Indexed in
Scopus Compendex and Geobase Elsevier,
Geo-Ref Information Services-USA, List B of Scientific
Journals, Poland, Directory of Research Journals

International Journal of Earth Sciences and Engineering

www.cafetinnova.org

ISSN 0974-5904, Volume 09, No. 04

August 2016, P.P.1383-1387

Dynamic Response of Cross-Sea Bridge Pile Foundation under the Coaction of Wave and Current

HUANG WEN[1], CHEN JIE[1], SONG QIAN[2] AND XU FENG[3]

[1]School of Urban Construction, Wuhan University of Science and Technology, Wuhan, China
[2]China United Northwest Institute for Engineering Design & Research Co., Ltd, Xian, China
[3]School of Resource and Civil Engineering, Wuhan Institute of Technology, Wuhan, China
Email: rover824@163.com

Abstract: Bridges under the circumstances of marine environments are subject to extremely complicated loads. The precise calculation and estimation of two most important loads in deep sea, ocean waves and currents, is of essential influence to the construction of cross-sea bridges. On the basis of analyzing the effect of currents on the motion of waves and considering fluid-solid coupling effect, the paper derives the structural dynamics equation under the combined influence of waves and currents. Then, the finite element model for columns under the coaction of wave and current is constructed, and the corresponding computation program is compiled with MATLAB. The model can simultaneously estimate the drag force of current on the structure and the effect of structural deformation on the inertial force applied on it. Through model experiment, and comparing the varying effect of waves and currents on pile foundation with the changes of velocity, pile diameter and incident angle, the paper analyses the interactive effects between waves and currents, and the basic rules by which waves and current forces change with parameters.

Keywords: *wave-current load; cross-sea bridge; pile foundation; dynamic response; Fluid structure interaction*

1. Introduction

The marine environment is extremely complex and unpredictable. Besides supporting the bridge and live load, the cross-sea bridge piers must also be capable of sustaining a variety of forces from the ocean, such as waves, ice, currents, wind, tides, even earthquakes[1]. The situation is even more complex for bridges built in the bell mouth of rivers or the long and narrow straits between two block of lands, because in the surrounding water areas, the sudden change of course will result in turbulent water movement, which is most likely to generate wave-current force (also called as wave-current coupling effect) on bridges.

Ocean engineering is a relatively new multidisciplinary field of technology, which has few ripe theories and successful precedents to draw upon. In order to fully grasp the potential danger of waves to structures for prevention and reduction of ocean accidents, researchers both at home and abroad have been conducting extensive studies on the mechanisms through the interactions on loads of waves and currents as well as those on structures of underwater piers.

By employing the ALE method to treat the boundary conditions of coupling, Nomura, Wei, et al[2] analyzed the coupling oscillation of elastically supported structures in viscous and incompressible fluid. In 1981, Lirt and Nichols[3] proposed to use the VOF method to simulate free surface for the first time, which overcomes the disadvantages of previous methods of requiring massive storage and calculation capacity and therefore is especially suitable for three-dimension computations. Liu Yimin and other researchers[4] analyzed the kinetics characteristics of high-piled caps subject to wave load; Zhang Xinlai[5] simulated the wave-current force applied on small-dimension double-pier structures through numerical analysis; Wang and other researchers[6] analyzed the non-linearity characteristics of column groups subject to wave load. bridges.

2. Theoretical Background

2.1 Dynamics Equation under Wave-current Load

In engineering, it is generally recognized that the velocity of currents on the same vertical line are approximately the same and the change of velocity with time t can be neglected. So the force of current applied on per unit length of vertical cylinder can be expressed as follows [7]:

$$f_c = \frac{1}{2} C_D \rho_w D u_{c\max}^2 \quad (1)$$

In which C_D is the drag coefficient; $u_{c\ \max}$ is the maximum possible velocity of current.

From the above equation, it is obvious that the drag force is significantly proportional to the square of velocity. However, the wave-current load is rather complex that it will definitely change the original motion characteristics of waves and accordingly change the drag force applied on the structure. Therefore, by no circumstance, the wave-current load can be regarded as equivalent to the linear superposition of the wave force and current force.

The common method to calculate wave-current load in engineering is still based on Morison equation. Let the angle between velocity vector $\vec{u_c}$ and x coordinate be α, then its components in three directions are {$u_c \cos\alpha$, $u_c \sin\alpha$, 0}, and the total horizontal wave-current force on per height of vertical column is[8]

$$f = \rho C_M \dot{u}\, dV + \frac{1}{2} C_D \rho A(u_x + u_x \cos\alpha)\left|\vec{u} + \vec{u_c}\right| \qquad (2)$$

In which, $\left|\vec{u} + \vec{u_c}\right| = [(u_x + u_x \cos\alpha)^2 + (u_x \sin\alpha)^2]^{\frac{1}{2}}$

However, the above expression fails to consider the feedback of oscillation produced under the joint effect of wave and current to its surrounding current field, namely, the coupling effect between current and structure subject to wave-current load.

Considering the effect of column vibration, the Morison equation could be expressed as follows:

$$f = \frac{1}{2} C_D \rho D(u_x + u_c - \dot{x}) |u_x + u_c - \dot{x}| + C_M \rho \frac{\pi D^2}{4} \frac{\partial u_x}{\partial t} - C_m \rho \frac{\pi D^2}{4} \ddot{x} \qquad (3)$$

Therefore, the dynamic equation of structure considering FSI (Fluid structure interaction) is

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \frac{1}{2} C_D \rho D(\mathbf{u} + \mathbf{u_c} - \dot{\mathbf{x}})\left|\mathbf{u} + \mathbf{u_c} - \dot{\mathbf{x}}\right| + C_M \rho \frac{\pi D^2}{4} \dot{\mathbf{u}} - C_m \rho \frac{\pi D^2}{4} \ddot{\mathbf{x}} \qquad (4)$$

This equation contains both the coupling of fluid and structure and the influence of current and wave to structure.

Let $\mathbf{M_w} = C_m \rho \frac{\pi D^2}{4}$, equation (4) can be expressed as

$$(\mathbf{M} + \mathbf{M_w})\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \frac{1}{2} C_D \rho D(\mathbf{u} + \mathbf{u_c} - \dot{\mathbf{x}})\left|\mathbf{u} + \mathbf{u_c} - \dot{\mathbf{x}}\right| + C_M \rho \frac{\pi D^2}{4} \dot{\mathbf{u}} \qquad (5)$$

2.2 Solution of Coupling Equation

Using the Newmark-β[9]method to conduct discrete time of above equation so that the motion equation only satisfies on discreted time. Suppose that the acceleration rate within the period of t_i and t_{i+1} is constant, denoted as

$$a = (1-2\beta)\ddot{x}_i + 2\beta \ddot{x}_{i+1} \quad (0 \le \beta \le 0.5) \qquad (6)$$

By solving interger to acceleration rate a within the period of t_i and t_{i+1}, we can obtain the velocity and acceleration rate at the moment of t_{i+1}.

$$\dot{x}_{i+1} = \frac{\gamma}{\beta \Delta t}(x_{i+1} - x_i) - (1 - \frac{\gamma}{\beta})\dot{x}_i - (1 - \frac{\gamma}{2\beta})\ddot{x}_i \Delta t \qquad (7)$$

$$\ddot{x}_{i+1} = \frac{1}{\beta \Delta t^2}(x_{i+1} - x_i) - \frac{1}{\beta \Delta t}\dot{x}_i - (\frac{1}{2\beta} - 1)\ddot{x}_i \qquad (8)$$

Let $a_0 = \frac{1}{\beta \Delta t^2}$, $a_1 = \frac{\gamma}{\beta \Delta t}$, $a_2 = \frac{1}{\beta \Delta t}$, $a_3 = \frac{1}{2\beta} - 1$, $a_4 = \frac{\gamma}{\beta} - 1$, $a_5 = \frac{\Delta t}{2}(\frac{\gamma}{\beta} - 2)$

From the above two recurrence formula, we can derive the step-by-step integration formula of the multi-degree-of-freedom system.

$$\hat{\mathbf{K}}\mathbf{x}_{i+1} = \hat{\mathbf{P}}_{i+1} + \left\{\frac{1}{2} C_D \rho D(\mathbf{u} + \mathbf{u}_c - \dot{\mathbf{x}})\left|\mathbf{u} + \mathbf{u}_c - \dot{\mathbf{x}}\right|\right\}_{i+1} \qquad (9)$$

In which equivalent stiffness matrix:

$$\hat{\mathbf{K}} = \mathbf{K} + a_0(\mathbf{M} + \mathbf{Mw}) + a_1 \mathbf{C} \qquad (10)$$

Equivalent load:

$$\hat{\mathbf{P}}_{i+1} = \mathbf{P}_{i+1} + (\mathbf{M} + \mathbf{M}_w)(a_0 \mathbf{x}_i + a_2 \dot{\mathbf{x}}_i + a_3 \ddot{\mathbf{x}}_i) + \mathbf{C}(a_1 \mathbf{x}_i + a_4 \dot{\mathbf{x}}_i + a_5 \ddot{\mathbf{x}}_i) \qquad (11)$$

The solution to coupling equation (5) can be converted to the solution of equation (11). Since both sides of equation(11)has $\mathbf{x}_{i+1}$, it can be inferred that it is an implicit equation, which cannot be solved directly. Therefore the paper adopts the method below to solve it.

Step 1: Let $\mathbf{x}_{i+1} = \mathbf{x}_i$ in $\left\{\frac{1}{2} C_D \rho D(\mathbf{u} + \mathbf{u}_c - \dot{\mathbf{x}})\left|\mathbf{u} + \mathbf{u}_c - \dot{\mathbf{x}}\right|\right\}_{i+1}$

Step 2: Solving equation (8), we can obtain $\mathbf{x}_{i+1}$, denoted as $\mathbf{x}^*_{i+1}$

Step 3: Calculate $|\mathbf{x}^*_{i+1} - \mathbf{x}_{i+1}|$. If $|\mathbf{x}^*_{i+1} - \mathbf{x}_{i+1}| < \sigma$ (σ is the error allowed), then $\mathbf{x}_{i+1} = \mathbf{x}^*_{i+1}$, then enter next time; or else, execute Step 1 and let $\mathbf{x}_{i+1} = \mathbf{x}^*_{i+1}$.

Given the initial value of the movement $\mathbf{x}_0$, $\dot{\mathbf{x}}_0$, $\ddot{\mathbf{x}}_0$, we can calculate the displacement and force of the structure at any moment.

Based on the above algorithm, we use MATLAB software[10] program to calculate the horizontal force applied by wave and current on small-diameter foundation pile. Besides, we also discuss the effect of the velocity of current and its incident angle on the motion characteristics of waves and the magnitude of wave-current force, which casts new insights in calculating the wave-current force taking the fluid-solid coupling effect into consideration.

3. Example

Fig.1 is the layout of pier and pile foundation of a cross-sea bridge.

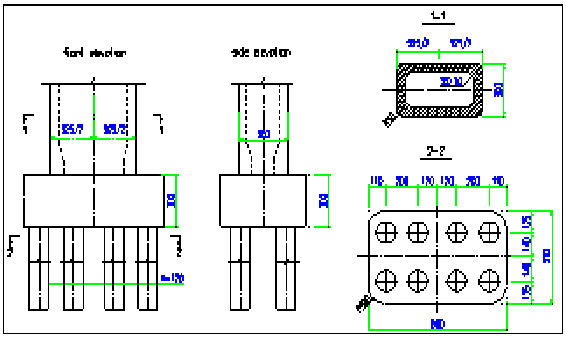

Fig.1 *Size of pier and pile foundation*

The wind spectrum of irregular wave adopts JONSWAP , the expression for which is

$$S(f) = \alpha H_s^2 T_p^{-4} f^{-5} \exp\left[-\frac{5}{4}(T_p f)^{-4}\right] \gamma^{\exp\left[-(ff_p^{-1})^2/2\sigma^2\right]}$$

In which,

$$\alpha = \frac{0.0624}{0.230 + 0.033\gamma - 0.185(1.9+\lambda)^{-1}};$$

$$\sigma = \begin{cases} 0.07 & f \le f_p \\ 0.09 & f > f_p \end{cases};$$

H_s is effective wave height; T_p is spectrum peak period; f_p is spectrum peak frequency; γ equals 2.8.

3.1 Experiment Arrangement and Model Design

1) Experimental tank

The experiment is conducted in a tank of 50 meters in length, 17.5 meters in width and 1.2 meters in depth. A wave absorption slope is located on one side of the pool, and a rolling irregular wave maker manufactured by US MTS Corporation is equipped on the other side, which is capable of generating regular or irregular waves in different spectrums according to the requirements of wave parameter given by computer automatically. The tank is also equipped with a high-pressure water jetting system. Jetting nozzles are distributed evenly on the walls of pools, through which stable current flows into the pool. On the opposite side of wave-maker, there is a grid-type wave absorption beach with a certain degree of slope to absorb wave and prevent reflected wave.

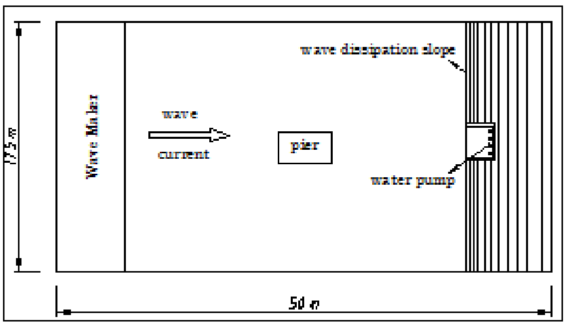

Fig.2 *Layout of wave tank*

Fig.3 *experiment tank*

2) Model Description

The experiment uses normal model designed by gravity similarity criterion (Froude number similarity). In the model, all components of structure, such as piers, pile cap and pile foundation, are fabricated with a geometric ratio by 1: 30. The model and the prototype are geometrically similar. All components are simulated in terms of rigid structure by adoption of wood or PMMA.

The experimental wave adopts unidirectional irregular wave. All the physics parameters of the wave, such as the height, period and velocity of the wave, are set by gravity similarity criterion. After inputting the elements of characteristic wave after scale conversion into computer to generate wave making signal, the wave-maker will generate irregular wave series correspondingly. The number of irregular waves in each experiment is larger than 120, and each experiment is repeated three times. The error of simulated height and period of wave from the designed value is kept within ±2%.

With different condition combinations of +level, the horizontal force applied on the fundamental structure of bridge by wave-current is measured by total force (tension plus pressure) sensor.

3) Experimental Situation

The experimental situation is simulated in combination of four different water depths (which corresponds to four different types of water velocity) and four types of static water wave parameters (See Table 1).

Table 1: *Wave and current conditions*

Water lever and current			**Wave elements**		
No.	***d*** **(m)**	***uc*** **(m/s)**	**No.**	***H*****(m)**	***T*** **(s)**
S1	13.0	1.63	W1	3.07	6.0
S2	14.23	1.95	W2	5.27	7.1
S3	15.86	2.12	W3	6.22	7.5
S4	16.48	3.03	W4	6.94	8.7

3.2 Numerical Computation and Result Analysis

Taking into consideration of S2+W2 for instance by using the method in 2.2 and MATLAB to compile programs for calculation, the horizontal wave-current force applied on pile foundations can be shown in Fig.

3. The experimental results are also shown there PMMA.

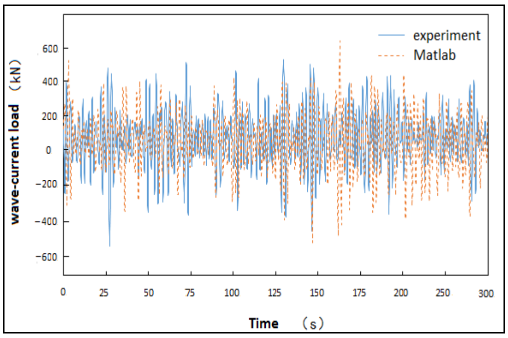

Fig. 4 *wave-current load time-history curve*

As can be seen from Fig.4, it is demonstrated that the current-wave load calculated by the method proposed in this paper (410kN) is very close to the tested value (432kN), and the difference is only 5%.

The magnitude of this effect is closely related to the velocity and direction of current, which is to be elaborately illustrated as follows.

4. Factors Influencing Wave-current Load

4.1 Effect of Current Velocity

In order to study the effect of velocity on wave-current load by calculating the forces applied on pile foundation under condition W2 and different current velocities. The total wave-current loads applied on pile foundation under different velocities are computed as below. (See Fig.5)

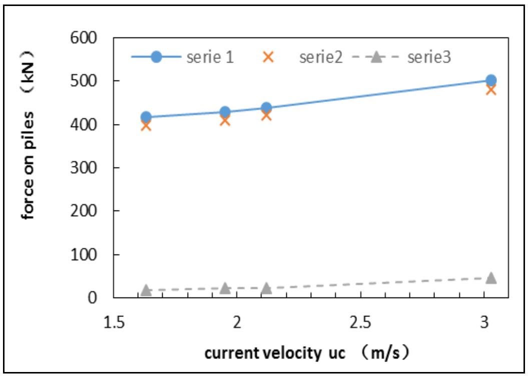

Fig.5 *current velocity vs wave-current load*

In Fig.5, serie1 is the current-wave load of pile foundation tested through experiment; serie2 is the value calculated by the method proposed in the paper; serie3 is the current force on pile foundation. From Fig. 5, it can be seen that the wave-current force applied on pile foundation is far larger than the sum of force applied simply by wave or by current. And with the increase of velocity, the gap between these two values enlarges conspicuously. The enlarging effect of wave-current coupling on wave-current force is extraordinarily significant and critical. As a result, the effect of wave-current force in marine engineering designing cannot be neglected.

4.2 Effect of Pile Diameter

Taking into consideration of S2+W2 for instance, the total wave-current force on the pile foundation when the diameter D ranges between 1.0 and 3.0 can thus be calculated. The results of calculation are shown in Fig.6.

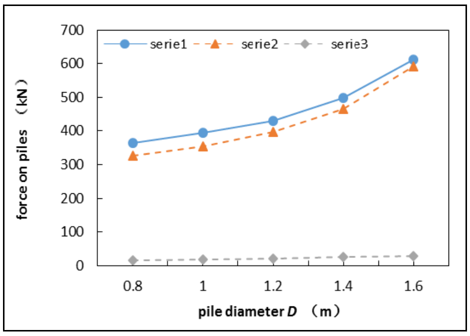

Fig.6 *pile diameter vs wave-current load*

In the figure above, serie1 is the current-wave load calculated by the mehod porosed in this paper; serie2 is the wave force; while serie3 is current force. From Fig.7, it is demonstrated that with the increase of the diameter of pillars, the wave-current force, wave force and current force are all increasing, in which the current force is in linear relationship with the diameter, while the wave force is increasing quadratically.

4.3 Effect of Incident Angle

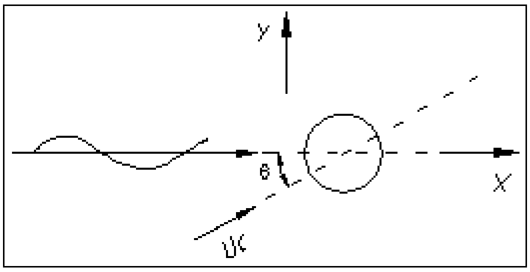

Fig.7 *interaction of wave and current*

From Fig. 7, it can be seen that the velocity component of current on X and Y axis are

$$u_{cx} = u_c \cdot \cos\theta \qquad (12)$$

$$u_{cy} = u_c \cdot \sin\theta \qquad (13)$$

The velocity of water particles in X and Y axis are

$$u(z,t) = \frac{\omega_r H}{2} \frac{chkz}{shkd} \cos(kx - \omega t) \qquad (14)$$

$$w(z,t) = \frac{\omega_r H}{2} \frac{shkz}{shkd} \sin(kx - \omega t) \qquad (15)$$

In which $\omega_r = \omega - ku_{cx}$. K can be calculated iteratively as below.

$$\left(\frac{2\pi}{T} - ku_{cx}\right)^2 = gk \tanh kd \qquad (16)$$

The velocity of water particle on two directions under wave-current force can be expressed as follows:

$$Ux=u_{cx}+u(z,t) \quad (17)$$
$$Uy=u_{cy}+w(z,t) \quad (18)$$

Taking into consideration of S2+W2 for instance, the wave-current forces on pile foundations can be calculated with the wave-current angles of (0°, 15°, 30°, 45°, 60°, 75°, 90°) respectively.

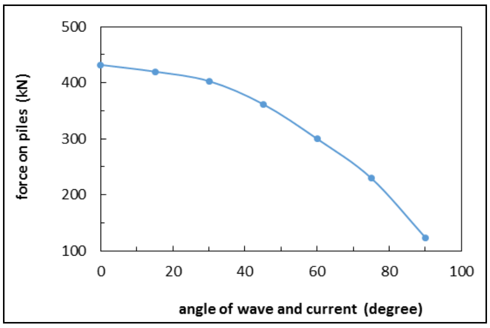

Fig.8 *angle of wave and current vs wave-current load*

From the above figure, it is demonstrated that with fixed velocity and wave parameters, the larger the angle between wave and current is, the smaller the enlarging effect of current on wave is. And with the increase of the inclined angle, the diminishing tendency is more conspicuous.

5. Conclusion

The paper analyzes the dynamics features of fundamental structure of cross-sea bridges under the joint effect of current and wave as well as deriving the structural dynamics equation, taking into account of the fluid-solid coupling effect. Newmark-β method is applied to make the equation discrete in time to decouple the problem. The model simulation is conducted to validate the effectiveness of the proposed method. Besides, by comparing the force applied on pile foundation with different wave-current velocities, column diameters and current-wave angles, it can be concluded that wave-current load varies with related parameters. The conclusions can be drawn as follows:

1) The proposed method is verified to be valid and effective;
2) The current will affect the height and length of waves, and accordingly affect the wave-current force on fundamental piers. When the wave and current are propelling in the same direction, the wave height increases with the decrease of wave height, while wave-current force on pile foundations increases correspondingly;
3) With the increase of wave velocity, the magnifying effect of wave-current coupling effect on the force applied on pile foundation increases conspicuously. While the wave-current force applied on pile foundations is larger than that applied merely by wave or current;
4) With the increase of the column diameter, the wave-current force aplied on the pile foundations also increases, while the wave-current coupling effect is decreasing;
5) With the increase of the wave-current angle, the wave-current force applied on the pile foundation in the propelling direction of wave and current is decreasing, and with the increase of the inclined angle, the diminishing tendency is more conspicuous.

References

[1] Okeil, C. Cai, “Survey of Short and Medium Span Bridge Damage Induced by Hurricane Katrina”, Journal of Bridge Engineering, 13(14), 377-387. 2007.

[2] P. Lin, C. Zale, “Wave-current Interaction with A Vertical Square Cylinder”, Ocean Engineering, 30, 855-876. 2003.

[3] J. Ojeda, A. Susin, Enhanced lattice Boltzmann shallow waters for real-time fluid simulations, New York: ACM Press, 2013.

[4] X. Z. Zhao, Riam, “Numerical Simulation of Extreme Wave Generation Using VOF Method", Journal of Hydrodynamics, 12(4), 235-243. 2010.

[5] Y. Boos, “Linear and nonlinear irregular waves and fores in a numerical wave tank”, Ocean Engineering, 29, 475-493. 2002.

[6] J. Eicher, H. Guan, D. Jeng. “Stress and Deformation of Offshore Piles under Structural and Wave Loading”, Ocean Engineering, 30,369-385. 2003.

[7] S.X. Liu, Y.C. Li and G.W. Li, “Wave Current Forces on the Pile Group of Base Foundation for the East Sea Bridge, China”, Journal of Hydrodynamics, 19(6), 661-670. 2007.

[8] B.L. Geng, B. Teng and D.Z. Ning, “A Time-Domain Analysis of Wave Force on Small-Scale Cylinders of Offshore Structures”, Journal of Marine Science and Technology, 18(6), 875-882.2010.

[9] S. Neelamani, N.U. Bhaskar and K. Vijayalakshmi, “Wave Force on a Seawater Intake Caisson”, Ocean Engineering, 29(10), 1247-1263.2002.

[10] M. Hassan, S.N. Bora. “Exciting Forces for a Pair of Coaxial Hollow Cylinders and Bottom-Mounted Cylinder in Water of Finite Depth”, Ocean Engineering, 50, 38-43.2012.