Experimental Study on Wave Force on Large-Scale Pier Column Foundation of Sea-Crossing Bridge for Preserving the Marine Environment

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Abstract

Based on the project sea area where the large-scale sea-crossing bridge is located, the marine environment is facing the threat of severe marine environmental issues such as strong typhoons and big waves. In order to resist the impact of the super wave load, the research focuses on a new structure derived from soft computing techniques in a simulated environment. Since the conventional methods cannot be used for handling such an important problem, soft computing techniques can certainly help to provide simulated solutions. These solutions can be exploited in a real-time environment to test their viability. The overall physical model test of the wave with a scale of 1 : 40 is carried out in this research study by using the proposed methodology. By setting a series of groups such as different wave height, period, water level (pier foundation scouring depth), and wave-current coupling, it is studied that the wave height and period are in positive proportion to the wave force on the pier column structure. However, there is no obvious relationship with the water level change (scouring depth). The buoyancy of the pile cap structure is about 1.27 times greater than that of the pier structure. Compared with the combined wave force of the single wave and wave current, the sensitivity and the relationship have been studied. Using this study and several engineering results completed in the early stage and also verified by the measured data, the results show that the proposed soft computing technique has good accuracy and can provide a reference for the load estimation of large-scale foundation structures.

1. Introduction

In recent years, with the frequent occurrence of global marine extreme weather, we face severe challenges of severe marine environment such as strong wind, huge waves, and rapids [1]. However, in order to meet the needs of the development of marine resources and higher requirements for marine transportation, the large-scale sea-crossing bridge is changing from theoretical design to reality. Therefore, structural safety must attract the high attention of bridge designers for preserving the marine life [2]. Especially in the face of the long-term contact structure between the lower pier foundation of a large sea-crossing bridge and seawater, it is greatly affected by the environmental load in the ocean such as the impact of horizontal load under hydrodynamic conditions which increases the risk of damage to offshore facilities [3]. There could be many examples of damage to the pier structure of marine engineering due to flaws in the structural designs of the sea bridges [4]. Therefore, in order to ensure the safety of large-scale sea-crossing bridge structures, it is necessary to calculate the load on the large-scale structure accurately to preserve the marine life safely [5]. However, there is no clear formula and method for wave load calculation of large-scale structure in the current design code for sea-crossing bridge pier column foundation structure, the large-scale structure of sea-crossing bridge is subjected to extreme waves and natural disasters [6, 7]. The research on the impact of the combined...
load of water flow has become a concern for many species and sea life [8].

In order to understand the research process of wave force on pier columns in the early stage based on the research results of domestic and foreign scholars on pier column structure [9], this paper is presenting a new approach based on wave force calculation methods of different scales over the years. It can be concluded from the existing literature that, for the wave force of bridge pier column foundation, the commonly used empirical formula is generally based on the ratio of the diameter (D) of bridge pier column foundation to the wavelength (L) of the incident wave [10, 11]. It can be roughly divided into two categories: one is the structure of small-diameter pier column (D/L < 0.2), which adopts Morison formula [12], and the calculation formula is shown as follows:

\[ F = F_I + F_D = C_M \frac{\rho \pi D}{4} \frac{d \eta}{dt} + C_D \frac{\rho D}{2} \eta |\eta|. \]  

(1)

In the above formula, \( F \) is the horizontal wave force acting on the vertical pier column, \( F_I \) is the inertial force on the pier column, \( F_D \) is the resistance on the pier column, D is the diameter of the pier column, \( \rho \) is the time, and when the wave crest passes through the center line of the cylinder, \( t = 0 \).

The second type is the large-diameter pier column which adopts the diffraction theory (also known as potential flow theory) proposed by Maccamy and Fuchs [13] and the calculation formula is shown in the following equations:

\[ F_{x,max} = \frac{2 \rho g H}{k^2} \frac{sh[k(d + \eta_{max})]}{ch(kd)} f_A, \]  

(2)

\[ \eta_{max} = \frac{H}{2} f_A J_1'(\pi D/L), \]  

(3)

\[ f_A = \frac{1}{\sqrt{[J_1'(\pi D/L)]^2 + [Y_1'(\pi D/L)]^2}} \]  

(4)

where \( F_{x,max} \) is the maximum total horizontal force, \( \eta_{max} \) is the maximum crest elevation, \( g \) is the acceleration of gravity, \( H \) is the traveling wave height, \( f_A \) is the coefficient, \( d \) is the water depth, \( k \) is the wave number, indicating the number of fluctuations in the length of \( 2\pi \), \( J_1' \) is the derivative of the Bessel function of the first kind, and \( Y_1' \) is the derivative of the Bessel function of the second kind.

For the first kind of wave force calculation method, the key problem is how to determine and select the two coefficients in the equation, that is, the mass coefficient \( C_M \) points and resistance coefficient \( C_D \). The research results of many scholars show that the coefficients applicable to their respective conditions are derived, the scope of application is narrow, and the calculation results are quite different from each other. For example, in [14], the authors have obtained the coefficient \( (C_D, C_M) \) of smooth cylinder through research which is a function of Reynolds number \( (R_e) \) and dimensionless number \( (K_G) \) related functions. In [15], the authors have obtained the coefficient \( (C_D, C_M) \) under different pile diameters through a large number of physical model experiments. In [16], the authors have obtained the coefficient \( (C_D, C_M) \) by analyzing the wave force generated by the wind on a platform in the Gulf of Mexico, the average values are 1.06 and 0.70, respectively, and the values obtained by the best fitting of peak wave force are 1.70 and 0.70, respectively.

For the second kind of wave force calculation method, it is found that the solution methods are based on the linear wave water diffraction theory to obtain the wave force on the large-scale pier column, and the calculation analytical formula lacks universality. For example, the authors have proposed linear diffracted wave theory which is solved through the coupling of finite element and infinite element [17]. In [18], the author has transformed the water wave diffraction problem into a two-dimensional Helmholtz equation to solve it and then applied relevant methods to solve the two-dimensional Helmholtz equation. The accuracy of the numerical model is proved by comparing the obtained numerical solution with the analytical solution. In [19], the authors have established the finite element numerical model with the second-order stokes wave as the incident wave and the second-order time-domain theory under the guidance of potential flow theory.

In addition, for the calculation method of wave current force on pier column under the combined action of wave and current, the research on the coupling theory of wave and current by scholars at home and abroad has been in the stage of continuous attempt and exploration. Therefore, most scholars only carry out the conservation of mass and momentum. For example, Matsui in 1991 has studied the interaction between waves and vertical circular piers with the introduction of current action by analytical method. In [15], the authors have studied the interaction of wave and weak current on structures by using the frequency-domain high-order boundary element method and obtained the results of first-order force, wave height, added mass, and radiation damping acting on vertical circular piers by numerical simulations. In [20], the authors have studied the influence degree of waves on tidal current and calculated it by using the wave model and current model. In [21], the authors have discussed the different effects of tidal current on waves and each other based on the experimental data and established the coupling between them. In [22], the authors have carried out physical model test research on the effect of wave and current on pier foundation by taking the JIN-Tang sea-crossing bridge as the background and obtaining the relationship between wave and current force under the combined action of the two. In [23], the authors have selected the foundation structure of No. 1 bridge of Yueqing Bay Bridge as the research object and calculated the wave current force on the pile cap and pile group, respectively. The outcome has been demonstrated by the physical model test and it is concluded that the wave current force on the pile cap can be approximately calculated by multiplying the sum of wave force and current force by 1.04.

According to the above research and analysis of wave, current, and wave force on piers, combined with the large sea-crossing bridge demonstrated in this paper, the
2. Proposed Model

2.1. Bridge Foundation Scheme. The bridge foundation is a large-scale pile cap group pile foundation in which the section of the cap is oval, the long axis is 102 m, the short axis is 80 m, the thickness is 8.5 m, the top elevation of the cap is 3.50 m, and the bottom elevation is −5.0 m. The lower part of the bearing platform is composed of 40 single piles, each with a diameter of 0.3 m and a mud surface elevation of −5.74 m, as shown in Figure 2.

2.2. Setting of Test Conditions. According to the objective of experimental research, in order to demonstrate the influence of wave force on large-scale pier structures under different hydrodynamic conditions, a series of groups of wave height (\(H\)), period (\(T\)), water depth (\(d\)), current velocity, and pier foundation scouring depth (\(h\)) (in the test, it can be realized by changing the water depth of foundation area) are set in the test. During the test, the relationship between structural stress and a variable is obtained by fixing one factor and changing other factors. Table 1 shows specific test conditions.

2.3. Design Fabrication and Testing

2.3.1. Model Design and Production. The test uses the normal model which is built using the Froude number similarity rule in accordance with the relevant provisions of the Technical Code for Simulation Tests of Water Transportation Engineering (JTS/T231-2021) [25]. The scale of each simulated physical quantity is as follows: geometric scale, \(L_r = 1: 40\); time scale, \(T_r = L_r^{1/2}\); weight scale, \(M_r = L_r^{3}\); wave current force scale, \(F_r = L_r^2\); pressure scale, \(P_r = L_r\); velocity scale, \(V_r = L_r^{1/2}\). The terrain is copied by the pile point method, which is 1.0 m × pile points shall be arranged at 1.0 m, and the deviation of plane dimension shall be controlled by 1 cm. The elevation of pile points shall be accurately controlled with a level gauge and the deviation shall be within ±1 mm. The plane dimension of the site shall be measured with steel tape.

In the model, the bridge pier, bearing platform, pile foundation, and other foundations are reduced according to the geometric scale of 1: 40, which are made of wood or Plexiglas materials. The structures are simulated according to the rigid structure. The model is arranged in the test harbor basin with a length of 50 m and a width of 50 m. The model is shown in Figure 3.

2.3.2. Instruments and Equipment

(a) Control equipment:

(1) Wave making device: the test harbor basin is equipped with an advanced L-shaped harbor basin absorption multidirectional wave making machine. The wave making capability is as follows: maximum wave making water depth is 1.0 m, wave height is 0–0.5 m, and period is 0.3–5.0 s, allowing for multidirectional wave creation from 0° to 180°. At the same time, wave eliminators are installed around the harbour basin to limit wave sidewall reflection.

(2) In order to generate the required flow conditions in different directions in the test harbor basin, 8 reversible pumps are designed at its end, and the flow velocity and direction are intelligently controlled according to the nature of rising and falling tides at the project location through the independently developed tidal current simulation system.
Figure 1: Bridge location and general layout. (a) Plane layout. (b) Facade layout.

Figure 2: Foundation structure of main bridge (unit: cm). (a) Facade layout. (b) Plane layout.

Table 1: Test conditions for structural stress.

| No. | Value of change factor | Value of fixed factor |
|-----|------------------------|-----------------------|
| 1   | $H = 3.0 \text{ m}, 3.5 \text{ m}, 4.04 \text{ m}, 5.0 \text{ m}$ | $d = 3.684 \text{ m}, T = 7.38 \text{ s}$ |
| 2   | $T = 4.30 \text{ s}, 5.5 \text{ s}, 6.5 \text{ s}, 7.38 \text{ s}, 8.5 \text{ s}$ | $d = 3.684 \text{ m}, H = 4.04 \text{ m}$ |
| 3   | $d = 1.874 \text{ m}, 3.684 \text{ m}, 4.004 \text{ m}$ | $H = 4.04 \text{ m}, T = 7.38 \text{ s}$ |
| 4   | $V = 1.25 \text{ m/s}, 1.34 \text{ m/s}, 1.51 \text{ m/s}$ | $d = 3.684 \text{ m}, H = 4.04 \text{ m}, T = 7.38 \text{ s}$ |
| 5   | $h = 12 \text{ m}, 15 \text{ m}$ | $d = 3.684 \text{ m}, H = 4.04 \text{ m}, T = 7.38 \text{ s}$ |
(b) Measuring equipment:

1. Wave height measuring system adopts TKS2008 wave height acquisition and analysis system independently developed to intelligently analyze the wave surface process and count the wave heights of different frequencies.

2. The velocity measurement system adopts Vectrino Profiler to measure the velocity change results before and after the pier column. The layout of wave height and velocity monitoring points is shown in Figure 3.

3. In the wave force measurement system, the pile group adopts the total force measurement device of underwater balance to monitor the horizontal force, and the bearing platform adopts the self-developed tension pressure sensor measurement device to measure.

2.3.3. Simulation Methods

Wave and Current Simulation. Irregular waves are used in the test. According to the wave characteristics of the sea area of the project, the JONSWAP spectrum is determined as the final spectrum after demonstration according to the relevant wave spectrum provisions of code for hydrology of ports and waterways (JTS145-2015) \(^{(25)} \) (\( \gamma = 3.3 \)). The number of irregular waves simulated each time is more than 120, repeated for 3 times, and the wave height and period error are controlled within \( \pm 2\% \). The flow simulation uses the intelligent control system of power flow to calibrate its size and direction and the error meets the specification requirements. For the coupling simulation, the wave and current are calibrated separately. During the test, the current flow state required by the simulation is controlled in the harbor basin and the previously calibrated waves are superimposed for coupling in this state. At the same time, TKS2008 wave height acquisition instrument and Vectrino Profiler are used to monitor the changes in waves and currents.

Wave and Current Force Measurement. In the test, in order to realize the measurement results of wave, current force on the bearing platform, and pile group, respectively, the bearing platform and pile group adopt an unconsolidated mode in the force measurement process. It reflects the interaction between bearing platform and pile group in the foundation and ensures the synchronous measurement of wave and current force. Therefore, two sets of force measurement devices are used in the model, that is, for the wave and current force of pile groups, the total force measuring device of underwater balance is adopted and the bearing platform adopts the measuring device of combined tension and pressure sensor. The computer collects, processes, and analyzes wave current force measurement sample data automatically. The sampling frequency is 100 Hz and the direction of wave force is defined as horizontal force \( (F_x) \) with the wave incident direction. The positive value of the force is in the same direction as the wave propagation, and the opposite is negative. The direction of the buoyancy force \( (F_B) \) is perpendicular to the direction of incident waves, and the upward direction is positive and vice versa.

3. Test Results and Analysis

3.1. Relationship between Influencing Factors and Variation of Wave Force. It can be seen from the test that the wave phenomenon around the large-diameter pier column is as follows: affected by the water resistance and reflection of the upper large-scale bearing platform, there is an obvious superposition of incoming and inverse waves in the wave facing measurement of the bearing platform, so the wave energy concentration and wave height increase are formed at this position. At the same time, because the cushion cap is elliptical and the top elevation is basically flush with the static water level, the cushion cap divides the incident wave into two parts. One part of the wave directly crosses the cushion cap, and the other wave diffracts through both sides of the cushion cap and overlaps again on its back wave side to form waves similar to horseshoe shape, resulting in phase
difference between the waves before and after the cushion cap. In general, the crest height on the upstream side of the cushion cap is higher than that on the backside as shown in Figure 4, which eventually leads to the risk of the backward overturning of the pier foundation.

Using the test data, the time history curves of wave current force of pile cap and pile group foundation are measured as shown in Figure 5. It can be seen that the pile cap structure is in the range of one-time wave height near the still water level. In the process of series wave action, the long-time series is subjected to great wave current impact force; the pile group structure under the bearing platform is affected by the submerged water depth, and the wave and current force generated by the wavelet are further weakened in the process of series of wave action. Therefore, the size distribution of wave and current force duration curve has obvious periodicity; that is, the bridge foundation is affected by the dynamic response of wave and current, and the upper bearing platform structure is greater than the pile group.

The variation of wave current force on bearing platform and pile group foundation with various factors is shown in Figure 6. It can be seen from the figure that the bearing platform shows different regularity with hydrodynamic factors due to the influence of the size and elliptical shape of the structure itself. The other observations are as follows: (1) Between the wave height and period, the amplitude of horizontal force and buoyancy force on the structure is in positive proportion. When the trough action is slightly greater than the peak action, the former is 1.09 times as much as the latter, and the maximum value is 11132.7 kN. The change law of the two is the same; only the former is more sensitive to the change of slope. (2) The water level, scouring depth, the horizontal force, and buoyancy force of the structure increase slightly with the increase of water level but the change range must be small. The main reason is that the change of water level is still inconsiderable as compared to the size of the bearing platform. (3) The buoyancy force of the structure is greater than the horizontal force. According to statistics, the former is 1.27 times that of the latter, and the maximum value is 14198.1 kN.

For the pile group, the following rules are shown:

(a) The variation law of force between wave height and period is the same as that of pile cap structure but the sensitivity between force and various factors is greater than that of the former

(b) For the water level and scouring depth, the variation law is basically the same as that of the cushion cap structure
Figure 6: Variation of wave force on foundation varies $T^*H/D$ and wave current coupling. (a) Influence of wave height change. (b) Influence of wave period change. (c) Influence of scour depth on pier foundation. (d) Influence of wave current coupling variation.
Comparing the combined action of a single wave and wave and velocity, the comparison of structural stress results is shown in Figure 7 which is obtained under the following conditions:

1. Under the condition of wave in the same direction, with the increase of current velocity, the structural stress gradually increases.
2. When the superimposed maximum velocity \( V = 1.51 \text{ m/s} \), compared with single wave, the stress of bearing platform and pile group increased by 17.3\% and 21.5\%, reaching 13702.9 kN and 10035.9 kN, respectively. It can be seen that when the wave height is affected by the water flow, the change sensitivity of force is more obvious (see Figures 6(a) and 6(d)).

3.2. Engineering Application Analysis of Wave Force of Pier Column Structure. Based on the bridge foundation of the special structure of large-scale pile group piles, the results are analyzed. In order to facilitate the application of structural stress test results to engineering design combined with the research results on the stress of the bridge at the junction of island and bridge of Hong Kong-Zhuhai-Macau and Shenzhen-Zhongshan Channel island, the analysis of the calculation formula of wave and current force is analyzed. The variation relationship between structural wave force and various influencing factors is established. The corresponding empirical formula is derived to provide basic data and reference for similar engineering design.

3.2.1. Calculation Method of Wave Force of Pile Group. According to the relevant provisions in section 10.3.1 of the current code for the hydrology of ports and waterways (JTS145-2015) [30], the pier column is subjected to a horizontal force \( F_{X_{\text{max}}} \) under wave action and can be decomposed into velocity component \( (F_{D_{\text{max}}}) \) and inertia component \( (F_{I_{\text{max}}}) \) as shown in equation (1). Therefore, for the wave calculation method of bridge foundation pile group this time, equation (1) is used. At the same time, in order to reflect the influence of pile group on horizontal force, the comprehensive influence coefficient \( (K_1) \) is introduced, which is considering the influence of water flow on wave height, and, after considering the combined action of wave and current, the wave and current coupling influence coefficient \( (K_2) \) is introduced again. After transforming equation (1), the wave horizontal force \( F_X \) of pile group under combined action of water flow calculation method is shown in the following equation:

\[
F_X = K_1 \cdot K_2 \cdot I(F_{D_{\text{max}}}, F_{I_{\text{max}}}),
\]

(5)

where \( F_X \) is the horizontal force on the pile group; \( K_1 \) is the influence coefficient of pile group; \( K_2 \) is the influence coefficient of wave current combined action, and other letters have the same meaning as above.

In order to obtain the coefficient \( (K_1, K_2) \) in equation (5), firstly, the results of wave force under single wave conditions are obtained by using the test, and then the results of wave force on pile groups are obtained by considering the conditions of superposition of pile groups and wave current combination, respectively. The results under different conditions are compared to obtain the influence coefficient \( (K_1, K_2) \) in equation (5). See Table 2 for details. The following can be seen from the results in the table: (1) The larger the ratio of pile group spacing to wavelength, the smaller the interference by piles. (2) In the same direction, the wave height decreases by about 20\%, and, in the reverse direction, the wave height increases.

In order to solve the relationship between the wave force on the structure and the influencing factors, the function expression is established. Firstly, according to the above series of test results, among the influencing factors, wave height, period, and pier diameter are the most sensitive to wave force. Therefore, the variation process between wave force \( f(F_{D_{\text{max}}}, F_{I_{\text{max}}}) \) and \( (T^*H)/D \) factor is established as
shown in Figure 8(a). It can be seen from the figure that the force is in positive proportion to \( \frac{TH}{D} \) fitting the test data to obtain the calculation formulas under the conditions of peak and trough, respectively. It is found by comparing the peak and trough calculation formulas obtained by fitting, and, combined with the experimental research results, the difference of the maximum wave force between pile groups at the peak and trough is about 1.1 times. Therefore, in order to facilitate the application of the formula, the two fitting calculation formulas are combined to obtain (6), which is the final calculation formula of wave force on pile groups.

\[
F_X = 1.10 \left( K_1^* K_2^* 7350 \ln \left( \frac{TH}{D} \right) - 5811 \right). \quad (6)
\]

### Table 2: Value of coefficient (\( K_1, K_2, \) and \( K_3 \)).

| Arrangement direction of pier column | \( L/D \) |
|--------------------------------------|-----------|
| Vertical wave direction of pile row  | 2.0 3.0 4.0 5.0 |
| Parallel wave direction of pile row  | 1.0 1.0 1.0 1.0 |

#### 3.2.2. Calculation Method of Wave Force on Bearing Platform.

The wave force of large-scale bearing platform under the action of wave and current is subjected to horizontal force and buoyancy force, respectively. The horizontal force can be calculated by (6); at this time coefficient \( K_1 \) is directly taken as 1.45, while coefficient \( K_2 \) can be obtained as shown in Table 2 and values are taken under different conditions.

For buoyancy force \( F_U \) calculation in section 8.5.1 of the current code for hydrology of ports and waterways (JTS145-2015), the calculation formula for the buoyancy force at the bottom of the slab of high column wharf is given in the three following equations:

\[
F_U = \left[ 0.85 + 0.35 \frac{th \left( \frac{L}{2B} - 2 \right)}{} \right]
\]

\[
\times \left( \frac{\Delta h}{C \eta} \right)^{0.3} - 0.9 \left( \frac{\Delta h}{C \eta} \right)^{0.75},
\]

\[
x = \frac{L}{\pi} \arccos \left( \frac{\Delta h}{C \eta} \right),
\]

\[
\eta = 0.5H + \frac{\pi H^2}{2L} \left( ch2\eta d/L \right) \left( ch4\eta d/L + 2 \right) \times \frac{4 \left( sh2\eta d/L \right)^5}{4 \left( sh2\eta d/L \right)^5},
\]

where \( F_U \) is the maximum buoyancy force; \( x \) is the wave action width at the bottom; \( \Delta h \) is the height of the bottom above the still water surface; \( C \) is wave reflection influence coefficient; \( \Delta h \) is the height of wave crest at still water level; \( B \) is the bottom width; \( \gamma \) is the gravity of water. The meanings of letters in other formulas are the same as above.

Since the section of bridge foundation bearing platform is generally not circular or square and the structure often shows a single type which is different from the panel connection form of wharf structure. In the case of wave action, the main differences are as follows: (1) The impact area of wave crest surface is different. (2) The reflection of the two structures is different. (3) The cushion cap is generally located under the water, and the flow force is also generated when it is impacted by waves. Therefore, based on the above analysis, there are obvious differences between the two stress
modes. If equation (7) is used to calculate the wave force of a large-diameter cylinder, there will be a large deviation. In addition, according to the calculation method of the second type of large-scale pier column, the calculation formula of buoyancy force is not given.

In order to solve the calculation method of the uplift force of pile cap, the same idea as horizontal force which is still adopted to establish between wave force \( F_{UC} \) and \( (T^* H)/D \) is shown in Figure 8(b). Similarly, the coupling influence coefficient \( K_2 \) of wave and current and the shape influence coefficient \( K_3 \) are introduced. The coefficient values are shown in Table 2. The calculation formula fitted at the time of wave crest and wave trough is combined to obtain the formula shown in equation (10), which is the final calculation formula of an uplift force of the bearing platform.

\[
F_{UC} = 1.25^* K_2^* K_3^* \left[ 7514 + \ln \left( \frac{T^* H}{D} \right) - 8460 \right] .
\]  

(10)

In order to verify the accuracy of the newly proposed wave force calculation in (6) and (10) of pier column structure, it is necessary to check through the calculation of specific engineering examples. Therefore, the wave force test result of the pier column foundation of Hong Kong-Zhuhai-Macau Bridge is used for verification. The research results have been reviewed by industry experts. The wave force results of bearing platform and pile group of Hong Kong-Zhuhai-Macau are calculated by using (6) and (10). The test values and calculation comparison results are shown in Figure 9. The oblique line in the figure is a 45° ideal line. Through comparison, it can be seen that the calculated value of horizontal force is greater than the test value shown in Figure 9(a). The main reasons are the great influence of pile groups and the breaking of waves on the structure; the buoyancy force shown in Figure 9(b) is distributed near the ideal line, and the correlation between them is more than 0.90. Generally, the theoretical calculation results can better reflect the measured results.

3.2.3. Discussion. The interaction of pier column structure in marine environment is a very complex problem. It involves the knowledge fields of fluid mechanics, wave theory, and fluid structure coupling theory, as well as structural dynamics. It is a typical interdisciplinary comprehensive problem. In this paper, a series of group studies are carried out on the pile group structure with large-diameter bearing platform such as different wave height, period, water level, and wave current coupling. The variation law between force and various factors is obtained, and a new calculation method for the structure is proposed. The following aspects need to be further studied in the follow-up: (1) The pier foundation in the ocean may be affected by external loads such as hurricanes in addition to wave and current loads. (2) The research object of this paper is isolated pier. In practical engineering, the structural form of double row pier or even group pier may appear; therefore, for major projects, carrying out experimental research again for verification is recommended.

4. Conclusion

This paper is based on the study of the engineering sea area where the large-scale sea-crossing bridge is located to safeguard the marine environment. Facing the threat of severe marine environments such as strong typhoons and big waves, the study needs some methods to investigate the impact of typhoons and high tides on the bridges and marine life. In order to resist the impact of the above super wave load, the foundation adopts the pile group structure of a large-diameter bearing platform; that is, the diameter \( D \) and wavelength \( L \) of pier column are greater than 1.50. The influencing factors such as wave height, wave period, water level, scouring depth, and wave current coupling and the variation of stress are studied. The stress results are directly proportional to the wave height and period, and the effect of wave trough is 1.09 times that of wave peak. Affected by the
size of the bearing platform, the water level changes slightly, and the stress change is not obvious. Compared with a single wave, the stress sensitivity of wave current coupling structure changes greatly, and the average variation range of the latter is about 25%.

In addition, it is convenient for the load calculation and application of similar bridge projects. Using this study and several engineering achievements completed in the early stage, the simple calculation formulas for the horizontal force and buoyancy force of the pier column structure are proposed, which are verified by the measured data of the real project. The results show that the proposed method has good accuracy and the correlation coefficient between the two can reach more than 0.9, which can be served as a reference for load estimation of large-scale foundation structures in the marine area. However, considering the complex factors affecting the bridge pier column structure by wave force, carrying out experimental research again for major projects is recommended.

Data Availability

The data can be made available upon valid request to the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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