SOIL-STRUCTURE-WATER INERACTION OF A CABLE-STAYED BRIDGE UNDER SEISIMIC EXCITATION

Yong GAO[1] Wancheng YUAN[2] and Xiaoguang JIN[3]

[1] *Ph.D Candidate, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China*
[2] *Professor, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China*
[3] *Associate Professor, College of Civil Engineering, Chongqing University, Chongqing, China*
Email:gao4443@126.com, yuan@mail.tongji.edu.cn

ABSTRACT :

Seismic performance of a long-span cable-stayed bridge is studied with soil-structure-water interaction being included in this paper. Soil-pile interaction is modeled using individual impedance matrix to replace piles below the mudline. Water-structure interaction is simulated with added mass and damping coefficients for pile foundations of the bridge. Hydrodynamic added mass and damping coefficients of the pile caps are obtained through the concise closed form expressions which were deduced by Bhatta and Rahman (2003). Morison Equation is applied to calculate the added mass and damping coefficients of a single pile. Hydrodynamic grouping effects of grouped piles are considered with grouping effect coefficients. Nonlinear time history analysis is conducted with the finite element model of the bridge. The analysis results show that hydrodynamic effects have no significant influence on the maximum internal force responses of towers and their underlying piles. However, hydrodynamic effects might increase the maximum internal force responses of piers' underlying piles about 10~20%. Therefore, it is necessary to consider water-structure interaction in seismic analysis of long-span cable-stayed bridges.

KEYWORDS: Soil-structure interaction, Structure-water interaction, Morison Equation, FFT, Cable-stayed bridges, Seismic analysis

1. INTRODUCTION

For long-span bridges, pile foundations can dramatically save project costs compared with caisson foundations as they are not so demanding to the construction equipments, personnel quality and management level as caisson foundations. But, the mass of pile caps might be a significant fraction of the total mass of each bridge, which has significant influence on structural dynamic characteristics of bridges. For a pile foundation, its seismic response to an earthquake may be an important factor in the response of the bridge as a whole. Moreover, seismic responses of a pile foundation with elevated pile cap are the result of complex interactions among the pile cap, the piles, the soil and the surrounding water.

Soil-structure interaction problem has been widely studied in the last two decades. Many efforts have been made to account for the soil nonlinearity of soil-pile system and various methods have been developed for modeling of soils surrounding a pile [Matlock et al. (1978), Badoni and Markis (1996) , El-Naggar and Novak (1996)]. The damage caused to pile foundations during recent earthquakes (e.g. Kobe Earthquake 1995 and Chi-Chi Earthquake of 1999) has emphasized the importance of understanding soil-pile-structure interaction (SPSI). Numerical analyses for SPSI include finite element method (FEM) [Cai et al. (2000)] and boundary element method (BEM) [Guin and Banerjee (1998)]. But, either FEM or BEM is indeed cumbersome because it requires numbers of numerical parameters to be identified for the entire model, moreover, computation work is time-consuming and expensive. Therefore, some simple approach is still widely used in these days for the design of pile foundations, such as substructure model [Ahn and Gould (1989)], impedance matrix model [Ingham et al. (1999)] and equivalent fixed model [Liu et al. (2007)].

Water-structure interaction problem has received considerable attention from the engineering community. A great deal of efforts has been put into the estimation of the hydrodynamic forces acting on an offshore structure during earthquakes and waves. Westergraard (1933) reported the first rigorous analysis for hydrodynamic forces on vertical wall during earthquakes. For a submerged cylinder with characteristic dimensions much smaller than the wave length (cylinder diameter / wave length < 1/5), Morison et al. (1950) proposed the most-widely accepted Morison Equation for prediction of wave loads. For large submerged cylinders, linear diffraction theory [MacCamy and Fuchs (1954)] provided concise closed form expressions of wave loads. Bhatta and Rahman (2003) studied the scattering and radiation problem for a floating vertical cylinder in water of finite depth and deduced the closed-form expressions of wave loads, added mass and damping coefficients matrices. Lai (2004) studied dynamic interaction between deep-water bridge substructure and water during earthquakes and waves by theoretical deduction and hydrodynamic pressure tests.

In this paper, the seismic performance of a long-span cable-stayed bridge including soil-structure-water interaction is studied. Soil-pile interaction is treated with a simple approach by using individual impedance matrix to replace the segment of piles under the mudline. Added masses and damping coefficients are adopted to account for the hydrodynamic effects due to earthquakes. The concise closed form expressions of added mass and damping coefficients, which were deduced by Bhatta and Rahman (2003), are adopted to obtain the hydrodynamic added mass of pile caps. Grouping effect of piles is considered by correcting the single pile's calculated hydrodynamic parameters with grouping effect coefficients.

2. DESCRIPTION OF THE BRIDGE

The subject of this study is a five span cable-stayed bridge that crosses Xiangshan Harbor, along the highway connecting Ningbo City and Xiangshan County. The bridge has a length of 1376m; it consists of a steel girder bridge deck, double plane semi-harp-type cables, two diamond-shape towers, two couples of concrete auxiliary piers and transition piers. The span layout of the bridge is shown in Figure 1.

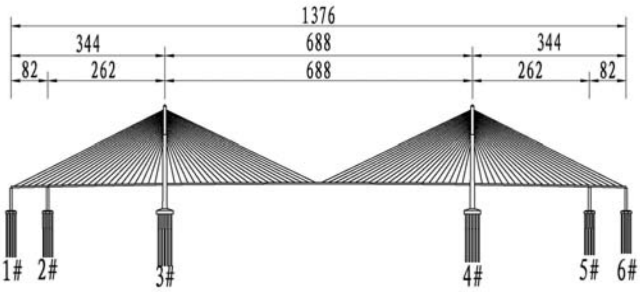


Figure 1 Layout of the bridge (Unit: m)

The prefabricated steel box girder has a height of 3.5m and a width of 31.6m. There are 88 couples of cable members, 44 supporting the main span and 22 supporting each side spans. The Cable members are evenly spaced at 15m c/c at the deck level on the side as well as main spans. The tower has a height of 224.5m from the top of the pile cap. The cable-tower anchorage zone of each tower is a steel box beam and the lower parts are made of concrete. The auxiliary pier has a height of 48.5m, and the transition pier has a height of 46.5m ,.both of which are made of concrete and have the same section of 5m×7m. The bridge towers are supported on rigidly capped vertical pile groups passing through deep, layered soil overlying rigid bedrock.

3. MODELLING OF SOIL-PILE SYSTEM

Although many sophisticated methods have been proposed by some researchers to include soil nonlinearity and SPSI in the seismic analysis of structures which supported by pile foundations, some of them are impractical for the preliminary design of bridges because detailed geological reports are always unavailable and soil profiles and parameters are not clear enough at this stage. As Xiangshan Harbor Bridge is at its preliminary design stage right now, it is appropriate to treat soil-pile interaction with a simple approach.

In this paper, piles are modeled between the pile cap and the mudline and then replaced with individual impedance matrix below the mudline. The finite element model of a pile foundation is schematically shown in Figure 2. The impedance matrix for each single pile is calculated by BCAD-PILE program, which was developed by the Department of Bridge Engineering of Tongji University and conformed to the Chinese

"Specifications for Design of Ground Base and Foundation of Highway Bridges and Culverts (JTJ024-85)".

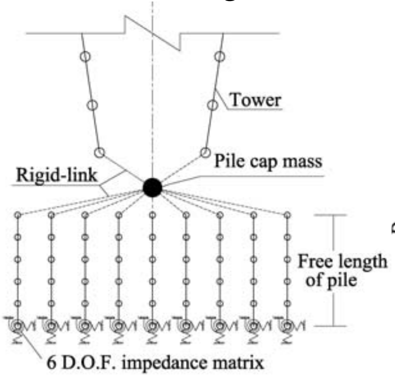


Figure 2 Individual pile model

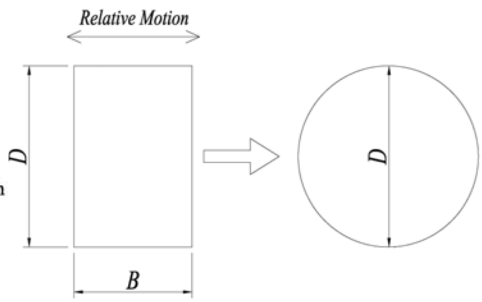


Figure 3 Sketch of equivalent section

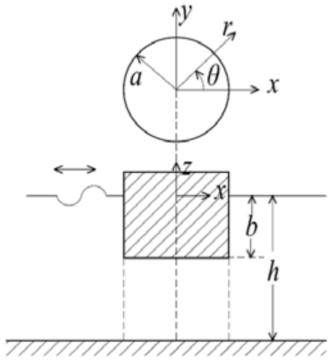


Figure 4 Definition sketch

4. STRUCTURE-WATER INTERACTION

Although Computational Fluid Dynamics (CFD) has made remarkable progress in recent years, it is still difficult to perform a realistic time history analysis for structure-water interaction problem by solid structural elements to simulate submerged components and fluid elements to simulate surrounding water. Therefore, hydrodynamic added mass and damping coefficient is still used by engineers as a practical method to account for hydrodynamic effects for the seismic analysis of structures at present.

For one structure subjected to a seismic excitation, the equation of motion can be written as

$$M\ddot{u}_s(t)+C\dot{u}_s(t)+Ku_s(t)=-M\ddot{u}_g(t) \tag{4.1}$$

where M, C, K is the structural mass matrix, damping matrix and stiffness matrix respectively; $u_s(t)$, $\dot{u}_s(t)$ and $\ddot{u}_s(t)$ is the structure's displacement ,velocity, and acceleration; $\ddot{u}_g(t)$ is the displacement of ground motion.

If hydrodynamic effects are considered, Eqn. 4.1 can be rewritten as

$$\left(M+M^a\right)\ddot{u}_s(t)+C\dot{u}_s(t)+Ku_s(t)=-\left(M+M^a\right)\ddot{u}_g(t)-C^a\left|\dot{u}_t(t)\right|\dot{u}_t(t) \tag{4.2}$$

where M^a, C^a is the hydrodynamic added mass matrix and added damping coefficients matrix respectively; $u_s(t)$, $\dot{u}_s(t)$, $\ddot{u}_s(t)$ is the relative displacement ,velocity, and acceleration of the structure's motion against surrounding water; $\dot{u}_t(t)$ is the absolute velocity of the structure's motion, $\dot{u}_t(t)=\dot{u}_s(t)+\dot{u}_g(t)$.

If the ground motion is horizontally inputted in a structure which supported on pile foundations with dozens of piles, the rotational and vertical displacement responses of each pile cap are always as small as negligible when compared with its horizontal displacement responses. In this paper, the hydrodynamic added mass and damping coefficients are considered only in the longitudinal and transverse direction of the bridge for each pile cap.

4.1. Pile cap-Water Interaction

To obtain the added masses and damping coefficients of a pile cap, the procedure would be used as follows: the pile cap would be treated as an equivalent cylinder as the first step, the relation between the rectangular section column and its equivalent cylinder is shown in Figure 3; then the hydrodynamic added masses and damping coefficients of the equivalent cylinder can be calculated by using the concise closed form expressions of added masses and damping coefficients which were deduced by Bhatta and Rahman (2003); the hydrodynamic added masses and damping coefficients of the pile cap can be obtained by multiplying its equivalent cylinder's results with a correction coefficient K_c at last.

Bhatta and Rahman (2003) studied the scattering and radiation problem for a floating cylinder in water of finite depth, the geometry of the situation in their work is depicted in Figure 4; the added mass μ and damping coefficients ν due to surge are given by

$$\mu + i\frac{\nu}{\sigma} = \pi\rho a^2 h\left[\frac{N_{\lambda_0}^{-1/2}\gamma_{10}}{\lambda_0 h}\{\sinh\lambda_0 h - \sinh\lambda_0(h-b)\} + \sum_{j=1}^{\infty}\frac{N_{\lambda_j}^{-1/2}\gamma_{1j}}{\lambda_j h}\{\sin\lambda_j h - \sin\lambda_j(h-b)\}\right] \tag{4.3}$$

where σ is the angular frequency, λ_0 is the wave number, λ_j is the eigenvalue which are given by

$$\sigma^2 = g\lambda_0\tanh\lambda_0 h = -g\lambda_j\tan\lambda_j h \tag{4.4}$$

with

$$N_{\lambda_0} = \frac{1}{2}\left(1 + \frac{\sinh(2\lambda_0 h)}{2\lambda_0 h}\right), \qquad N_{\lambda_j} = \frac{1}{2}\left(1 + \frac{\sin(2\lambda_j h)}{2\lambda_j h}\right) \tag{4.5}$$

γ_{10} and γ_{1j} are unknown coefficients to be determined.

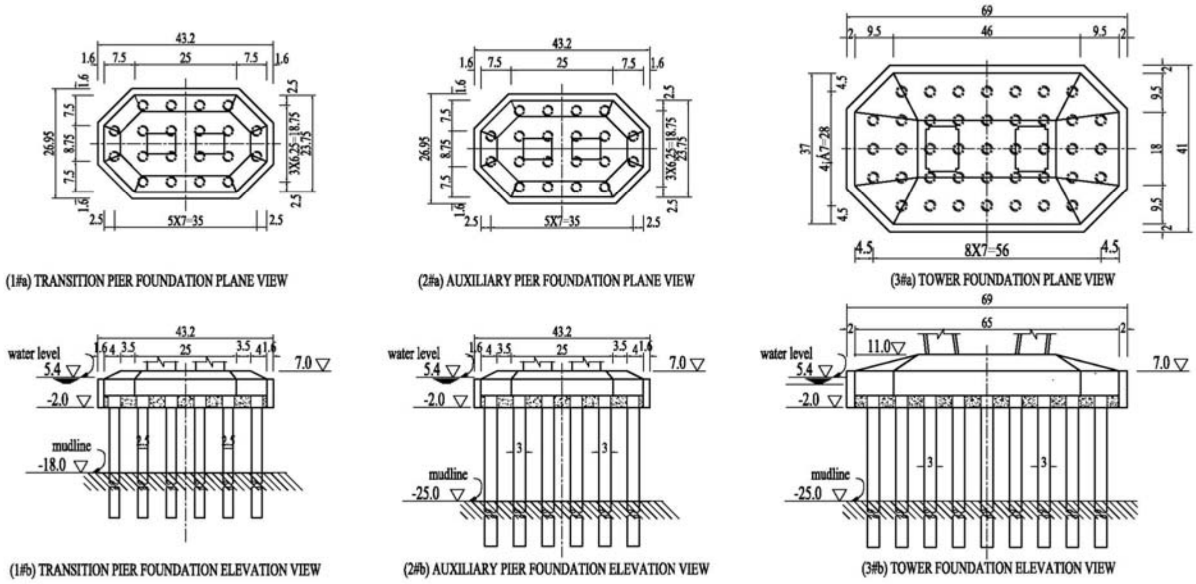
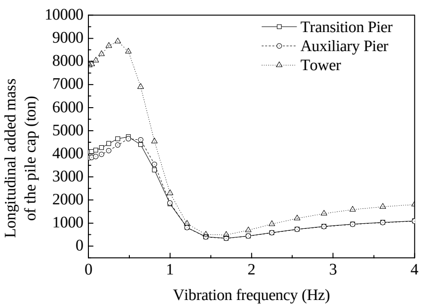
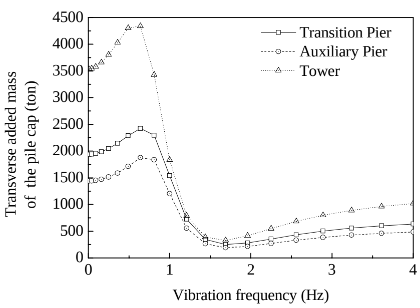


Figure 5 Pile foundations' geometry of the bridge (Unit: m)



(a) Longitudinal direction of the bridge



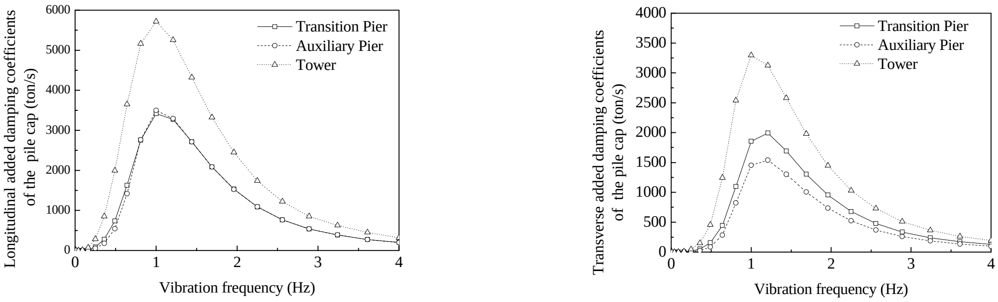
(b) Transverse direction of the bridge

Figure 6 Relation between pile caps' horizontal added mass and its vibration frequency

Based on the hydrodynamic tests' results of some rectangular section columns with different aspect ratios D/B (D is the length of the side which is perpendicular to the motion direction), Lai (2004) fitted an empirical formula to calculate the added mass correction coefficient K_c as

$$K_c = 0.94732 + \frac{2.59648}{1 + \left(\frac{D/B}{0.09516}\right)^{0.54638}}, \qquad 0.1 \le D/B \le 10 \tag{4.6}$$

For the Xiangshan Harbor Bridge, Figure5 shows the geometry of its pile foundations. Eqns.4.3 ~4.6 and other necessary formulae in the paper of Bhatta and Rahman (2003) were programmed; the horizontal added masses and damping coefficients were calculated for the pile caps, and the relation between pile caps' added mass and damping coefficients are shown in Figures 6 ~ 7.



(a) Longitudinal direction of the bridge (b) Transverse direction of the bridge

Figure 7 Relation between pile caps' horizontal added damping coefficients and its vibration frequency

4.2. Piles-Water Interaction

For a single pile, assuming the axis is identical with z-axis, the horizontal motion of the cylinder is along the x-axis and its displacement is $u_x(z,t)$, the displacement of a water particle which is on the axis of the pile is $u_w^x(z,t)$, then the relative displacement of the wave's water particle against the structure can be expressed as

$$r_x(z,t) = u_w^x(z,t) - u_z(z,t) \tag{4.7}$$

According to Morison Equation, the wave load acted on the pile's unit length at the depth of z can be written as

$$P(z,t) = (C_m - 1)\rho\Delta V \frac{\partial^2 r_x(z,t)}{\partial t^2} + \rho\Delta V \frac{\partial^2 u_w^x(z,t)}{\partial t^2} + C_D \frac{\rho}{2} D\Delta Z \frac{\partial r_x(z,t)}{\partial t} \left| \frac{\partial r_x(z,t)}{\partial t} \right| \tag{4.8}$$

Where: C_m is the coefficient of inertia, C_D is the coefficient of drag, ρ is the density of water, u is the displacement of the pile at the depth of z, ΔV is the volume of the pile's unit length at the depth of z, D is the outside diameter of the pile's section, ΔZ is the pile's unit length at the depth of z.

If the water is stationary when the pile begins to move along x-axis under seismic excitation, so the water particle's initial velocity and acceleration is zero, then Eqn. 4.8 can be rewritten as

$$P(z,t) = C_a \rho\Delta V \frac{\partial^2 r_x(z,t)}{\partial t^2} + C_D \frac{\rho}{2} D\Delta Z \frac{\partial r_x(z,t)}{\partial t} \left| \frac{\partial r_x(z,t)}{\partial t} \right| \tag{4.9}$$

Where: C_a is the hydrodynamic added mass coefficient, $C_a = C_m - 1$, it can take $C_a = 1$ for piles.

The hydrodynamic added mass of the pile's unit length can be written as

$$m_a = C_a \rho\Delta V \tag{4.10}$$

The hydrodynamic added damping of the pile's unit length can be written as

$$C_w = C_D \frac{\rho}{2} D\Delta Z \tag{4.11}$$

Table 4.1 The grouping effect coefficients of in-line, lift forces related to relative space S/D

S/D Direction of the pile array	2	3	4
Perpendicular to the wave spreading direction	1.5	1.25	1.0
Parallel to the wave spreading direction	0.85	0.9	1.0

Yuan (2005) investigated the effects of hydrodynamic damping on the seismic response of bridge piles; the research results shown that hydrodynamic damping provides slight contribution for the seismic response of the bridge piles. Hence, the hydrodynamic added damping of piles can be neglected and piles' hydrodynamic effects may be considered with added masses only. The hydrodynamic added masses for each pile of a pile group can be obtained by correcting the single pile's calculated hydrodynamic added masses with grouping effect coefficients. The grouping effect coefficients used in this study is shown in Table 4.1, which is stipulated by Chinese "Code of Hydrology for Sea Harbor (JTJ 213-98)".

5. SEISMIC ANALYSIS OF THE BRIDGE INCLUDING STRUCTURE- WATER INTERACTION

Finite element model is built for the Xiangshan Harbor Bridge. Acceleration records of El Centro N-S earthquake (1940) with scaled PGA of 0.2g, which is shown in Figure 8, is used as inputted seismic excitation in longitudinal and transverse direction of the bridge respectively.

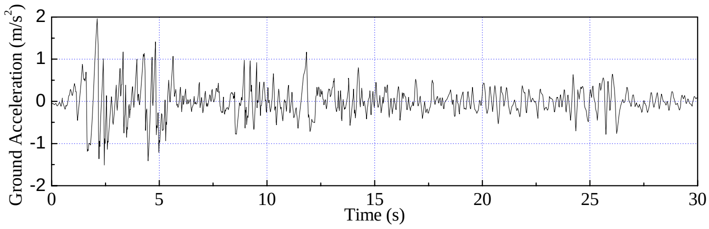
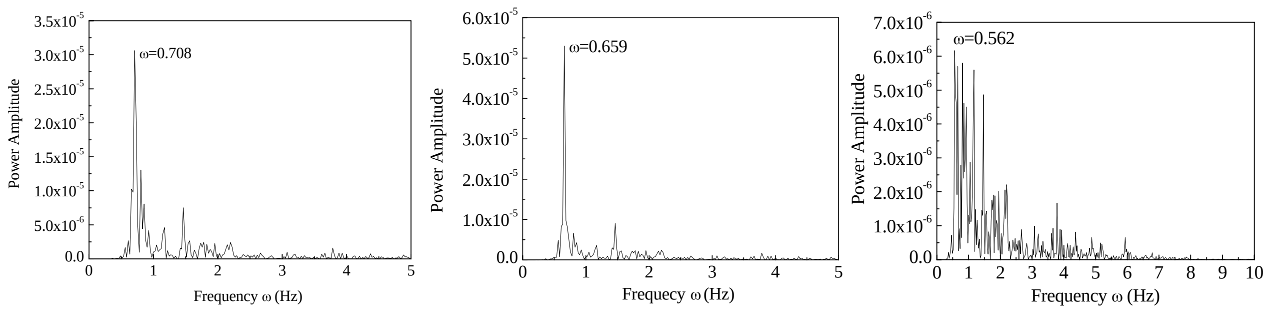
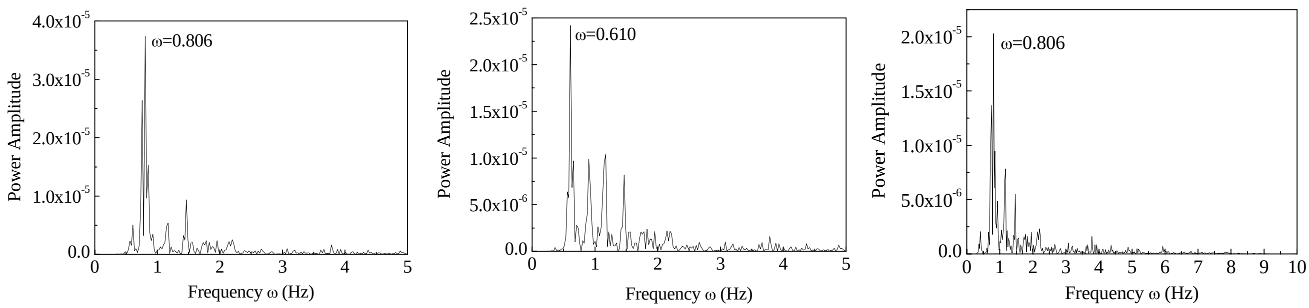


Figure 8 El Centro N-S earthquake wave records with scaled PGA of 0.2g



(a) 1# transition pier (b) 2# auxiliary pier (c) 3# tower

Figure 9 FFT results of the pile caps' acceleration response under longitudinal seismic excitation



(a) 1# transition pier (b) 2# auxiliary pier (c) 3# tower

Figure 10 FFT results of the pile caps' acceleration response under transverse seismic excitation

To obtain the predominant frequency of each pile cap's horizontal acceleration response, linear time history analysis is conducted for the bridge finite element model with only soil-structure interaction being included. The Fast Fourier Transformation (FFT) is performed for every pile cap's acceleration responses under longitudinal and transverse seismic excitation respectively, the FFT results are shown in Figures 9~10. The added mass and damping coefficients of each pile cap are determined for its predominant frequency of seismic acceleration responses, the results are shown in Table 5.1. For each of tower, the self-weight of its pile cap is 65447 tons; while the pile cap's maximum added mass is about 11% of its self-weight. For each auxiliary pier or transition pier, the self-weight of its pile cap is 21054 tons; while the pile cap's maximum added mass is about 20% of its self-weight in longitudinal direction and 10% in transverse direction of the bridge.

It is clear from Figures 9 ~10 that the seismic energy of a pile cap is mainly distributed in the neighbor of its predominant vibration frequency. Therefore, the added mass and damping coefficients corresponding to the predominant vibration frequency can represent the pile cap's interaction with water during the earthquake. Using the hydrodynamic parameters listed in Table 5.1 and added masses of piles calculated by Eqn.4.10, the water-structure interaction can be realized in the analytical finite element model. Comparison results of seismic responses of the bridge are shown in Tables 5.2~5.4 with structure-water interaction being considered or not.

Table 5.1 Predominant vibration frequency and its corresponding added mass and damping coefficients of the pile caps

Pile cap	Predominant frequency (Hz)		Added mass (ton)		Added damping coefficients (ton/s)	
	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
1# pier	0.708	0.806	4030	2305	2063	1081
2# pier	0.659	0.610	4541	1849	1552	223
3# Tower	0.562	0.806	7809	3460	2745	2515

Table 5.2 Maximum shear and moment response of piers and towers under longitudinal seismic excitation

Cross section's location	Soil-structure interaction		Soil-structure-water Interaction		R_V	R_M
	Vx（kN)	My(kN-m)	Vx(kN)	My(kN-m)		
	①	②	③	④	⑤=③/①	⑥=④/②
Bottom of 1# pier	4.75E+03	1.43E+05	4.08E+03	1.15E+05	85.8%	80.8%
Bottom of 2# pier	4.94E+03	1.54E+05	4.86E+03	1.49E+05	98.3%	97.2%
Bottom of 3# tower	1.07E+04	5.25E+05	1.11E+04	5.23E+05	103.7%	99.7%

Table 5.3 Maximum shear and moment response of piers and towers under transverse seismic excitation

Cross section's location	Soil-Structure Interaction		Soil-structure-water Interaction		R_V	R_M
	Vy (kN)	Mx (kN-m)	Vy (kN)	Mx (kN-m)		
	①	②	③	④	⑤=③/①	⑥=④/②
Bottom of 1# pier	6.19E+03	2.01E+05	5.76E+03	1.91E+05	93.0%	94.7%
Bottom of 2# pier	7.17E+03	3.33E+05	7.63E+03	3.53E+05	106.4%	106.1%
Bottom of 3# tower	3.59E+04	1.24E+06	3.75E+04	1.28E+06	104.3%	103.7%

Table 5.4 Maximum internal force responses of piles under longitudinal seismic excitation

Pile foundation	Soil-structure interaction		Soil-structure-water interaction		R_V	R_M
	Vx (kN)	My (kN)	Vx (kN)	My (kN)		
	①	②	③	④	⑤=③/①	⑥=④/②
1# pier	1.46E+03	2.01E+04	1.57E+03	2.21E+04	108.2%	109.6%
2# pier	1.54E+03	2.90E+04	1.82E+03	3.48E+04	118.7%	119.8%
3# tower	2.09E+03	3.73E+04	2.00E+03	3.65E+04	95.9%	97.9%

Table 5.5 Maximum internal force responses of piles under transverse earthquake excitation

Pile foundation	Soil-structurer interaction		Soil-structure-water interaction		R_V	R_M
	Vy (kN)	Mx (kN)	Vy (kN)	Mx (kN)		
	①	②	③	④	⑤=③/①	⑥=④/②
1# pier	2.16E+03	2.97E+04	2.08E+03	2.91E+04	96.4%	98.2%
2# pier	2.11E+03	3.94E+04	2.47E+03	4.80E+04	117.1%	121.7%
3# tower	2.31E+03	4.14E+04	2.21E+03	4.00E+04	95.8%	96.5%

Note: The Cartesian coordinate systems are defined with x-axis along the bridge's longitudinal direction, y-axis along the bridge's transverse direction and z-axis along the vertical direction.

It is clear from Tables.5.2~5.5 that hydrodynamic effects have no significant influence on the maximum shear and moment responses of towers and their underlying piles, auxiliary piers, transition piers' underlying piles. However, hydrodynamic effects have remarkable influence on maximum internal force responses of transition piers and auxiliary piers' underlying piles. Hydrodynamic effects might increase the maximum internal force responses of piers' underlying piles about 10~20%.

The afore-mentioned mechanical behaviors might result from changes of structural dynamic characteristics which induced by water-structure interaction.

6. CONCLUSIONS

In this paper, seismic performance of a long-span cable-stayed bridge is studied with soil-structure-water interaction being included, during which course the individual impedance matrix is adopted to simulate soil-pile system as well as structure-water interaction is considered through added mass and damping coefficients. The analysis results show that hydrodynamic effects have no significant influence on the maximum internal force responses of towers and their underlying piles. However, it may increase the maximum internal force responses of piers and their underlying piles about 10~20%. The afore-mentioned mechanical behaviors might result from changes of structural dynamic characteristics as hydrodynamic effects were considered. Therefore, it is necessary to consider water-structure interaction in seismic analysis of long-span cable-stayed bridges.

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