frac{\partial}{\partial x} \left[ \frac{\partial u}{\partial \xi} \right] + \frac{\partial}{\partial y} \left[ \frac{\partial u}{\partial \eta} \right] + f_u = \\
- \frac{1}{\rho \sqrt{G_{xx}}} P_x + \frac{1}{(d + \xi)^2} \frac{\partial}{\partial \xi} \left[ \frac{\partial u}{\partial \xi} \right] + M_x
\end{align*}
\]

\[
\begin{align*}
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{\partial \psi}{\partial x} + \frac{\partial v}{\partial y} + \psi = & \frac{\partial}{\partial x} \left[ \frac{\partial v}{\partial \xi} \right] + \frac{\partial}{\partial y} \left[ \frac{\partial v}{\partial \eta} \right] + f_v = \\
- \frac{1}{\rho \sqrt{G_{yy}}} P_y + \frac{1}{(d + \xi)^2} \frac{\partial}{\partial \xi} \left[ \frac{\partial v}{\partial \xi} \right] + M_y
\end{align*}
\]

Density changes are ignored except in the baroclinic term, and \( P_x \) and \( P_y \) represent pressure gradients. Sum in momentum equation \( F_x \) and \( F_y \) represents imbalance of horizontal Reynolds stress. And \( M_x \) and \( M_y \) represent contributions from sources and sinks of external momentum (external drive, hydraulic structures, discharge or extraction of water, wave stress, etc.).
2. Water quality model control equation

The control equation of pollutants described by the model is as follows:

\[
\frac{\partial (d + \xi)}{\partial t} + \frac{1}{\sqrt{G_{xx}}} \left[ \frac{\partial}{\partial \xi} \left( \sqrt{G_{xx}} (d + \xi) u \right) + \frac{\partial}{\partial \eta} \left( \sqrt{G_{xx}} (d + \xi) v \right) \right] = 0
\]

(6)

Where, \( c \) is the pollutant concentration (kg/m\(^3\)); \( u \), \( v \) is \( \xi \), which \( \eta \) is the velocity vector (m/s) of the direction; \( d \) is the horizontal diffusion coefficient (m\(^2\)/s); \( \lambda \) is the first order attenuation coefficient (l/s) of pollutants; \( S \) is the source and sink term, indicating adsorption, degradation or settlement of pollutants (kg/ m\(^3\)/s).

3. Characteristics of the study area

Jiu’ao Bay is located in the northeastern waters of Luhuan Island. It is connected with Macao Waterway in the north and Lingdingyang and South China Sea in the south. There is a navigation channel in Jiu’ao Bay, and the underwater topography is greatly influenced by human beings. The current situation forms a "claw" type. The average water depth in Jiu’ao Bay is between 2 and 3 meters. The elevation of the bottom of channels such as Jiu’ao Port is basically about -6m, and the water depth is maintained at about 4.4m. A breakwater is arranged outside the water intake of Luhuan Power Plant. The breakwater is located on the shallows -5m south of the airport runway. The breakwater plane is annular, the maximum width of the exposed seabed part is 115m, the elevation of the top of the breakwater is 5.2m, and the width of the breakwater is 6.5m. At present, two schemes have been presented for the location of water intake. In Scheme 1, the breakwater is located at the top of the shallows -5m south of the airport runway, while in Scheme 2, the breakwater is located at 98m in the direction of 36 degrees east-north of Scheme 1. [7]

3.1 Upstream characteristics

The rising tide in the South China Sea is influenced by the coastline, and its direction is toward the northeast. The rising tide is divided into east and west flows on the south side of the airport runway. The water flow on the east side follows the coastline, bypasses the airport runway, and then goes up north along the east side of the runway. The water flow on the west side directly enters Jiu’ao Bay, enters Macao Waterway along the middle water passage of Macao Airport on the north side, and then merges with the water flow from Lingdingyang to ascend Macao Waterway together. [10]

3.2 Characteristics of ebb current

After the ebb tide flows out of the Macao waterway, it starts from the near shore to the northern end of the Macao airport runway and is divided into two sections. One merges with the Lingdingyang ebb tide to enter the waters on the eastern side of the Macao airport runway, and the other enters the water passage in the middle of the Macao airport along the passage between the Macao airport runway and
the Bei’an wharf, and enters the South China Sea along the southwest via the Jiu’ao Bay outlet and the east ebb tide to the southern end. Except for the large flow velocity at the northern and central parts of the west side and at the mouth of Jiu’ao Bay, the ebb flow velocity at the east and west sides of the airport runway is approximately the same. With the strengthening of the ebb current, the mainstream of the ebb current gradually deflects eastward, and the west side of the airport runway becomes a weak flow area.

![Figure 3. Tidal current characteristic chart](image)

4. Discussion

4.1 Tidal Current Changes

After the implementation of Scheme 1, when the tide rises, the rising tide flowing upward along the eastern side of the airport is affected by the extension of the southern end of the airport. Its flow direction changes from northeast to northeast and slightly deflects to south. It is divided into two flows through the water intake and flows upward along the original flow direction before the project after converging at the southern end of the airport. The upwelling along the mouth of Jiu'ao Bay was
squeezed by the upwelling on the east side of the airport, which deflected to the north, slightly deflecting to the north with an angle change within 3 degrees. After the implementation of scheme 2, the characteristics of tidal current changes are similar. However, scheme 2 is completely located in the weak tidal current area, with small overall impact and angle changes within 2 degrees.

After the implementation of scheme 1, when the tide falls, due to the influence of the extension of the southern end of the airport, it moves southward along the confluence area where the tide falls on both sides of the airport. Due to the implementation of the airport expansion project, the west side downflow tidal current has slowed down and is divided into two streams through the water intake, bypassing the proposed water intake, and the flow field slightly deflects to the south when it merges downstream. However, the mainstream of the downflow from the east side of the airport is not directly affected because it does not pass through the proposed intake. However, due to the squeezing effect of the downflow from the west side of the water body, the downflow from the east side of the airport moves slightly southward to the downstream of the proposed intake. However, the breakwater in Scheme 2 is located at 98m in the direction of 36 from the east to the north of Scheme 1, and the water intake enters the shield area on the south side of the runway of Macao Airport. Although the change of the ebb current is similar to that in Scheme 1, the flow in the east side is basically unchanged and the flow line in the west side is slightly changed because Scheme 2 is completely located in the weak flow area.

Figure 4. Tidal current characteristic change
4.2 Changes in Water Exchange Capacity
Water exchange capacity is an important indicator of water environmental capacity and an important factor affecting water quality distribution characteristics. The initial conditions for model calculation are: the initial concentration of conservative tracer in Jiu’ao Bay is 1mg/L, and the initial concentration values in other areas in the model are set to 0mg/L[8-9]. For the convenience of statistics, this article divides Jiu’ao Bay into three areas, A for the North District of the power plant, B for the South District of the power plant, and C for the access area.

Under the condition that the water intake is not constructed, the A half exchange period of Jiu’ao Bay is 59.8h, the B half exchange period of Jiu’ao Bay is 21.1h, and the C half exchange period of Jiu’ao Bay is 9.5h. The two-day water exchange rate of Jiu’ao Bay A is 71.3%, Jiu’ao Bay B is 84.5%, and Jiu’ao Bay C is 86.7%.

Under the significant influence of tidal power, the water exchange capacity in the channel area is relatively strong, and the water exchange rate in two days is relatively high. However, due to the shielding effect of the power plant land area, the hydrodynamic force on the shoal is extremely weak, the half exchange period is obviously longer than the other two areas, and the water exchange rate in two days is the smallest.

| Subregion | Present Situation | Scheme 1 | Scheme 2 | Present Situation | Scheme 1 | Scheme 2 |
|-----------|-----------------|----------|----------|-----------------|----------|----------|
| A         | 59.8            | 70.1     | 64.3     | 71.30           | 42.4     | 53.7     |
| B         | 21.1            | 26.0     | 23.9     | 84.50           | 72.7     | 78.4     |
| C         | 9.5             | 11.3     | 10.1     | 86.70           | 82.5     | 84.2     |

After the water intake is implemented according to scheme 1, the half exchange periods of A, B and C in Jiu’ao Bay are prolonged, and the water exchange rate is reduced as a whole. Jiu’ao Bay C is located in the passage area, with strong hydrodynamic force, which is prior to the exchange in other areas and is less affected. A and B are located in Jiu’ao Bay. The exchange of water in C is weakened, and the contact time between A and B with low concentration conservative tracer is delayed. Therefore, the half exchange period of C is longer than that of C. In Scheme 2, the influence of water intake on tidal dynamics at the mouth of Jiu’ao Bay is reduced. Compared with Scheme 1, the half exchange cycle time of Jiu’ao Bay is shortened and the water exchange rate is increased in two days.

5. Conclusion
Coastal waters are rich in resources and bring convenience to the development of human society. However, human activities and natural disasters have caused certain damages to the coastal water environment, affecting the carrying capacity of the water environment. The current in coastal waters is
affected by coastline, buildings in water and tidal current, and the flow pattern is complicated. The location of permanent buildings not only affects the flow pattern of nearby water, but also indirectly affects the water environment of the water area. Therefore, the scientific location of permanent buildings is of great scientific and practical significance for the sustainable development and utilization of coastal zones.

This paper takes the proposed intake at Jiu’ao Bay as an example to study the location of intake and its impact. Through mathematical model and physical model simulation, it is found that the proposed intake is located in the confluence area on the south side of the runway of Macao Airport, and the flow conditions are complicated. After the construction of the water intake, the water flow was squeezed by the water intake. The water flow was forced to deflect to the east while the water flow in the west was deflected to the south. The flow diversion of the rising tide was advanced and the flow convergence of the falling tide was delayed. The hydrodynamic changes indirectly affect the water exchange capacity of Jiu’ao Bay. According to the simulation results, the water exchange capacity has decreased. Compared with scheme 1, scheme 2 is located in a weak hydrodynamic condition, so its impact is relatively small.

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