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WAVE CURRENT FORCES ON THE PILE GROUP OF BASE FOUNDATION FOR THE EAST SEA BRIDGE, CHINA*

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ABSTRACT: On the basis of the two structures of the bridge foundation designed for the East Sea Bridge, the wave current forces on four types of oblique piles, the pile group and the single piles at different positions in the pile group considering the effect of the super structures were experimentally investigated. The relationship between the wave current forces and the associated wave parameters, and the comparison of the wave current forces on the pile groups and the single piles were systematically analyzed. The group effectiveness and the reduction coefficient for the wave current forces on the group were examined for engineering design.

KEY WORDS: base foundation, pile group, wave current forces

1. INTRODUCTION

The East Sea Bridge is one of the most important projects for the Yangshan Deep-Water Port Project of the Shanghai International Shipping Center. Because of severe sea conditions in the engineering area, how to ensure safety in the period of construction of the foundation becomes a critical problem. The foundation consists of pile group and supper structures (see Fig.1) and the main loads on the foundation are the wave current forces. Therefore, how to calculate the wave current forces on the pile groups becomes an important issue for the reasonable design of the base foundation. However, until now, there are no commonly accepted methods for the calculation of wave current forces on the pile group because of its complexity, especially when the effect of supper structures is considered. Generally, the wave current forces on the pile group are calculated by the multiplication of wave current force on single pile with the pile numbers in the group. But the calculated total force is generally larger than the real value because of the phase difference of the waves passing through the different piles in the group and the group effects. A reduction coefficient for the calculation of wave current forces on pile group should be considered in the real design of the base foundation.

For the calculation of wave current forces on single piles, the commonly-used formula is the Morison equation, in which the hydrodynamic coefficients C_D and C_M can be determined by the KC parameter calculated under the wave and current conditions[1,2]. Many references can be found in literature with regard to the investigation of wave or wave current forces on cylinders. Li et al.[3] conducted a series of model tests for wave forces using both regular and irregular waves combined with currents on single piles and bi-piles in tandem and parallel arrays, and the characteristics of the wave forces were investigated. Kang et al.[4] compared various calculation methods of wave current forces on cylinders and a proper method was proposed. Wang et al. [5] investigated

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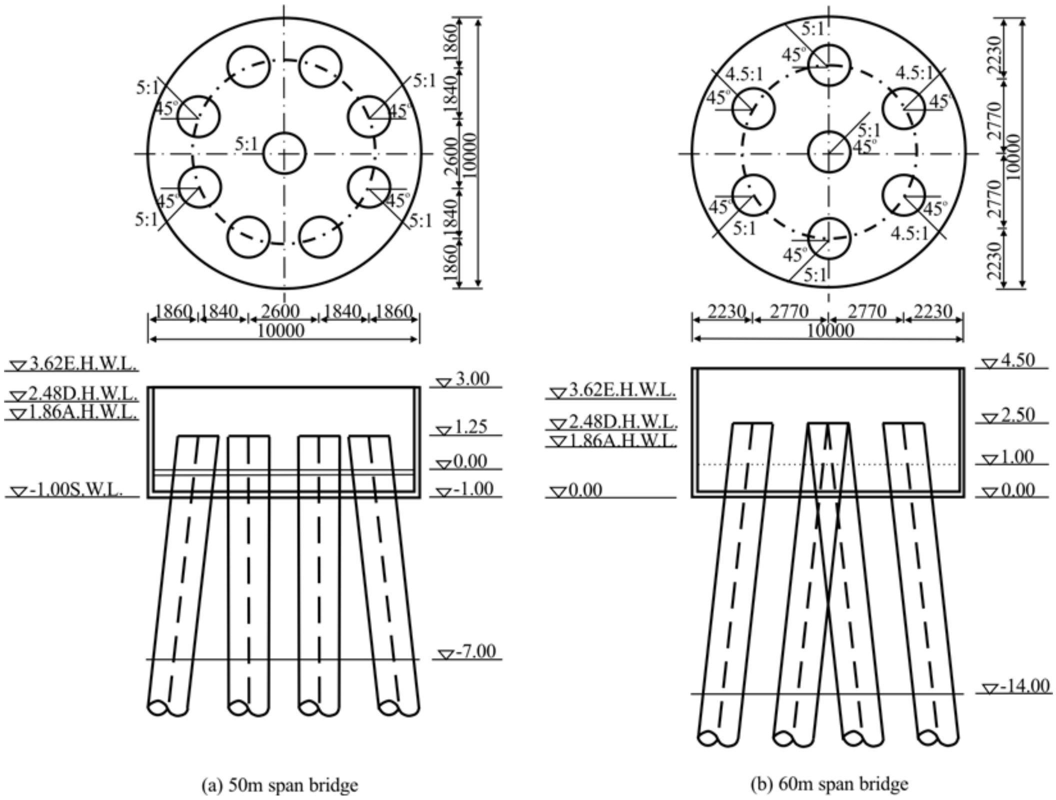


Fig.1 The sketch of the structure of the base foundation

the effects of wave current interaction on the hydrodynamic coefficients. Li[6] discussed the normalization of the hydrodynamic coefficients in the Morison equation. Sundar et al.[7] gave a detailed review on the hydrodynamics of slender piles and the variations of the hydrodynamic coefficients with the *KC* parameter. But for the wave current forces on pile groups, only simple combinations as tandem and parallel arrays of two or three piles were investigated. Typical results can be referred to Sarpkaya et al.[8], Chakrabati[9], Wang and Li[10], Yu and Zhang[11], Yu and Shi[12] and Zhang and Yu[13]. The Chinese Code of Hydrology for the Design of Sea Harbor [14] gave the specification of group effective factor for bi- and tri-pile groups. However, no systematic investigations have been carried out on complicated pile arrangements in a group, especially the effect of super structures. Lan et al.[15] gave the experimental results for the effect of hydrodynamic forces on pile array and slab in wave current combinations based on the foundation structure of the Donghai Bridge (i.e., the East Sea Bridge). Except for the wave current forces on the base foundation, the scour around the structures is another problem for engineering design[16].

In this article, the wave current forces on four types of oblique piles, the wave current forces on the pile group and the single piles in the group by considering the effect of the supper structure are experimentally studied for the 50 m and 60 m span bridge base foundations of the East Sea Bridge. The relationship between the wave current forces and the wave fluctuations are analyzed. The difference between the forces on single piles and those on the piles considering the effect of the pile group and supper structures are given. A total force reduction coefficient for the wave current forces on the pile group is suggested. Because of the complex structures, no accurate method is available for the calculation of wave current forces on the pile groups. The results given in this article can be used as a reference for similar engineering design and as the verification data for numerical calculation.

2. EXPERIMENTAL CONDITIONS

In this article, the experimental structures are based on the base foundation of the East Sea Bridge. Two structures shown in Fig.1 are considered, which consists of supper structure and pile groups, which are designed for 50 m and 60 m bridge spans.

The two structures are similar to each other except for the different lengths of the used piles and the bottom level of the supper structures. Bottom elevation for the 50 m and 60 m spans are –9 m and –14 m, respectively and the diameters of the piles used for the two structures are 1.2 m and 1.5 m, respectively.

Four water levels are considered during the experiment, i.e., the specified water level (S.W.L.: −1.0 m), the averaged water level (A.W.L.:+0.23 m), the averaged high water level(A.H.W.L.:+1.86 m), and the designed high water level (D.H.W.L.:+2.48 m). Corresponding to the water levels, the used vertical averaged current velocities are 1.46 m/s, 2.02 m/s, 1.85 m/s, and 1.53 m/s for 50 m span case and 1.77 m/s, 1.81 m/s, 1.96 m/s, and 1.59 m/s for 60 m span case, respectively. The used significant wave heights are $H_{1/3}$= 0.9m, 1.2m, 1.5m, and 2.0m, and the corresponding significant wave periods are $T_{H_{1/3}}$ =3.80s, 4.37s, 4.88s, and 5.61s respectively.

Irregular waves are used in the experiments and the JONSWAP spectrum modified by Goda[17] is used as the frequency spectrum, i.e.,

$$S(f)=\beta_J H_{1/3}^2 T_{1/3}^{-4} f^{-5}\exp\left[-1.25(T_P f)^{-4}\right]\cdot \gamma^{\exp\left[-(T_P f-1)^2/2\sigma^2\right]} \tag{1}$$

$$\beta_J \approx \frac{0.06238}{0.230+0.0336\gamma-0.185(1.9+\gamma)^{-1}}\cdot [1.094-0.01915\ln\gamma] \tag{2}$$

$$T_p \approx \frac{T_{H_{1/3}}}{1.0-0.132(\gamma+0.2)^{-0.559}} \tag{3}$$

$$\sigma=\begin{cases}0.07, f\le f_P\\ 0.09, f>f_P\end{cases} \tag{4}$$

where γ takes the value of 2.8.

The experiments were conducted in the wave-current 2-D flume at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. The wave flume is 69 m long, 2 m wide, and 1.8 m deep. At one end of the flume, an irregular wave maker introduced from MTS Cooperation of USA was installed. It was controlled by a microcomputer, which could collect and analyze the test data. The flume was equipped with two pumps of discharge capacity 0.8 m^3/s for the generation of bi-directional current . The maximum water depth could be up to 1.5 m.

In the experiments, wave data were collected using a DLY-1 wave sensor made by the State Key Laboratory. The wave forces were measured using the force sensors made by the Wuxi Research Center of Shipping Technology, China. The current was measured using the ADV meter introduced from USA.

The model was designed according to the Froude law. The length scale factor of 1:30 was used in the experiment in consideration of the experimental contents and the conditions of the experimental facilities. Before the physical model tests were conducted, the waves and currents were carefully calibrated in the flume to match with the inputted values. The generated wave spectra were identical with the theoretical one. Typical comparison of the measured wave frequency spectra and the target spectra is shown in Fig.2. The figures show that they conform to each other.

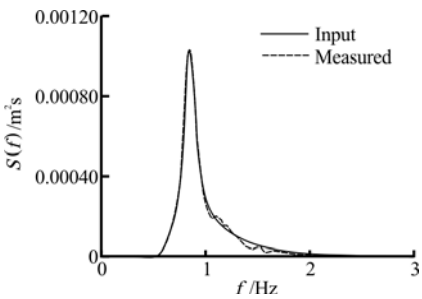


Fig.2 The comparison between the simulated and target wave spectra (model values)

In the experiments, the time interval of 0.025 s and the data length of 8192 for long waves or 4096 for short waves were used in each run. The averaged number of waves for the irregular waves were around 120-170, which conforms to the general requirement of irregular wave experiment[2]. The up crossing zero method was used for the statistical analysis of wave data and wave current force data. The wave and force spectra were analyzed using FFT method.

During the experiments, each run was repeated at least thrice to ensure the accuracy of the experiments. The test results are taken from the average value of the repeated test results.

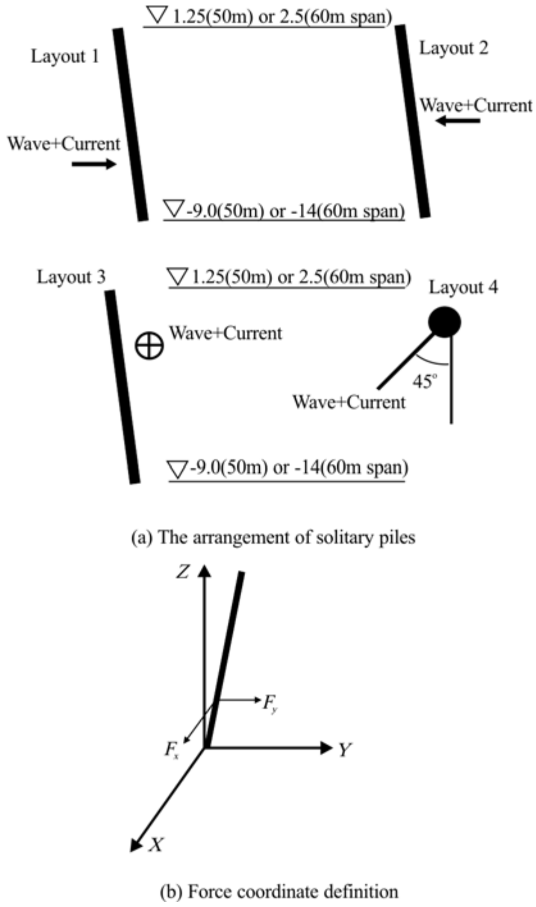


Fig.3 Experimented solitary piles and force coordinate

3. EXPERIMENTAL RESULTS

3.1 *Experimental results for single cylinder*

To investigate the group effects and to determine the reduction coefficients of the wave current forces on the pile groups, the wave current forces on four types of oblique cylinders shown in Fig.3 are first experimentally investigated. The length of the cylinders used for the experiments are the same as the real length of the designed piles. Typical arrangement of the model is shown in Fig. 4. For higher water levels, the top of the pile merges into water. To avoid the effect of the wave current forces on the model between the top of the pile and the force sensor, a short tube, which was installed on the supporter and no touch with the pile, was used to protect this part of pile from the action of wave currents.

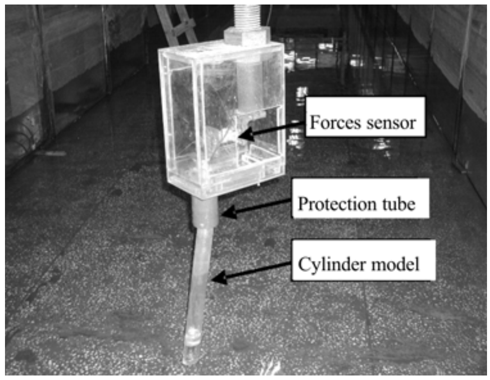


Fig.4 The sketch of the pile model

The definition for the wave force coordinate of the single piles is also shown in Fig.3. The total wave current forces F_T and their direction θ_T on the cylinders can be calculated from the measured simultaneous forces F_x and F_y using the following equations:

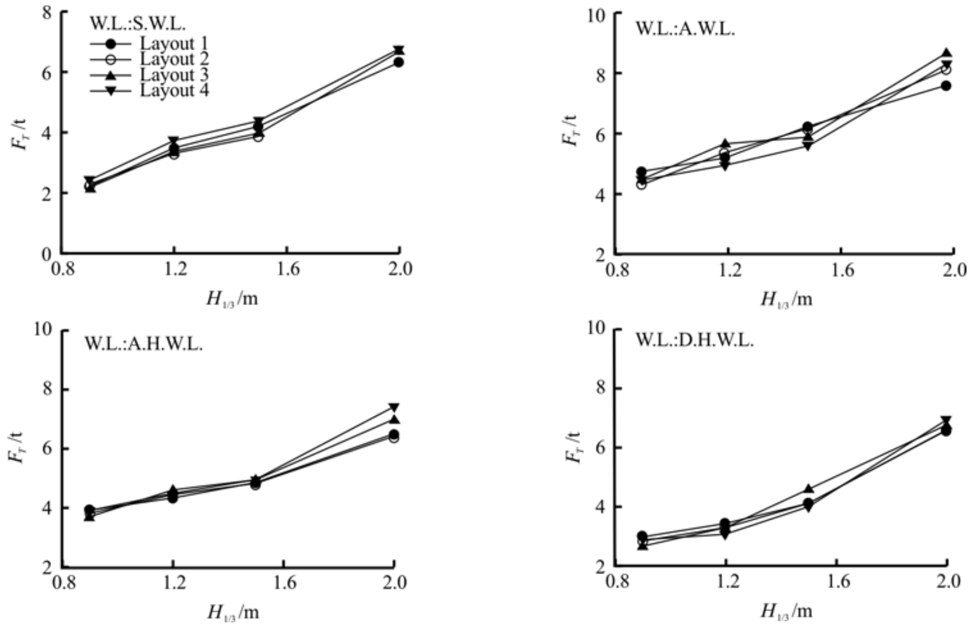
$$F_T = \sqrt{F_x^2 + F_y^2}\ ,\ \ \theta_T = \arctan(\frac{F_y}{F_x}) \tag{5}$$

Figure 5 shows the variation of experimental total wave current forces F_T along the wave height. It is reasonable that the wave current forces increase with the increase in wave height. The forces on the cylinder used in 60 m span bridge are larger than that in 50 m span bridge because of its larger diameter. It can also be seen from the figures that the wave current forces on the four types of piles are identical with each other at the same water level because the oblique angle of the cylinders is not very large. In fact, from Ref.[1], the relationship between the hydrodynamic coefficients for oblique cylinders and the vertical cylinders is described as follow:

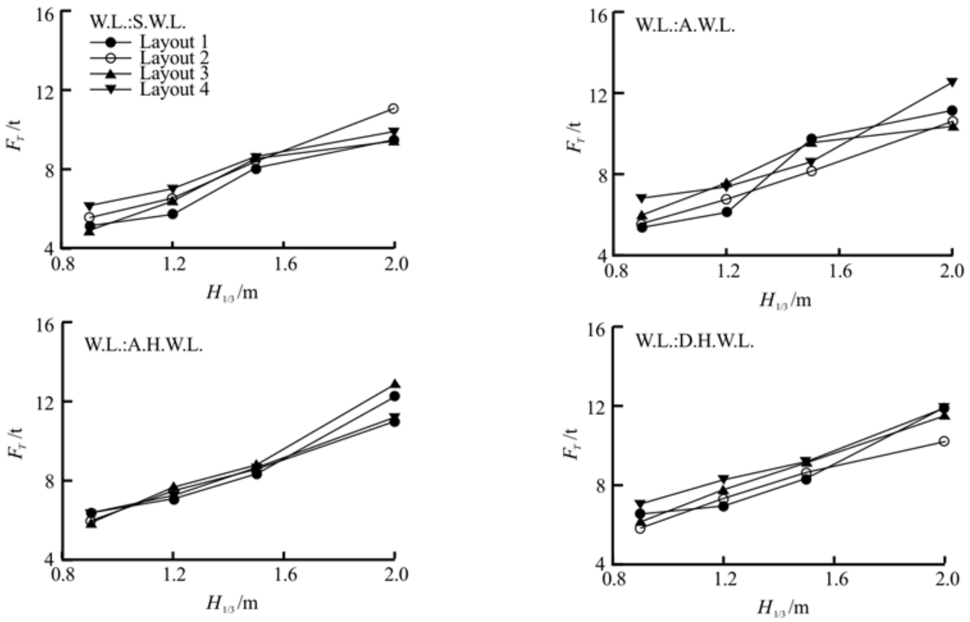
$$C_d' = \frac{C_d}{(1-\cos^3\mu)^{-1}} \tag{6}$$

$$C_M' = \frac{C_M}{\sin\mu} \tag{7}$$

$$\tan\mu = \frac{\tan\theta}{\cos(\alpha+\beta)} \tag{8}$$



(a) 50m span bridge with pile diameter of 1.2m



(b) 60m span bridge with pile diameter of 1.5m

Fig.5 The variation of the wave current forces on the solitary piles along wave heights

where C_d' and C_M' are the hydrodynamic coefficients for oblique cylinders, C_d and C_M are the coefficients for vertical cylinders, α is the angle between the waves and currents, β is the angle between the oblique direction of the pile and currents, θ is the oblique angle of the pile. As shown in Fig. 1, the oblique angle is smaller than 75^o in the experiments. From Eqs.(6)-(8), the difference between the hydrodynamic coefficients for oblique and vertical cylinders is found to be less than 3%. This means that the oblique pile can be taken as a vertical pile for the calculation of wave current force. In addition, the length of the single pile is the same with the depth of water for specified water level. The experimental results will be identical with the calculated results using the Morison equation if the coefficients are taken as C_d=1.2 and C_M≈1.5.

In the above mentioned three types of piles, the experimental results show that the inline forces and transverse forces generally do not occur simultaneously. The ratio of the total forces to the inline forces for the piles with the diameters 1.2 m and 1.5 m are 1.0-1.13 and 1.0-1.19, respectively.

From the results shown in Fig.5, it can be concluded that the wave current forces on the piles at averaged water level are the largest of the four water levels for 50 m span bridge because the length of piles is the same with the real one, and the elevation of the pile top is lower than the averaged water level. Also the current velocity is the largest at this water level. In the piles for 60 m span bridge, the elevation of the pile top is higher than the designed high water level. Although the current velocity at designed high water level is smaller, the water depth is the largest. Except the wave current forces at the specified water level are slightly smaller, the wave current forces at the other three water levels are basically identical with each other.

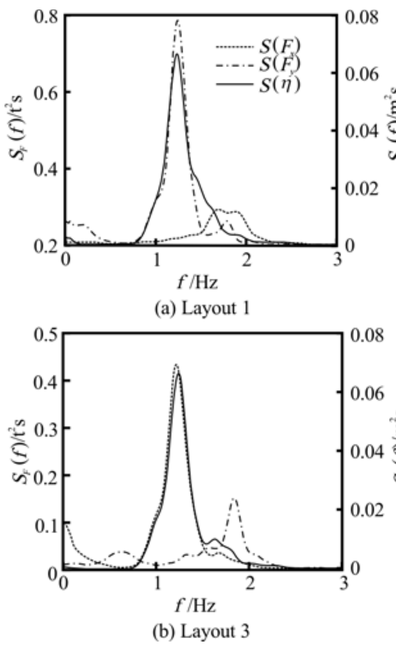


Fig.6 The comparison between the force and wave spectra of solitary piles (D=1.2m, H_S=0.9m, $\overline{T}$ =3.80s, V=2.02 m/s)

To investigate the relationship between the wave current forces and the associated waves, the waves are measured at the same time with the wave current forces using a wave sensor at the same section with the tested piles. Figure 6 gives the wave current force spectra and the wave spectra for the piles of diameter 1.2 m. It is shown that the spectral properties of the inline forces are basically identical with the spectral properties of the wave, and the peak frequencies of the force spectra and the wave spectra are almost the same. But the peak frequency of the transverse forces is generally higher than that of waves and inline force. The reason is that the oblique angle of the pile is small and the pile can be taken as vertical pile and the transverse force is mainly caused by the asymmetrical vortex shedding. The frequency of vortex releasing is much higher than the wave frequencies [1]. Although the length and diameter of the piles for 60 m span bridge are larger than those of 50 m span bridge, the experimental results show that they have the similar frequency properties.

To compare the phase of the wave current force with the wave phase, the cross-spectra between the wave current force and the waves are analyzed using the Fourier transform[2]. Figure 7 gives the typical analysis results. In the figures, $\theta_{\eta x}$, $\theta_{\eta y}$ and $\theta_{\eta T}$ are the phase differences between the water waves and horizontal forces F_x, F_y and the total force F_T, respectively. The figures show that the inline force phase are basically the same as in the water waves, but transverse force phase has some difference with that of the water waves.

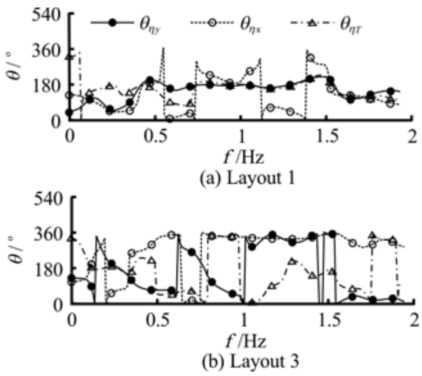


Fig.7 The phase spectra between the force and waves ofsolitary piles (D=1.2 m, H_S= 0.9 m, $\overline{T}$ =3.80s, V = 2.02m/s)

3.2 *Experimental results for pile groups*

To investigate the wave current forces on the pile group, the experiments for the wave current forces on the pile groups were conducted by considering the effects of the supper structures as shown in Fig.1. The pile distribution and the force coordinate definition for the pile groups are shown in Fig.8. Typical model of the pile group experiment is shown in Fig.9. Similar to that in the experiment for single pile, the total force and its acting direction can also be calculated from the simultaneously measured wave current forces along the *X* and *Y* directions using Eq.(5).

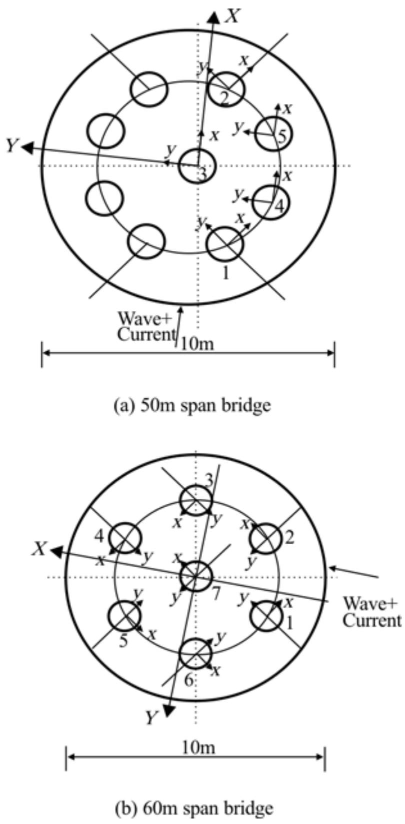


Fig.8 The tested pile numbers in the group and the force coordinate definition

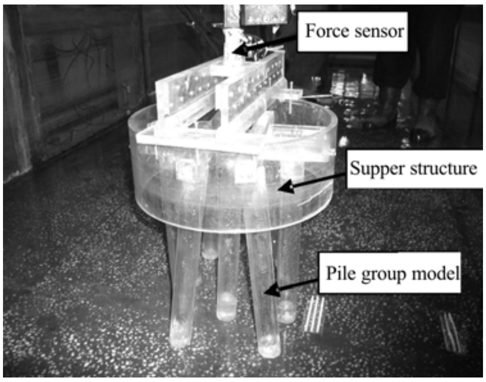


Fig.9 The model arrangement for pile group

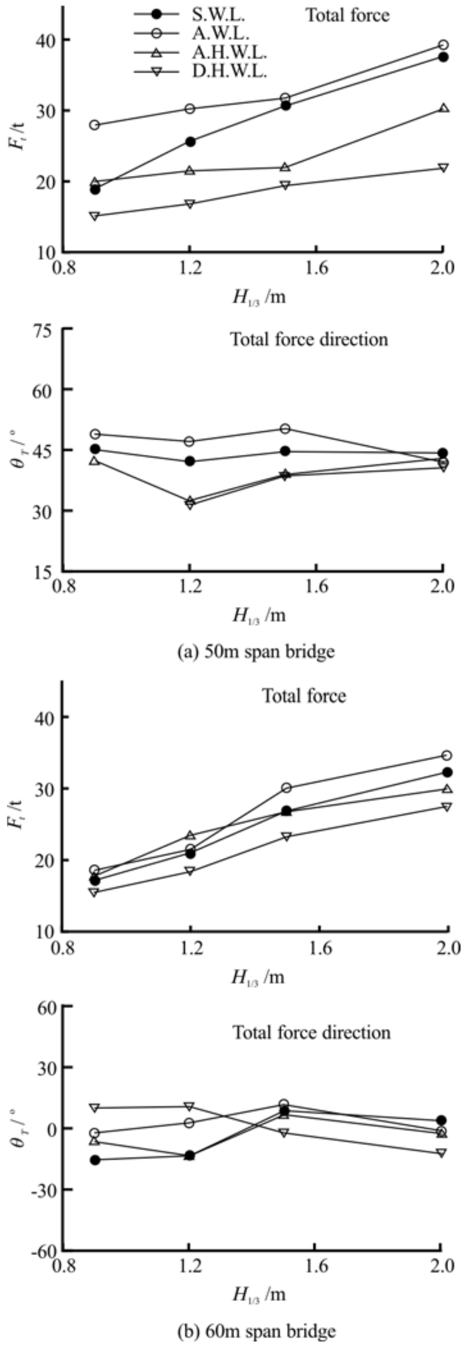


Fig.10 The wave current forces on the pile groups and their acting directions

Figure 10 shows the largest total wave current forces on the pile groups and their directions. The force direction shown in the figures is defined as the angle between the direction of wave force and the coordinate X , which is identical with the direction of wave and current . The figures show that the wave current forces on the pile groups increase with the increase in wave height for the same water level similar to that for single pile. For the base foundation of 50 m span bridge, as the effect of the supper structure is considered and the lower elevation of the supper structure is -1.00 m, the wave current forces on the pile groups at the specified water level and averaged water level are identical with each other. The wave current forces at the averaged water level +0.23 m are the largest. As the water level goes up, the wave current forces on the pile group decreases under the action of the same wave height because of the protection of the supper structure and the decrease in current velocity . However, there are significant differences between the directions of total force and the wave current, and the ratio of the total forces and inline forces is in the range of 1.16–1.40. This is larger than that in single pile experiment. This can be attributed to the fact that the direction of wave current is not along the symmetrical line of the structure and that may cause more asymmetrical vortex shedding and larger transverse forces.

For the base foundation of 60 m span bridge, the lower elevation of the supper structure is +0.00 m. The wave current forces on the pile group at the averaged water level +0.23 m are still the largest. Because the lower elevation of the supper structure is higher than that for 50 m span bridge, the wave current forces on the pile groups at the three lower water levels are basically identical with each other due to the same wave action even though some little decrease appears with the enhancement in the protection of the supper structure and decrease in the current velocity as the water level increases. In addition, though the diameter of 60 m span bridge is larger than that of 50 m span bridge, the number of piles in the pile group of 50 m span bridge is larger. The wave current forces on the two types of pile groups are identical with each other. However, there are no large difference between the force direction for 60 m span bridge and the wave current direction.

3.3 *Pile group effectiveness*

To investigate the relationship between the forces on the pile groups and single pile and the pile group effectiveness, the wave current forces on single piles in pile group by considering the pile group and supper structures are further experimentally investigated. The water level takes the average water level +0.23 m because the wave current forces on the pile groups are largest at this level. The selected pile numbers is also shown in Fig.8, that is No.1-No.5 for 50 m span bridge and all the piles for 60 m span bridge. Figure 11 gives the total wave current forces on the single piles in the groups. The figure shows that in the pile group of 50 m span bridge, the wave current forces on No.3 and No.2 piles are the largest although they are at the backside corresponding to the wave current action. This may be caused by the strong vortex shedding in the pile groups because the vortex shedding is a random process and that can cause larger forces on piles. For No.4 and No.5 piles, the wave current forces are smaller because of the effective protection of the front piles.

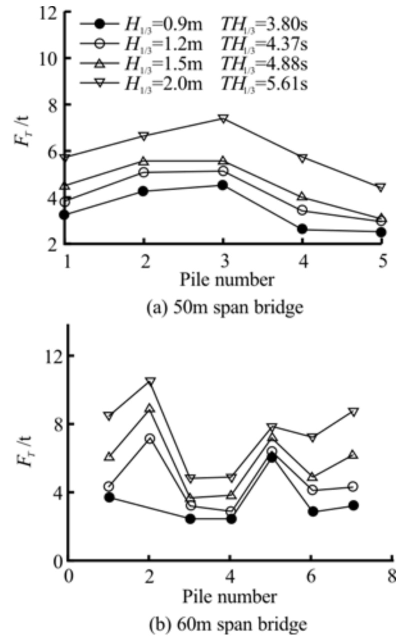


Fig.11 The wave current forces on the piles in pile groups (W.L.: +0.23 m)

The variation of the wave current forces on the single piles in the pile group of 60 m span bridge is different from that of 50 m span. The basic tendency is that the wave current forces on the front side piles are larger than that on the backside piles corresponding to the wave current action. The reason may be that the diameter of 60 m span bridge is larger, and thus the protection of the front side piles to the backside pile is more evident.

It is deserved to point out that the wave current forces on the piles in pile groups are very complex. The forces on piles depend on the type of pile group, pile diameter, the number of piles, and the pile position in the group. All the factors should be considered together during real application.

To compare the wave current forces on solitary cylinders and that on the piles in group, Table 1 gives the ratio of the wave current forces on solitary single piles and the maximum forces on piles in group. In the table, F_{T_1} to F_{T_4} stand for the maximum forces for the four layouts shown in Fig. 3 and $F_{T_{max}}$ is the maximum value of the wave current forces acting on the measured piles in the pile group. The results show the effectiveness of the pile group. Most of the ratios of the maximum total forces on a single pile and the corresponding forces on a pile in a group is greater than 1.0. The scatter in the experimental data means that the design is acceptable if the wave current forces on a solitary

Table 1 Ratio of the wave current forces on solitary single piles and the maximum forces on piles in group

Structure	$H_{1/3}$(m)	$T_{H_{1/3}}$ (s)	$\frac{F_{T_1}}{F_{T_{max}}}$	$\frac{F_{T_2}}{F_{T_{max}}}$	$\frac{F_{T_3}}{F_{T_{max}}}$	$\frac{F_{T_4}}{F_{T_{max}}}$
50 m span	0.9	3.80	1.05	0.96	1.00	0.98
	1.2	4.37	1.02	1.05	1.12	0.97
	1.5	4.88	1.13	1.11	1.07	1.01
	2.0	5.61	1.04	1.11	1.19	1.13
60 m span	0.9	3.80	0.88	0.90	0.97	1.11
	1.2	4.37	0.89	0.94	1.05	1.03
	1.5	4.88	1.09	0.91	1.08	0.97
	2.0	5.61	1.06	1.01	0.99	1.19

pile calculated from the Morison equation is used for the calculation of forces on a pile in a group in real application.

As described above, because there is no available method to calculate the exact total wave current forces on the pile group, the simple way to calculate the wave current forces on pile group is through the multiplication of wave current force on a solitary pile with the pile number in the group. However, it is evident that the obtained forces on pile group by this way are much larger than the real forces on pile group because of the group effectiveness. So a reduction coefficient should be considered. To compare the measured forces and the calculated wave current forces on the pile group by the simple way, the reduction coefficient is defined by

$$C_{\text{group}} = \frac{\text{measured force on pile group}}{\text{force on solitary pile} \times \text{number of piles}} \tag{9}$$

Figure 12 gives the variation of C_{group} along the wave heights, in which C_{group1} to $C_{\text{group 4}}$ stand for the four types of layout in the experiments on solitary piles. The figure shows that the ratio for 60 m span case is generally smaller than that for 50 m span case. But the group effect is evident. The ratio values are between 0.4-0.7. So for the two structures, the reduction coefficient can take the larger value of 0.7 for safety. However, it must be pointed out that the reduction coefficient depends on the diameter of the piles and the pile group arrangements, and should be carefully selected.

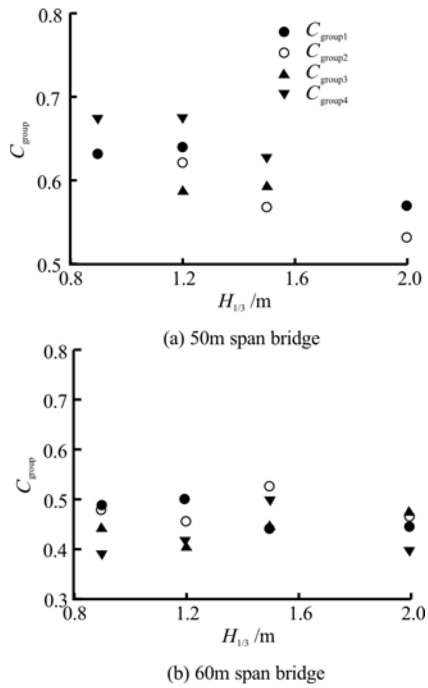


Fig.12 Variation of the ratio of the calculated wave current forces and measured forces on pile groups

4. CONCLUSIONS AND DISCUSSIONS

This article reports the experimental results for the wave current forces on the pile group of base foundation of the 50 m and 60 m span bridge of the East Sea Bridge. Basic conclusions can be described as follows:

(1) The wave current forces on the solitary piles and pile groups increase with the increase in wave height.

(2) The experimental results for four types of

oblique piles corresponding to the direction of wave current are basically identical with each other. The oblique piles can be considered as vertical piles for the calculation of wave current force because of small obliqueness. The in-line force frequency properties are the same as the wave frequency, and the frequencies of the transverse forces are evidently higher than the wave frequencies.

(3) The wave current forces on the pile groups are the largest at the averaged water level because of the consideration of the effect of the supper structures and their protection. But the total force directions for the different pile groups are different because of the different arrangements of the piles in the group.

(4) By the comparison of the experimental results for solitary piles and the pile groups, it can be seen that the total wave current forces on the pile group are smaller than the wave current forces on a solitary pile multiplied by the number of piles in the pile group because of the group effectiveness. If the wave current forces on the pile groups are calculated from the force on a solitary pile, the reduction coefficient for the wave current forces on pile groups can be taken as around 0.7 for the two structures for safety.

(5) It is deserved to point out that the wave current forces on a pile group is a very complex problem. The forces depend on the arrangement of the piles in the pile group, the diameter and number of the piles and the supper structures. Therefore, the reduction coefficient should be carefully selected.

REFERENCES

[1] LI Yu-cheng, TENG Bin. **Wave action on maritime structures**[M]. Beijing: China Ocean Press, 2002(in Chinese).

[2] YU Yu-xiu. **Random waves and their applications in engineering**[M]. Dalian: Dalian University of Technology Press, 2002 (in Chinese).

[3] LI Yu-cheng, WANG Feng-long and KANG Hai-gui. Wave-current forces on slender circular cylinders[J]. **China Ocean Engineering,** 1991, 5(3): 287-310.

[4] KANG Hai-gui, LI Yu-cheng and WANG Hong-rong. Method for the calculation of inline forces on a vertical circular cylinder and the analysis of hydrodynamic coefficient C_d and C_m in wave current co-existing field[J]. **Journal of Hydrodynamics, Ser. A,** 1990, 5(3): 91-101 (in Chinese).

[5] WANG Tao, LI Jia-chun and Huhe Aode et al. Effect of the wave current interaction on hydrodynamic coefficients[J]. **Journal of Hydrodynamics, Ser. A,** 1995, 10(5): 551-559 (in Chinese).

[6] LI Yu-cheng. Aspect of the normalization of hydrodynamic coefficients in Morison equation[J]. **Journal of Hydrodynamics, Ser. A,** 1998, 13(3): 329-337 (in Chinese).

[7] SUNDAR V., VENGATESAN V. and ANANDKUMART G. et al. Hydrodynamic coefficients for inclined cylinders[J]. **Ocean Engineering,** 1998, 25(4-5): 277-294.

[8] SARPKAYA T., CINAR M. and OZKAYNAK S. Hydrodynamic interference of two cylinders in harmonic flow[C]. **OTC, 3775.** Houston, TX, USA, 1980.

[9] CHAKRABATI S. K. In-line and transverse forces on a tube array in tandem with waves[J]. **Applied Ocean Research,** 1982, 4(1): 25-32.

[10] WANG Feng-long, LI Yu-cheng. Current effect for wave forces on bi-pile in tandem array[J]. **Journal of Dalian University of Technology,** 1995, 35(5): 714-718 (in Chinese).

[11] YU Yu-xiu, ZHANG Ning-chuan. Irregular wave forces on array of bi-pile[J]. **Journal of Dalian University of Technology,** 1998, 27(1): 103-111 (in Chinese).

[12] YU Yu-xiu, SHI Xiang-hong. The hydrodynamic coefficients of pile groups under irregular waves[J]. **Acta Oceanologica Sinica,** 1996, 18(2): 138-147 (in Chinese).

[13] ZHANG Ning-chuan, YU Yu-xiu. The hydrodynamic characteristics and pile grouping effect of transverse forces on an array of three-piles in random waves, **Journal of Hydrodynamics, Ser. A,** 1996, 11(4): 385-393 (in Chinese).

[14] THE MINISTRY OF COMMUNICATIONS OF CHINA. **Code of hydrology for the design of sea harbor JTJ213-98**[M]. The Press of People's Communication Publication, 1998 (in Chinese).

[15] LAN Ya-mei, LIU Hua and HUANGFU Xi et al. Experimental studies on hydrodynamic loads on piles and slab of Donghai bridge-Part II: Hydrodynamic forces on pile array and slab in wave current combinations[J]. **Journal of Hydrodynamics, Ser. A,** 2005, 20(3): 332-339 (in Chinese).

[16] LI Lin-pu, CUI Li. Prediction of maximum scour depth around large-diameterncy linder under the effects of both wave and current[J]. **Journal of Hydrodynamics, Ser. B,** 2005, 17(1): 74-79.

[17] GODA Y. **Random seas and design of maritime structure**[M]. Tokyo, Japan: University of Tokyo Press, 1985.