Experimental study of the wave load on the main pier of Huangmaohai Bridge under wave-current coupling effect

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Abstract. For the wave-current coupling effect on the main pier of Huangmaohai Bridge, experimental study is conducted to measure the load under wave-only and wave-and-current actions. Parametric studies are carried out to reveal the variation trend of the wave load with wave height and period. With the scouring depth of 12m and under the high-water level and wave height of 300-year return period, the maximum horizontal force F_X on the pile cap is 13686.1kN, the maximum overturning moment M_Y is 260115.5kN·m, while the maximum horizontal force on the pile cluster is 13775.0kN. For the cap and cluster, the load caused by irregular wave is greater than that caused by regular wave. The load increases with increasing wave height and period. Under the wave-current coupling effect, the variation trend of the wave load is similar to that under wave-only conditions. The load on the cap decreases with the increase of scouring depth, due to the wave deformation in shallow water. The load on the pile cluster increases with the increasing scouring depth due to the greater exposure to the fluid environment.

1. Introduction
Huangmaohai cross-sea channel from Zhuhai to Jiangmen is about 25km away from Yamen Bridge in the north, connects Zhuhai Hezhou to Gaolan Port Expressway and Hong Kong-Zhuhai-Macao Bridge in the East, crosses Huangmao Sea area at Yamen in the west, successively crosses the East and West lanes of Yamen sea route, lands at Chixi town of Taishan City, and finally intersects with the Western Coastal Expressway Connecting to Xintai expressway. The water depth of the river crossed over by the bridge is not large, with the value of 2.0m on both sides and more than 5.0 m in the middle. When the channel is completely built, the distance from Macao to Guanghai Bay of Jiangmen will be shortened by 18 km, and that from Zhuhai Gaolan Port Economic Zone to Guanghai Bay of Jiangmen will be shortened by 30 km. The total length of the project is 30.32 km, and the cross-sea section is about 14.35 km. There are two main bridges crossing three channels, four interchanges, one medium tunnel and one long tunnel.

In order to study the wave-current coupling effect on the stability of the pier of the main bridge, the integral model test is conducted under different water levels, extreme wave conditions and scouring depths. The high-water level of 300-year return period combining with the wave height of 300-year return period [1-3] is adopted as the control conditions. The loads and corresponding moments on the superstructure (pile cap and column) and the substructure (pile cluster) are measured and analysed on variation trends. The results of the wave-only and wave-current coupling conditions are compared.
Many researches [4-6] have been conducted on the wave-current coupling effect and hence are as the basis of the present work.

2. Experimental design

2.1. Wave and current generating
The model test is conducted in the tank with the length of 42m and the width of 34.2 m. The moveable wave generator is used to make the required wave. The wave maker is composed of wave making board, servo amplifier, electric cylinder, computer and its peripheral equipment. According to the requirement, the corresponding wave height and period parameters are input, and the corresponding signal is generated by the computer. After D/A conversion, the servo amplifier compares the corresponding feedback signal with the displacement feedback signal, and the deviation signal is sent to the servo valve, so as to control the movement of the electric cylinder and drive the wave plate to generate the desired water wave. The submerged pump is used to pump the water from the pool and inject it into the local jet pipe to spray the water into the test section.

The elevation of the model is controlled by a level and the length is measured with a steel ruler. Wave height sensor is used to collect and analyze wave height through TK-2008 dynamic water level measurement system. The flow velocity was measured by three-dimensional point current meter.

2.2. Model making
The model is designed according to gravity similarity criterion and the structure size is designed according to the geometric similarity criterion. The scale relationship of each physical quantities between the prototype and model is listed in Table 1. The pier of the main bridge is made according to the similarity criteria. Based on the test requirement, the site size and the wave generator capacity, the scale is 50 in this study.

| Quantity        | Code | Scale |
|-----------------|------|-------|
| Length          | L    | \(\lambda\) |
| Height          | h    | \(\lambda\) |
| Wave height     | H    | \(\lambda\) |
| Wave period     | T    | \(\lambda^{1/2}\) |
| Mass            | m    | \(\lambda^3\) |
| Frequency       | f    | \(\lambda^{1+2}\) |
| Force           | F    | \(\lambda^3\) |
| Pressure        | p    | \(\lambda\) |

\(\lambda = l_p/l_m;\ l_p:\) length of prototype; \(l_m:\) length of model

The upper part of the tower column, tower base and bearing platform are made of wood materials, and the lower part of the high piles is made of PVC pipes. The pile cap and pile cluster are not connected and the gap is less than 5 mm. There is rigid connection between the pile cap and the total force instrument. The pile cluster is connected to a wooden plate, which is then connected to the underwater balance. The scouring depth is described by the length of the PVC pipes. The model of the main pier of the bridge is shown in Figure 1.
2.3. Experiment methodology
In this study, regular wave spectrum and irregular wave spectrum are used, and JONSWAP spectrum is used to simulate irregular wave, which is given by

\[
S(f) = \beta H_{1/3}^2 T_P^4 f^{-5} \exp \left(-\frac{5}{4}(T_P f)^2\right) \times \exp\left\{-(f/f_p)^{-2} \right\}
\]

where, \( r \) is the peak factor; \( f_p \) is the peak frequency; \( S(f) \) is the spectral density; \( H_{1/3} \) is the significant wave height; \( f \) is the frequency.

For each group of wave elements, the number of irregular waves is kept at 150 and that of regular is 50. Before the formal test, wavelet is kept for a period of time. The wave action time of the prototype under each water level is simulated according to the technical requirements, so as to observe the change of the structure under the wave accumulation.

The total forces of the wave on the cap and pile cluster are separately measured by the six-component principle, which contains three forces and three moments. The six components are calculated from the total 12 forces in the four corners of the plate, which is illustrated in Figure 2. The total force on the cap is measured by 2010 force instrument and the total force on the pile cluster is obtained by transforming the components from the four balances to the total force and moment. In this work, the horizontal force along the wave direction is defined as \( F_X \), and the corresponding overturning moment is defined as \( M_Y \).

Figure 1. The model of the main pier of the bridge.

Figure 2. The six-component principle adopted in this study.
3. Results and discussions
The experimental cases and the measured load results are listed in Table 2, which shows conditions of different scouring depth, different return period of wave, different return period of water level and conditions with and without current.

| No. | Scouring depth | Return Period | Water Level (m) | Wave height and period (m),(s) | Current (m/s) | Pile cap $F_{\text{max}}$(kN) | $M_{\text{max}}$(kN m) | Pile cluster $F_{\text{max}}$(kN) |
|-----|----------------|---------------|----------------|-------------------------------|--------------|------------------------------|---------------------|--------------------------|
| 1   | 12m            | 300a          | 4.004          | $H_1%=4.54,T_s=7.87^\triangle$ |              | 13686.1                      | 260115.5            | 13775.0                  |
| 2   | 100a           | 3.684         | 3.004          | $H_1%=3.00,T_s=7.38^\ast$    |              | 4765.7                       | 176281.2             | 3748.9                   |
| 3   | 100a           | 3.684         | 3.504          | $H_1%=3.50,T_s=7.38^\ast$    |              | 5123.4                       | 192501.5             | 6788.7                   |
| 4   | 12m            | 300a          | 4.004          | $H_1%=4.04,T_s=7.38^\triangle$ |              | 8726.4                       | 230232.0             | 10862.0                  |
| 5   | 100a           | 3.684         | 4.040          | $H_1%=4.04,T_s=7.38^\ast$    |              | 6361.7                       | 205504.6             | 10429.1                  |
| 6   | 100a           | 3.684         | 5.000          | $H_1%=5.00,T_s=7.38^\ast$    |              | 6979.8                       | 208863.9             | 15243.2                  |
| 7   | 1.874          | 3.684         | 6.824          | $H_1%=3.41,T_s=6.82^\triangle$ |              | 5170.7                       | 143815.9             | 5978.5                   |
| 8   | 300a           | 4.004          | 7.87^\triangle | 0                             |              | 8907.1                       | 233145.2             | 16667.7                  |
| 9   | 100a           | 3.684         | 3.406          | $H_1%=4.04,T_s=7.38^\ast$    |              | 3948.3                       | 138881.6             | 2885.8                   |
| 10  | 100a           | 3.684         | 5.506          | $H_1%=4.04,T_s=7.38^\ast$    |              | 6079.6                       | 184685.3             | 4680.2                   |
| 11  | 15m            | 3.684         | 6.506          | $H_1%=4.04,T_s=6.50^\ast$    |              | 8021.4                       | 206941.2             | 6999.7                   |
| 12  | 100a           | 3.684         | 5.394          | $H_1%=4.04,T_s=7.38^\ast$    |              | 8409.8                       | 232799.9             | 13034.4                  |
| 13  | 100a           | 3.684         | 6.506          | $H_1%=4.04,T_s=7.38^\ast$    |              | 8228.6                       | 222173.4             | 12306.4                  |
| 14  | 100a           | 3.684         | 7.506          | $H_1%=4.04,T_s=8.50^\ast$    |              | 11031.4                      | 235649.4             | 14129.3                  |
| 15  | 1.874          | 3.684         | 6.824          | $H_1%=3.41,T_s=6.82^\triangle$ |              | 3718.4                       | 114257.1             | 7772.0                   |
| 16  | 300a           | 4.004          | 7.87^\triangle | 1.51                          |              | 15593.0                      | 226325.4             | 11159.6                  |
| 17  | 100a           | 3.684         | 3.786          | $H_1%=3.00,T_s=7.38^\ast$    |              | 4129.9                       | 75794.9              | 3999.0                   |
| 18  | 100a           | 3.684         | 5.306          | $H_1%=3.50,T_s=7.38^\ast$    |              | 4823.9                       | 146908.2             | 6335.7                   |
| 19  | 12m            | 300a          | 4.004          | $H_1%=4.04,T_s=7.38^\ast$    |              | 9576.7                       | 195960.8             | 10163.3                  |
| 20  | 12m            | 300a          | 4.004          | $H_1%=4.04,T_s=7.38^\ast$    |              | 7324.8                       | 130705.6             | 9772.0                   |
| 21  | 100a           | 3.684         | 7.386          | $H_1%=5.00,T_s=7.38^\ast$    |              | 8533.7                       | 240670.8             | 15396.6                  |
| 22  | 1.874          | 3.684         | 6.824          | $H_1%=3.41,T_s=6.82^\triangle$ |              | 6028.4                       | 106950.7             | 5959.0                   |
| 23  | 300a           | 4.004          | 7.87^\triangle | 1.29                          |              | 9363.1                       | 215100.8             | 15702.9                  |
| 24  | 300a           | 4.004          | 8.406          | $H_1%=4.04,T_s=8.50^\ast$    |              | 3832.7                       | 34224.6              | 2408.6                   |
| 25  | 15m            | 3.684         | 5.506          | $H_1%=4.04,T_s=5.50^\ast$    |              | 5802.2                       | 152237.0             | 4937.4                   |
| 26  | 100a           | 3.684         | 4.004          | $H_1%=4.04,T_s=6.50^\ast$    |              | 6397.8                       | 170858.1             | 6603.8                   |
| 27  | 15m            | 3.684         | 7.386          | $H_1%=4.04,T_s=7.38^\ast$    |              | 8519.3                       | 168486.4             | 13991.8                  |
| 28  | 100a           | 3.684         | 7.386          | $H_1%=4.04,T_s=7.38^\ast$    |              | 8250.1                       | 152029.4             | 12522.5                  |
| 29  | 100a           | 3.684         | 8.506          | $H_1%=4.04,T_s=8.50^\ast$    |              | 11752.0                      | 237211.4             | 13806.3                  |
| 30  | 1.874          | 3.684         | 6.824          | $H_1%=3.41,T_s=6.82^\triangle$ |              | 3754.9                       | 71411.4              | 7769.8                   |

Note: “DHWL” denotes design high water level; “^” denotes irregular wave; “*” denotes regular wave.

It can be seen from Table 2 that with the scouring depth of 12 m and the wave condition of $H_1%=4.04m$, $T_s=7.38s$, the load caused by irregular wave is greater than that caused by regular wave for both the cap and cluster. This is because the irregular waves are in random wave trains distributed in the spectrum, in which there must be waves whose height and period are greater than the above values. In regular waves, the wave height and period of all waves are almost the same, and the maximum wave pressure generated in the wave train stays almost unchanged.
The wave load in Case 1 is illustrated in Figure 3, which shows the horizontal force on the pile cap with the test duration time. The wave load in Case 5 is demonstrated in Figure 4, which shows the horizontal force process on the cap.

Figure 3. The wave load process in Case 1.

Figure 4. The wave load process in Case 5.

With the condition of $T_S=7.38s$ unchanged, when $H_{1%}$ increases from 3.00m to 5.00m, the wave load on the pile cap and pile cluster increases. Under the wave-current coupling effect, the variation trend of the wave load is similar to that under wave-only conditions. Compared to the wave-only condition, the load under wave-current coupling effect gets bigger in some cases and becomes smaller in other cases.

Then it comes to the scouring depth of 15m. With the condition of $H_{1%}=4.04m$ unchanged, when $T_S$ increases from 4.30s to 8.50s, the wave load on the pile cap and pile cluster increases. Whether for the wave-only or the wave-current coupling conditions, the load on the pile cap is greater under the scouring depth of 12m than under the depth of 15m. This is because there is greater deformation of the waves in the shallower water, which induces greater wave load [7]. When the water depth is bigger, the pile cluster is exposed to the fluid environment with a greater extent, which induces bigger wave load.

4. Conclusions
In this work, experimental study is conducted to measure the load under wave-only and wave-and-current actions, aiming at revealing the wave-current coupling effect on the main pier of Huangmaohai Bridge. Parametric studies are carried out to reveal the variation trend of the wave load with wave height and period. With the scouring depth of 12m and under the high-water level and wave height of 300-year
return period, the maximum horizontal force $F_X$ on the pile cap is 13686.1 kN, the maximum overturning moment $M_Y$ is 260115.5 kN-m, while the maximum horizontal force on the pile cluster is 13775.0 kN. For the cap and cluster, the load caused by irregular wave is greater than that caused by regular wave. The load increases with increasing wave height and period. Under the wave-current coupling effect, the variation trend of the wave load is similar to that under wave-only conditions. The load on the cap decreases with the increase of scouring depth, due to the wave deformation in shallow water. The load on the pile cluster increases with the increasing scouring depth due to the greater exposure to the environment.

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