Numerical Simulation of Hydrodynamic Condition on Shielding Measures of Hong Kong-Zhuhai-Macao Bridge

Jie He¹,²,* and Xinsheng Zhao³
¹Nanjing Hydraulic Research Institute, Nanjing, China
²Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing, China
³Hydrology Bureau of Yellow River Conservancy Commission, Zhengzhou, China

*Correspondence author email: jhe@nhri.cn

Abstract. According to the characteristics of water flow movement in the junction area of island and tunnel, the "asymmetric" type double diversion dike measures for the north and south sides of basement shelter area were formulated. The 3D mathematical model of flow in the water area of local sinking base was established in this article. The hydrodynamic simulation of the diversion dike was carried out. The results showed that the flow velocity in shelter area of basement is greatly reduced. The maximum flow velocity of artificial flattening section of E33 pipe joint base is less than 0.5 m/s, and the maximum flow velocity of flattening ship construction section is not more than 0.8 m/s. The flow rate can meet the conditions of immersed tube installation. For safety reasons, E33 pipe joint placement time is suitable for the small tide period with weaker power flow.

Keywords: Hong Kong-Zhuhai-Macao Bridge; Artificial island, Island tunnel junction; Diversion dike.

1. Introduction
The Hong Kong–Zhuhai–Macau Bridge is a large-scale channel spanning the Lingdingyang Bay next to the Pearl River Estuary, which connects the Hong Kong Special Administrative Region, Zhuhai of Guangdong Province and the Macao Special Administrative Region in China. In order to meet the navigation of large-scale waterways, such as Lingding Channel, the project adopts the combination of "bridge-island-tunnel" for building the bridge. And the undersea tunnel beneath the main traffic zone of Lingdingyang is constructed by immersed tubes. The water of the Lingding Channel and the Dajing Deep that the immersed tube tunnel passes through is deep with rapid flow. Thus, the sinking installation of immersed tubes is easily affected by the hydrodynamic factors including tidal current and wave. Besides, at the junction of island and tunnel, the installation is obviously affected by the ski-jump flow from the island-head, and the severe turbulence at the front of island-head will also cause complex and changeable flow pattern in the basement. E33 pipe section is located at the island-and-tunnel junction of east artificial island. There are strict requirements on flow pattern and velocity in the basement of submerged zone in the construction code of pipe section installation. According to the methods of flattening gravel in basement, E33 section base can be divided into three parts: dry work area (area A), artificial work area (area B) and ship work area (area C). The velocity of area A, where flatten gravel with the method of dry working, and area B where flatten gravel artificially can not exceed 0.5 m/s during the construction. And that of area C can not exceed 0.8 m/s, where flatten gravel with flattening ship. The velocity here refers to the velocity at any depth in the construction.
area. The allowable maximum velocities set in each zone of E33 pipe joint base are important technical indexes to judge the optimal scheme for sheltering diversion dike. In order to make the hydrodynamic conditions in the submerged zone of island tunnel junction meet the installation requirements, ensuring the construction safety, it is necessary to arrange the corresponding temporary cover around the basements of island tunnel junction (Figure 1).

The research object of this paper is the submerged zone of island-tunnel-junction base in east artificial island. The ski-jump flow at the head of east artificial island is obvious and the flow in basement is east-west transverse flow, which results in turbulent flow and strong dynamic in island tunnel junction. This characteristic is related to the dynamic of the sea where east artificial island is located. Initially, the hydrodynamic environment of east artificial island is analyzed. According to hydrological data collected before and after artificial island construction, changes of dynamic conditions of the area are analyzed and summarized. With the characteristics of flow at junction, the protective and sheltering measure that adopting double diversion dikes on both sides of basement is proposed. Based on 2D flow mathematical model of large-scale flow in Lingdingyang what is simulated in this paper is that the 3D flow characteristics in local area of the basement combined with 3D mathematical model of local area in the basement. And the necessity of shelter in island tunnel junction base is analyzed. After that, the model calculates flow condition of each area of basement with shelter from double diversion dikes whose effect is analyzed. From the perspective of reducing hydrodynamic conditions of submerged zone at the head of island, this research provides technical support for relevant departments to formulate the construction scheme and technology.

2. The Scheme of Base Sheltering

The cover measures on both sides of basement of island tunnel junction at east artificial island is adopting double diversion dikes. According to engineering experience, maximum cover area appears when tidal current is orthogonal to the trend of dikes. Based on the analysis of measured data of tidal current in basement with numerical simulation results of flow at the head of island, taking into account the layout of slopes and berm on both sides of basement, protective measures of double diversion dikes are worked out, as shown in Figure 1. Total length of dikes on the north and south sides is 168m, including 72m for north dike with a 27° angle for the axis of basement, 18m for south dike with a 35° angle for the axis, and 78m for the dike parallel to axis. As dikes coming out of the water, top elevations of dikes are all above high tide level. E33 pipe joint is a sunk pipe which is close to the head of east artificial island. In line with the methods of flattening gravel in basement, E33 joint base can be divided into three parts: dry work area (area A), artificial work area (area B) and ship working area (area C). Flattening the gravel in area A is done by dry work and that in area B is finished
artificially, and in area C flattening ship flattens stone. The velocity of area A and area B can not exceed 0.5 m/s during construction and that of area C can not exceed 0.8 m/s, which are the allowable maximum velocities set in each zone of E33 pipe joint base and important technical indexes to judge the optimal scheme for sheltering diversion dike. Calculated hydrological condition of model is measured spring tide process in October 2015. And ebb tidal range of the basement is 1.83 m which belongs to monthly maximum tidal range.

3. Mathematical Model of Local 3D Flow in Foundation Trench Waters

In the Cartesian coordinate system, a simplified Reynold time-averaged water flow equation can be obtained according to the static pressure assumption, which is expressed as follows:

Continuity equation,

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]  

(1)

Momentum equation in direction \( x \),

\[ \frac{Du}{Dt} = -f v - \frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \left( K_s \frac{\partial u}{\partial z} \right) + \frac{\partial}{\partial y} \left( K_s \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_s \frac{\partial u}{\partial z} \right) \]

(2)

Momentum equation in direction \( y \),

\[ \frac{Dv}{Dt} = -f u - \frac{1}{\rho} \frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \left( K_s \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_s \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_s \frac{\partial v}{\partial z} \right) \]

(3)

The continuity equation is integrated in the water depth and the water level evolution equation can be get from the free surface and bottom boundary.

\[ \frac{\partial \eta}{\partial t} + \int_{\eta}^{\eta} u \, dz + \int_{\eta}^{\eta} v \, dz = 0 \]

(4)

Where: \( \frac{1}{\rho} \) is the reciprocal of the fluid particle; \( g \) is the acceleration of gravity; \( u(x, y, z, t), v(x, y, z, t), w(x, y, z, t) \) are the average flow velocities of the water flow in the horizontal direction \( x, y \) and the vertical direction \( z \) respectively; the Coriolis force coefficient \( f \) is assumed to be a constant; \( K_s, K_t \) are eddy viscosities in the horizontal and vertical directions.

Figure 2. Flood tide pattern in sinking base at present.

(a) at present

(b) at cover measures
4. Velocity Distribution in the Surface Layer of Base
Figures 2 shows the distribution of velocity and flow pattern in water surface layer of E33 pipe joint base area under present condition. In this area, under the shelter of steel cylinder at the head of island and berm on the north and south sides of basement, there is clockwise circulation during flood tide, when main current flows from south to north across E33 pipe joint base from the central and western part of the base. The average velocity in area A is 0.10 m/s (Table 1), and that in area B is 0.59 m/s where velocity decreases from west to east. In area C, the average velocity is 0.76 m/s and the velocity everywhere is relatively uniform. Generally, average velocity of whole area is 0.86 m/s. Under the present condition, part of surface velocity of E33 pipe joint base water is more than 1.0 m/s. And it can not completely meet the requirement of flow condition during installing pipe joint. The velocity distribution in the scheme about double diversion dikes construction is shown in picture. The main current of flood tide which is affected by ski-jump flow in south dike, flows across E32 pipe joint base from south to north, while in E33 pipe joint base circulation flows in a clockwise direction. The center of circulation is located in the northeast of area C where average velocity is 0.53 m/s. Meanwhile, the average velocity of flow in area B is 0.28 m/s and that in area A is 0.13 m/s. With the influence from ski-jump flow in north dike, the main current flows obliquely west-southwest across E31 pipe joint base from south to north. The base of E33 pipe joint is sheltered totally and average velocities in area A, area B and area C are all less than 0.2 m/s. It means the distribution of velocity in the area can meet the requirement of flow condition of pipe joint installation during flood and ebb tide after carrying out sheltering scheme.

Table 1. Mean velocity statistics of different area in E33 pipe

| area | ebb tide period/(m/s) | flood tide period/(m/s) |
|------|-----------------------|------------------------|
|      | current condition     | sheltering measure     | current condition | sheltering measure |
| A    | 0.10                  | 0.13                   | 0.09              | 0.13               |
| B    | 0.59                  | 0.28                   | 0.25              | 0.16               |
| C    | 0.76                  | 0.53                   | 0.86              | 0.20               |

5. Vertical Velocity Distribution in Base
The velocity distribution is shown in figs.4 along longitudinal section of basement after implementing double-drainage sloping scheme. At flood peak, the circulation flowing in an anticlockwise direction appears in the base at the junction of area B and area C of E33 pipe section near south dike. Maximum velocity of surface water is close to 0.6 m/s, and that of most area in basement center is about 0.1 m/s. During ebb tide, the velocity in the area outside dike reaches 1.0 m/s, but inside base the velocity is generally small, below 0.3 m/s. In the longitudinal section of junction of E33 and E32, the velocity distribution is characterized by "big at both ends and small in middle". The velocity of flow outside base generally exceeds 1.0 m/s while that of flow inside base is relatively small. When current spanning berm on both sides of base, the flow velocity increases and then decreases sharply after entering base, and the difference between the velocity of surface layer and that of bottom layer is not obvious. The velocity at flood peak is larger than that at ebb peak, which is related to ski-jump flow in south dike. At the base, current velocity at flood peak is generally not more than 0.8 m/s and that at ebb peak is generally not more than 0.5 m/s. According to the velocity distribution at the base, velocity in area B and area C are less than 0.5 m/s and 0.8 m/s respectively. Therefore, velocity in everywhere can reach the flow conditions for E33 pipe joint installation.

At flood peak, the velocity in the longitudinal section of junction of E33 and E32 near the berm on both sides of base can reach 1.0 m/s. there are two reasons. One is that section is in the area where can be influence by ski-jump flow in south dike. The other is that the flow is compressed and velocity in local area will increase when it crosses berm on both sides of basement. Velocity variation should be paid attention to in the water around the west end of the E33 pipe section during installation of E33 pipe section. In this model, the water regime appears with maximum tidal range of the month which is also the most adverse water regime. Therefore, for safety it is more appropriate to choose neap tide period, when dynamic of tidal current is weak, as the time for E33 pipe section sinking and installation.
6. Summary

The model test demonstrates that the current in the sea area where east artificial island is located shows the characteristics of "flowing in NE direction during flood tide and in SW direction during ebb tide", which is influenced by underwater topography and boundary near shore. With the influence from ski-jump flow at island-head, flood tide flows in N direction in the base at the junction of island and tunnel. In line with the characteristics of water flow in the area, the scheme of constructing the "asymmetric" type double-drainage sloping for sheltering were formulated. And the hydrodynamic simulation of the shelter scheme is carried out with 3D flow model in base local area. The simulation results show that under the sheltering of two-side diversion dikes the velocity of flow in base decreases greatly. The maximum velocity in artificial flattening section of E33 pipe joint base is less than 0.5 m/s, and that in the construction section flattened by flattening ship does not exceed 0.8 m/s. Thus, the velocity of each area can achieve the requirement of flow condition during installing E33 pipe joint. In the water near junction section of E33 and E32 velocity still can reach 1.0 m/s. So for safety, the period of neap tide is suitable for E33 pipe joint sinking and installation when the tidal current is weak.

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