3D Numerical Simulation of Sea-cross Bridge Pier Wave Current Force Considering Local Scour Effect

Chen Taoxiao¹,² *, Hu Jinchun¹,², Chen Gang¹,², Dong Weiliang¹,², Yue Shubo¹,²

¹ Zhejiang Institute of Hydraulics & Estuary (Zhejiang Institute of Marine Planning and Design), Hangzhou 310020, Zhejiang, China
² Key Laboratory of Estuarine and Coastal of Zhejiang Province, Hangzhou 310020, Zhejiang, China

*Corresponding author’s e-mail: chentaoxiao2968@dingtalk.com

Abstract. The combined force of wave and current is the key load to the foundation of the sea-cross bridge, which is directly related to the design scale. Local scour pits are quickly formed after the piers enter the water, so the influence of local scour pits on the wave current force should be taken into account. Typical bridge pier structure is selected as the research object by the project of Yushan Bridge. Physical model test was applied to research the wave current force on the current terrain. Through the application of Fluent-3D, the mathematical model was established, and the model was verified by the test results. By using the 3D mathematical model, the wave current force considering the bridge pier local scour was calculated to provide technical support for the design of the bridge.

1. Introduction
With the rapid development of economic construction, more and more sea-cross Bridges have been built in recent years. The piers of the bridge are influenced by the interaction of waves and currents, and the wave force of the pier becomes one of the important conditions for the reasonable and safe design of the sea-crossing bridge. The wave current force of the bridge pier is not only affected by the wave current and ocean current dynamics, but also closely related to the water depth. The pier foundation of the sea-crossing bridge is large in size, strong in hydrodynamic force, local scour pit depth and influence range are often large. With the formation of local scour pits, the water depth around the pier increases, and the current force will reach more than 50% of the wave force [1].

There are three mainly means to study the pier wave current force. One is the empirical formula based on Morison equation recommended by The Hydrologic Code for Ports and Waterways JTS145-2015 [2]; another is by physical model test research; in addition, the mathematical model is established to calculate the wave current force. The wave force of the pier calculated by the formula is divided into three parts: the superstructure, the cap and the pile foundation. For the small-scale pile foundation, the calculation method is based on the extended Morison equation. In the early 1990s, Based on Morison equation and linear wave theory, Li Yucheng et al. analysed the distribution law of wave current force on vertical pile, series double pile, parallel double pile and small-scale cylinder under the condition of wave and water co-existence [3-6]. Yu Jinxiu et al. Through the test method, studied the wave force of double pile columns, three pile column, it is concluded that coefficient of pile group with KC number and relative pile according to the changing rule of the [7,8]. For the calculation of large
scale piers (such as piers and piers) and pile group wave current forces, physical model tests and mathematical models are mostly used, such as the research on the piers of Donghai Bridge, Hangzhou Bay Bridge, Yueqing Bay Bridge, Pingtan Strait Highway Bridge [9-12]. Nie Feng [13] et al., by establishing a mathematical model, applied boundary element method to solve the wave load of large-scale columns. In the foundation design of the HZMB bridge, Sun Tianting [14] et al., by revising the parameters such as velocity, CD and CM in the calculation model, proposed a calculation method for the wave current force of pile foundation considering the local scour shape. It can be seen that it is necessary to fully consider the influence of local scour pits on the wave current force of bridge piers in practical engineering application.

In this paper, the typical pier structure of Yushan Bridge was selected as the research object. And the three-dimensional wave and current mathematical models were established by FLUENT 3D, combined with the experimental results of physical model, the calculation of the pier wave-current force considering the scour pit was carried out to study, which provided technical support for the design of the bridge.

2. Project summary

Yushan bridge project of Daishan county is located in Zhoushan islands New District of Zhejiang province, connecting Daishan island and Yushan island, the line direction is S shape, the whole line length is 8.947km, among which the length of the super large bridge at sea is 8080m. The bridge consists of the main bridge and the approach bridge. The piers include the main span of 260m the main pier, 180m-140m auxiliary pier, and 70m transition pier (See Table 1). In this paper, the main pier of the main span is selected as the research object. The structure of the main pier is shown in Figure 1.

| Table1. Size of Yushan Bridge main pier |
|----------------------------------------|
| Structure       | Pile Diameter (cm) (with the sleeve) | Number | Cap Size (m) |
| Main Pier       | 400                                      | 3 rows 10 roots | 22.60*31.10 |
| Auxiliary Pier  | 400                                      | 3 rows 7 roots  | 20.60*25.60 |
| Transition Pier | 400                                      | 2 rows 4 roots  | 14.60*16.60 |

Figure 1 Main span 260m main pier structure

According to hydrological calculation, the high water level in the project area is 3.60m once in 100 years, and the average water level is 0.23m. The tidal type is regular semi-diurnal tide, with flood current velocity of 3.58m/s and ebb current velocity of 3.64m/s in 100 years return period. The waves are mainly caused by wind.

According to the local scour test results, after the pier enters the water, h-shaped local scour pits are formed under the action of the tidal current. The maximum scour depth is 20.6m and the elevation is scour to -39.3m. The water depth nearly doubled. The width of the scour pit is about 2-3 times of the width of the pier, and a certain length scour groove is formed in the upstream and downstream of
both sides of the pier. Actually after the bridge pier is installed into the water, the scour can reach the maximum in about 2 ~ 3 days, and gradually approaches dynamic equilibrium state.

Therefore, after the formation of local scour pits, the influence of the change of water depth on the wave current force of the bridge piers cannot be ignored. However, due to the limitation of conditions, it is difficult to fully simulate the wave current force of bridge piers under local scour conditions in model tests. In this paper, three-dimensional numerical simulation is used to calculate the wave force of bridge piers after scour pits.

3. The research methods

3.1. Introduction to 3d mathematical model

Based on the theory of viscous fluid mechanics, the computational fluid mechanics software Fluent-3D was used to simulate the stress of the pier under the combined action of the wave current.

3.1.1. Governing equation

The governing equation for solving the hydrodynamic field around the pier structure is the Reynolds average Navier-Stokes equation of non-static pressure:

Continuity equation:
\[
\frac{\partial u_i}{\partial x_i} = 0 \quad (1)
\]

Momentum equation:
\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( 2\nu S_{ij} - u'_i u'_j \right) \quad (2)
\]

In the formula, \(u_i\) is the fluid velocity; \(\rho\) is the density of the fluid; \(\nu\) is the fluid viscosity coefficient; \(p\) is the pressure; \(\nu\) is the kinematic viscosity coefficient of the fluid; \(S_{ij}\) is the average strain rate tensor; \(u'_i\) is speed fluctuation values; \(u'_i u'_j\) is the Reynolds stress tensor.

3.1.2. Wave current boundary structure method

Use the boundary wave-making method, stacking current velocity to couple the wave and current. According to the characteristics of incident waves, appropriate wave theory is selected to determine the expressions of wave field velocity and wave height. Based on the second order Stokes wave theory, the formulas of horizontal wave and current velocity, vertical velocity and water surface fluctuation are as follows:

\[
u = u_0 + \frac{A \omega \cosh(kz) \cos(-\omega t)}{2 \sinh(kh)} + \frac{3kA^2 \omega \cosh(-2\omega t)}{16 \sinh^4(kh)} \quad (3)
\]

\[
\omega = \frac{A \omega \sinh(kz) \sin(-\omega t)}{2 \sinh(kh)} + \frac{3kA^2 \omega \sinh(2kz) \sin(-2\omega t)}{16 \sinh^4(kh)} \quad (4)
\]

\[
\eta = h + \frac{A}{2} \cos(-\omega t) + \frac{kA^2 \omega \cosh(kh)[2 \cosh(2kh)] \cos(-2\omega t)}{16 \sinh^3(kh)} \quad (5)
\]

In the formula, \(u_0\) is the constant current velocity, \(A,k,h,T\) are wave height, wave number, static water depth and period respectively, \(\omega = 2 \pi / T\). The above formula is written by the FLUENT UDF.

3.1.3. Wave elimination method

In the numerical wave flume, in a certain area by adding momentum equation of damping source term make wave attenuation in the damping layer, so as to eliminate the influence of reflected wave. The damping layer is arranged near the downstream outlet, and the length of the damping layer is about 3 ~ 3.5 times of the wavelength. The damping source term and attenuation coefficient in the vertical momentum equation of damping layer are respectively taken as follows:

\[
S_l = \rho D_e (u_l - u_0) \quad (6)
\]

\[
D_e(x) = 1.8 \sqrt{g/\eta} \left( \frac{x-x_0}{L} \right)^2 \quad x_0 \leq x_L \leq x_0 + L \quad (7)
\]
In the formula, $x_0$ is the starting point of damping layer abscissa, $L$ is the length of damping layer, $x_L$ is the abscissa of any point in the damping layer.

### 3.1.4. Modeling

The mathematical model calculation diagram of the main pier is shown in FIG. 2 ~ FIG. 4.

![Structural type of the main pier](image)

Figure 2 Structural type of the main pier

![Computational grid](image)

Figure 3 Computational grid

![Pier model calculation (including scour pit)](image)

Figure 4 Pier model calculation (including scour pit)

### 3.2. Model Validation

Based on the test results of bridge pier wave current force under the current terrain, the parameters of the 3D mathematical model were calibrated and verified to ensure the reliability and accuracy of the model calculation results. Then, with the validated model, the calculation of the pier wave force considering the scour pit is carried out.

#### 3.2.1. Wave current force tests

Due to the limitation of site size and simulation, the wave current force test is mainly based on the stress test of bridge pier under current terrain. The hydrologic conditions in the test were mainly
considered as in 100 years return period: the design high water level was 3.6m, and the current velocity was 3.64m/s.

Test in the downstream direction of the hydrological conditions, the deformation and reduction of wave under the action of current are not considered. At the same time superimpose the corresponding design current velocity in 100 years return period. First, the current velocity is calibrated without wave, and then the wave is calibrated under the calibrated current condition. The experiment was carried out in a wide flume of wave current in Zhejiang Institute of Hydraulics and Estuary, The flume is 50m long, 7m wide and 1.2m high. Model ruler =50, In line with The Wave Model Test Regulations (JTJ/T 234-2001) [15].

Table 2 shows the results of the physical model test of wave-current force on the main pier on the current terrain in 100 years return period design condition. The maximum horizontal forces of the main pier's cap and pile foundation are 6768.5kN and 4393.7kN respectively, the buoyancy force of the cap is 4616.1kN, and the maximum horizontal force of the single pile is 507.4kN.

| Structure   | Wave current Force | Water Level (m) | Test Results (kN) | 3-D Numerical Simulation Results (kN) | Error (%) |
|-------------|--------------------|-----------------|--------------------|--------------------------------------|-----------|
| Main Pile Cap | Horizontal Force (kN) | 3.6             | 6768.5             | 7475.0                               | 10.4      |
|             | Buoyancy Force (kN)  |                 | 4616.1             | 4567.0                               | 1.1       |
|             | Piles Maximum (kN)   |                 | 4393.7             | 4591.0                               | 4.5       |
| Main Pile Foundation | Single Pile maximum (kN) |     | 507.4             | 516.0                               | 1.7       |

3.2.2. Analysis of model validation results
In 100 years return period design condition, the 3D-mathematical model is verified by the test results of the main pier on the current terrain, listed in Table 3. It can be seen from the table that the numerical simulation results of the buoyancy force of the main pier cap, the maximum force of pile foundation and single pile are consistent with the test results, the relative error of pile foundation is less than 5%, and the maximum error of cap is about 10%. The results show that the parameters of the mathematical model are reasonable and the calculation method is reliable, which can be applied to the calculate the wave current force of the bridge pier.

4. The results application
The validated 3D mathematical model is applied to the wave force calculation of the main pier area of Yushan Bridge, and the influence of local scour pits is considered. Table 4 is the summary of the total horizontal force of wave current in the main pier area of Yushan Bridge. The results are divided into two columns, the left one is the total horizontal force of piers under current terrain which is provided by physical model test. The other is the total horizontal force of bridge piers considering the influence of local scour pits by 3-D mathematical model FLUENT -3D.

It can be seen from Table 4 and Figure 5 that under the design condition in 100 years return period, the total horizontal forces of main piers, auxiliary piers and transition piers in the main pier area all increase when considering the local scour pits. This indicates that the increase of water depth caused by local scour of piers has a certain influence on the wave current force. The increase amplitude is
proportional to the size of the pier. The larger the pier, the greater the scour depth and the greater the amplitude of force. In the calculation, the total horizontal force of the Yushan bridge pier increases by 6.3%-16.3% after considering the effect of local scour pits. Therefore, from the perspective of engineering design and safety, the influence of local scour pits should be considered in the wave current action of bridge piers, so as to make the research and design results more practical and safer.

Table 4. List of total horizontal forces of wave flow for each bridge pier (cap + pile foundation)

| Structure   | Direction | Condition     | Current Terrain | Local Scour Considered | Amplitude (%) |
|-------------|-----------|---------------|-----------------|------------------------|--------------|
| Main Pier   | Cross-bridge | 100 years Return Period | 11162.2 | 12612.1 | 13.0 |
|             | Along-bridge | 100 years Return Period | 9352.1 | 10881.1 | 16.3 |
| Auxiliary Pier | Cross-bridge | 100 years Return Period | 9474.6 | 10377.2 | 9.5 |
|             | Along-bridge | 100 years Return Period | 8123.8 | 8869.7 | 9.2 |
| Transition Pier | Cross-bridge | 100 years Return Period | 6986.3 | 7429.9 | 6.3 |
|             | Along-bridge | 100 years Return Period | 5562.2 | 5928.8 | 6.6 |

Figure 5 The comparison between the current terrain and the consideration of local scour

5. Conclusion
In this paper, Yushan Bridge project is taken as an example. Based on the model test, Fluent-3D mathematical model is applied to study the wave and current force of bridge piers by considering the influence of local scour pits. The conclusions are as follows:

(1) After the piers of a cross-sea bridge enter the water, local scour pits are formed in the nearby riverbed rapidly. With the increase of the water depth around the piers, the wave current force on the pier pile foundation also changes accordingly. It is necessary to fully consider the influence of the local scour pits on the wave current force of the bridge piers in the practical engineering wave current force calculation.
(2) The Fluent 3D mathematical model was established, and its parameters were verified through the results of piers wave current force physical model test under the current terrain. The verification results show that the parameters adopted by the three-dimensional mathematical model are basically reasonable, and the calculation method is reliable, which can be used to research on bridge pier wave current force characteristics.

(3) According to the calculation results of 3-D mathematical model, considering the influence of local scour pits, the total horizontal force in the main pier area of Yushan Bridge Pier (Pier + Pile Foundation) increases by 6.3%-16.3%. From the perspective of engineering design and safety, the influence of local scour pits should be taken into account in the wave current force of the pier.

Acknowledgments:
This work was financially supported by Zhejiang Provincial Natural Science Foundation of China under Grant No. LY20E090001; Zhejiang Province Water Resources Department Science and Technology Planning Project (RC1906).

References
[1] Hu Yong, Lei Liping, Yang Jinxian. Study of Wave Force on Foundation of Sea-Crossing Bridges [J]. Journal of Waterway and Harbor, 2012, 33(2):101-105.
[2] JTS145-2015, Port and Waterway Hydrological Code [S].2015.
[3] Li Yucheng, Zhang Fulan. Wave Currents Forces on Vertical Piles [J]. Acta Oceanologica Sinica,1986,8(6):751-761.
[4] Li Yucheng, Wang Fenglong. Wave-Current Forces on Bi-piles in Tandem Array [J]. Journal of Hydrodynamics and Connections, 1992,7(2):141-149.
[5] Li Yucheng, Wang Fenglong, Wang Hongrong. Wave Current Forces on Parallel Double Piles [J]. Acta Oceanologica Sinica, 1992, 14(2):106-121.
[6] Li Yucheng, He Ming. Extreme The Statistical Distribution of Extreme Values of Wave-Current Forces Acting on Slender Circular Cylinder in Irregular Waves [J]. Advances in Water Science, 1993,8(Suppl.):609-616.
[7] Yu Yuxiu, Zhang Ningchuan. Irregular Wave Forces on Array of Bi-Pile [J]. Journal of Dalian Institute of Technology, 1988,27(1):103-112.
[8] Yu Yuxiu, Zhang Ningchuan. Irregular Wave Forces on Three Piles [J]. Port Engineering, 1989,3:1-7.
[9] Lan Yamei, Liu Hua, Huangpu xi, et al. Experimental Studies on Hydrodynamic Loads on Piles and Slab of Donghai Bridge——Part two: Hydrodynamic Forces on Pile Array and Slab in Wave-Current Combinations [J]. Journal of Hydrodynamics, 2005,20(3):332-339.
[10] Lin Guoxiong, Fang Mingshan, Li Yucheng. Research report of wave force model test on bridge foundation of Hangzhou Bay Bridge [R]. Zhejiang: Hangzhou Bay Bridge Engineering Headquarters, 2003.
[11] Zhou Weibin, Xu Zuen, Yu Huixue. Research on Calculation of Wave Forces of Yueqing Bay Bridge Foundation [J]. Technology of Highway and Transport, 2015,8(4):80-86.
[12] Zhang Hu, Liu Qingjun, Wang Dengting. Research on calculation of wave forces acting on the large scale structure [J]. Journal of Waterway and Harbor,2018,39(2):151-156.
[13] Nie Feng, Pan Junning, Wang Xiaoming, etc. A study of wave-current force acting on large scale cylinder structure [J]. Hydro-Science and Engineering, 2013,3:65-70.
[14] Sun Tianting, Wang Shupeng, Pan Junning, etc. Study on wave-current force for pile foundation of sea-crossing bridge considering local scouring [J]. Advances in Water Science,2019,30(6):863-871.
[15] JTJ/T 234-2001, Code for Wave Model Test [S].2002.