SEISMIC RESPONSE OF DEEP-WATER BRIDGE PIERS UNDER STRONG EARTHQUAKE CONSIDERING FLUID-STRUCTURE INTERACTION

S. Dong [(1)], Q.H. Zhao [(2)]

[(1)] *PhD candidate, Key Laboratory of Coast Civil Structure Safety of Ministry of Education, and School of Civil Engineering, Tianjin University, Tianjin 300072, China, sdong@tju.edu.cn*
[(2)] *Professor, Key Laboratory of Coast Civil Structure Safety of Ministry of Education, and School of Civil Engineering, Tianjin University, Tianjin 300072, China, qzhao@tju.edu.cn*

Abstract

Hydrodynamic pressure on deep-water bridge piers would occur during fluid-structure interaction under seismic action, which can be considered as the inertial force caused by the added-mass based on Morison equation, and added-mass intensifies seismic response of piers. However, the applicability of the added-mass of hydrodynamic pressure under strong earthquake is not taken into consideration in research. In order to investigate the seismic response of composite bridge piers in deep water, a refined 3-D fluid and pier model was constructed using software ADINA, which directly simulated the fluid-structure interaction. A 3-D pier model with added-mass was also constructed, which represented a simplified way to consider the influence of surrounding water on the pier during seismic events, based on Morison equation. Nonlinear time history analyses and parametric studies were conducted on both the refined and the simplified models to investigate the influence of slenderness ratio and water-depth ratio on the pier seismic response, as well as to evaluate accuracy of the simplified method. Results indicated that fluid-structure interaction and the hydrodynamic pressure acting on the submerged surface of deep-water bridge pier increased its seismic responses, especially under strong earthquake. The top relative displacement, shear forces and bending moment of the pier bottom could increase as high as 40%, but there was very limited influence on the pier top acceleration. When the height or outer dimension of the pier increased, the influence of hydrodynamic pressure increased as well. When the slenderness ratio of the pier increased, the influence of hydrodynamic pressure on the top relative displacement of pier increased. When the water-depth ratio exceeded 0.4, the influence of hydrodynamic pressure on pier seismic response was generally more than 15%. Accuracy of the simplified method increased with the slenderness ratio of the pier, but was not affected much by the water-depth ratio. After the slenderness ratio exceeded 53, accuracy of the simplified method would generally be within 10%, which makes it suitable for engineering calculation.

Keywords: deep-water composite bridge piers, fluid-structure dynamic interaction, nonlinear time history analysis, simplified method of added-mass, Morison equation, evaluate accuracy

1. Introduction

With the increasing human activities in the ocean, a number of coastal economic zones have emerged, and more and more cross-sea bridge has been built, such as Hong Kong Zhuhai Macao Bridge, Hangzhou Bay Bridge and Jiaozhou Bay Bridge. In consideration of navigation and sediment discharging, it is necessary to control the water blocking effect of the cross-sea bridge. Low pile caps are often used for cross-sea bridge, the foundations of which are usually buried below the seabed, and the piers are often located in the deep-water environment [1, 2]. Deep-water bridge serves as lifelines following earthquake events, and their protection is critical for minimizing loss of life, reducing economic impacts, and expediting post-disaster recovery. Deep-water bridge piers are the main load-bearing component and the main anti-lateral force component of the bridge, which plays an important role in the seismic resistance of the bridge.

Seismic response behavior of deep-water bridge piers is influenced by the surrounding water. Interaction with water causes additional dynamic forces on the structures and also modifies its dynamic properties, eventually even the deep-water bridge was damaged or collapsed [4, 5]. In the Wenchuan earthquake, the deep-water bridge piers were seriously damaged. The 10th bridge span of Miaoziping Bridge failed and dropped down, and many transverse cracks were found on the underwater part of the main pier [6]. It can be seen that it is of great significance to deeply understand the interaction mechanism between the pier and the surrounding water under earthquake excitation, and the details of how the earthquake and hydrodynamic pressure are applied to a deep-water bridge pier require some knowledge of simulated bridge and numerical modeling framework.

At present, there are mainly two approaches to calculate hydrodynamic pressure of bridge piers, including the fluid-structure interaction numerical simulation method and the method based on Morison equation. Dynamic fluid-structure interaction (FSI) has attracted more attention in the past 50 years. Since the analytical solutions are difficult to obtain for general FSI problems, the numerical techniques for FSI problems are developed. Wang [8] proposed a FSI method based on finite element method for dynamic response of structures in water under seismic excitations. Chen [9, 10] used the finite difference method to simulate the seismic hydrodynamic pressure on the breakwater and vertical column. Li and Liu [11] performed the pier-water coupling vibration experiments and computational simulation for the hydrodynamic force on deep-water piers by *ANSYS* software, and the effectiveness of the simulation calculation results was verified by comparing with the experimental results. The Morison equation was widely used to evaluate the hydrodynamic force [12-16], which contains two empirical hydrodynamic coefficients including an inertia coefficient and a drag coefficient, which are determined from experimental data [17, 18]. The Morison equation is not strictly from the theory of fluid mechanics. And the Morison equation is mainly suitable for a slender structure (cylinder $D/L< 0.2$, D denotes diameter and L means wavelength) [18]. Gao and Zhu [15] investigated the hydrodynamic effect on seismic response of bridge pier in deep-water, and the hydrodynamic forces were considered as the added-mass based on the Morison equation. Li and Song [16] presented a simplified method for calculation of hydrodynamic forces on the deep-water long span cable-stayed bridge based on Morison hydrodynamic theory.

Traditional reinforced concrete bridge pier has the characteristics of large self-weight, low bearing capacity and poor deformation capacity, which cannot meet the performance requirements of the deep-water bridge piers. Composite structure has great advantages in improving bearing capacity, increasing ductility and energy dissipation capacity, reducing self-weight and improving construction speed, which is very suitable for the deep-water bridge pier. However, the seismic response of composite bridge pier is greatly different from the reinforced concrete in deep-water. In order to study the influence of hydrodynamic pressure on the nonlinear seismic response of deep-water composite piers, the refined 3-D fluid-structure interaction numerical simulation model (FSI) and the simplified method of added-mass for FSI (AM) of composite piers were constructed by using the finite element analysis software ADINA. By the nonlinear time history analysis, the influence of slenderness ratio and water-depth ratio on the seismic response of composite piers and the accuracy of the simplified method of added-mass was investigated.

2. Finite element model

In order to consider the influence of the hydrodynamic pressure on the nonlinear seismic response of deep-water composite piers, and check the accuracy of the simplified method of added-mass, the bridge pier model without water (W/O), the refined 3-D FSI model (FSI) and the simplified models of added-mass (AM) of bridge pier with water were established.

2.1 Bridge pier model

Bridge piers in this paper are concrete-filled circular steel tube piers. The detailed dimensions of bridge composite pier models are shown in Table 1. The yield strength of steel used for steel pipe is 205MPa, with the elasticity modulus 206GPa. The strength grade level of concrete used for pier is C30, with the elasticity modulus 2.31×10^4MPa. The bridge piers are modeled as 3D-solid element by using the ADINA. The material nonlinearity of the pier is considered in the model. Face link is used to model the conjunction of the steel tube and infilled concrete. The mass of a span of bridge deck at the top of pier is considered as the concentrated mass, which is 5×10^5kg. The X direction translational constraint is released at the bottom of the pier, and the seismic excitation is applied along the X direction. The bridge pier model is shown in Fig. 1.

Table 1 – Bridge pier model

Model	Height H/m	Diameter D/m	Slenderness ratio λ	Water-depth ratio γ	Steel pipe thickness t /mm
P-1	30	3	80	0.8	26
P-2	10	3	27	0.8	26
P-3	20	3	53	0.8	26
P-4	30	5	48	0.8	46
P-5	30	7	34	0.8	62
P-6	30	3	80	0.4	26
P-7	30	3	80	0.6	26
P-8	30	3	80	1.0	26

Notes: λ=Slenderness ratio, $\lambda=l/i$, where l is the effective calculation distance of piers, i is gyration radius of piers; γ =Water-depth ratio, $\gamma=h/H$, where h is the depth of water.

2.2 Water fluid model

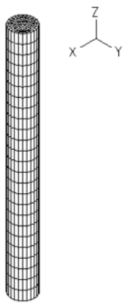

Fig. 1 – Bridge pier model.

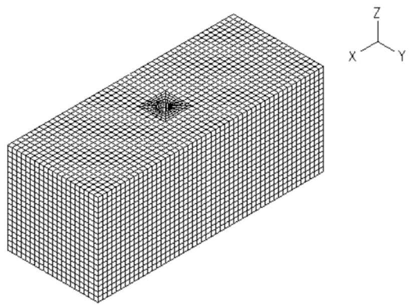

Fig. 2 – Water flow model

The length of the fluid model along the direction of seismic excitation is 100m, which is 20 times of the pier diameter. And the length of the fluid model along the direction perpendicular of the seismic excitation is 40m, which is 8 times of the pier diameter. The fluid is modeled as 3-D fluid element by the ADINA. The viscosity coefficient of fluid is 0.001Pa·s, with the bulk modulus 2.2×10^3MPa. The upper surface of the fluid model is free boundary, the bottom of the fluid model is solid, the surrounding of the fluid model is symmetrical boundary, and the interface between the fluid model and the bridge pier is fluid structure coupling boundary. The finite element model of water fluid is shown in Fig. 2.

2.3 Added-mass method of FSI

The hydrodynamic pressure can be simplified as the added-mass of the piers. The added-mass can be achieved by applying the corresponding surface mass on the surface of the pier under water. The magnitude of the added-mass , M_W, is given as [19]

$$M_W = (C_M - 1)\rho \frac{\pi}{4} D^2 H \tag{1}$$

Where C_M = inertia coefficient, the value of C_M is 2.0 [19]; ρ = fluid density.

3. Results and discussion

In this paper, nonlinear time-history analyses were performed using the scaled component of Taft and ChiChi earthquake with peak ground acceleration (PGA) equal to 0.6g and the duration is 10s.

3.1 Influence of the hydrodynamic pressure

Nonlinear time-history analyses are performed using the finite element model of the bridge pier with and without water. The influence of hydrodynamic pressure on the seismic response of model P-1 is shown in Table 2. The comparison of seismic time-history response of model P-1 under Taft earthquake with or without water is presented in Fig. 3. The relative displacement and acceleration of the pier top, shear force and moment of the pier bottom increase because of the effect of hydrodynamic pressure. It can be seen that hydrodynamic pressure has a greater influence on the relative displacement of the pier top, shear force and moment of the pier bottom, and a smaller influence on the acceleration of the pier top.

Table 2 – Bridge pier seismic response in Model P-1

Seismic waves	**Case**	**Pier top disp. /m**	**Pier top acce./m·s^{-2}**	**Pier bottom shear force/$\times10^6$N**	**Pier bottom moment /$\times10^6$N·m**
Taft	W/O	0.15	5.06	2.33	53.8
	FSI	0.16	5.65	3.47	63.6
	Diff./%	3.54	11.58	48.93	18.22
ChiChi	W/O	0.92	7.00	5.63	89.90
	FSI	1.08	7.51	5.89	99.1
	Diff./%	17.34	7.22	4.62	10.23

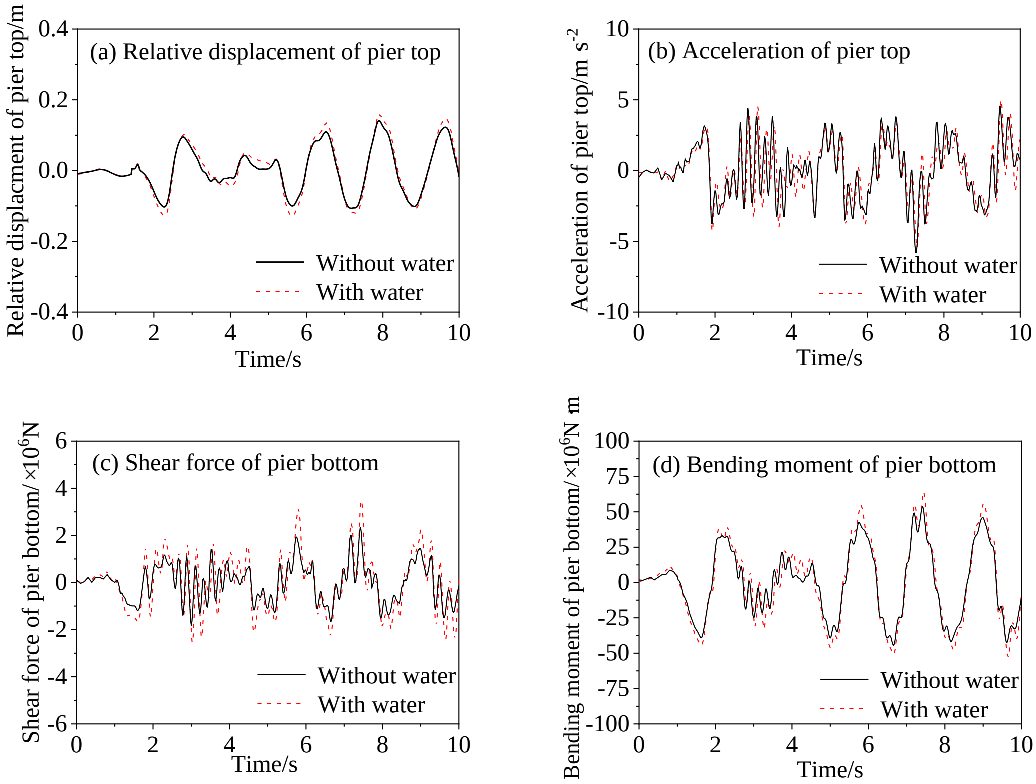

Fig. 3 Comparison of seismic time history response of P-1 with or without water

3.2 Influence of the slenderness ratio

In order to study the influence of the slenderness ratio on the seismic response of bridge pier and the accuracy of AM, nonlinear time-history analyses are performed on bridge pier of the five cases (P-1~P-5) defined in Table 1. The results of analyses are presented in Fig. 4, Fig. 5 and Table 3. The difference coefficient of seismic response under different slenderness ratio is shown in Fig. 6.

Influence coefficient of the hydrodynamic pressure is defined to study the influence of the hydrodynamic pressure on the seismic response of bridge pier., which is described as Eq. (2)-(3).

$$IC_{FSI} = \frac{R_{FSI} - R_{W/O}}{R_{W/O}} \times 100\% \tag{2}$$

$$IC_{AM} = \frac{R_{AM} - R_{W/O}}{R_{W/O}} \times 100\% \tag{3}$$

Where R_{FSI}, R_{AM} and $R_{W/O}$ are the seismic response of FSI, AM and W/O, respectively.

In order to study the accuracy of the simplified method of added-mass, difference coefficient of FSI and AM is defined as following equation:

$$E = \frac{R_{AM} - R_{FSI}}{R_{FSI}} \times 100\% \tag{4}$$

3.2.1 Influence of the slenderness ratio on seismic response of bridge pier

As shown in Fig. 4, the hydrodynamic pressure increases the relative displacement of the pier top. And with the increase of the slenderness ratio and flexibility of piers, the peak relative displacement of the pier top. By comparing the results under ChiChi and Taft earthquake motion, the increase of relative displacement of pier top is more obvious with the increases of slenderness ratio under ChiChi earthquake motion. When the slenderness ratio reaches 80, the influence coefficient of the relative displacement of pier top is 24.26%, the displacement angle reaches 3.79%, and there is obvious drum at pier bottom.

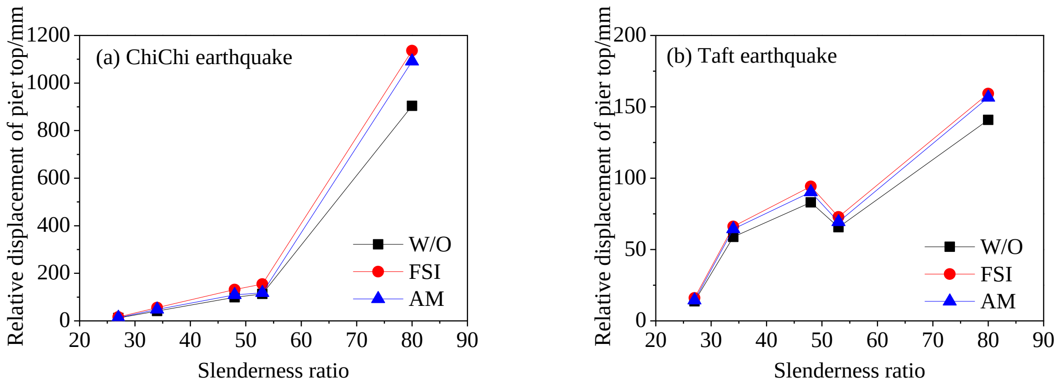

Fig. 4 –Pier top relative displacement under different slenderness ratio

As shown in Fig. 5, the pier top acceleration of the bridge pier with water is always greater than without water, the difference between them is reduced with the increase of the slenderness ratio. With the increase of the slenderness ratio of piers, the pier top acceleration decreases. The acceleration of P-5 is larger than that of P-2, which is mainly due to the rigidity of P-5 is larger than that of P-2. The acceleration response of P-5 is the most affected by the hydrodynamic, the influence coefficient of hydrodynamic pressure is 15.03%.

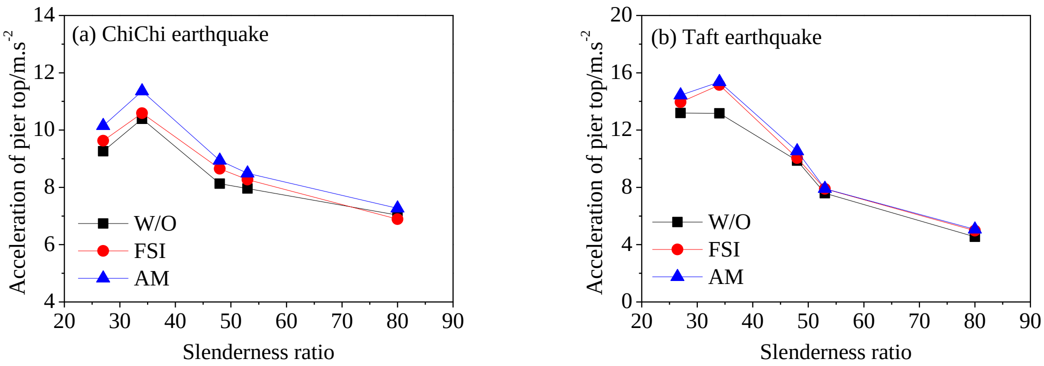

Fig. 5 –Pier top acceleration under different slenderness ratio

As shown in Table 3, the hydrodynamic pressure increases the peak shear force and bending moment of the pier bottom. The peak shear force of pier bottom is related to the size of the cross section. With the increase of diameter of the cross section of bridge pier, the shear force of the pier bottom increases obviously. The shear influence coefficients of high piers are larger, up to more than 40% (P-1, P-4, P-5). And the smaller the pier height is, the smaller the shear influence coefficient is. This is because the hydrodynamic pressure on the pier increases with the increase of pier height and water-depth. The peak bending moment of pier bottom is related to the height and section size of pier. The peak bending moment of pier bottom increases with the increase of pier height and section size. The influence coefficients of bending moment of

P-4 and, P-5 reach more than 26%. This is due to the higher the height and the larger the section size, the larger the interaction area between pier and fluid, and the greater the influence of hydrodynamic pressure on the seismic response of bridge pier.

Table 3 – Comparison of peak shear force and bending moment of pier bottom in model P-1 ~P-5

Model	**Seismic waves**	**Peak shear force of pier bottom/×10^{6}N**			**Influence coefficient**		**Peak bending moment of pier bottom/ ×10^{6}N·m**			**Influence coefficient**	
		W/O	FSI	AM	IC_{FSI}	IC_{AM}	W/O	FSI	AM	IC_{FSI}	IC_{AM}
P-1	ChiChi	5.63	5.89	5.39	4.62%	-4.26%	89.90	99.10	96.00	10.23%	6.79%
	Taft	2.33	3.47	3.21	48.93%	37.77%	53.80	63.60	61.90	18.22%	15.06%
P-2	ChiChi	5.00	6.24	5.33	24.69%	6.64%	41.75	45.68	43.06	9.41%	3.13%
	Taft	5.23	5.99	5.16	14.63%	-1.16%	44.40	50.60	46.33	13.97%	4.36%
P-3	ChiChi	5.28	6.61	5.96	25.20%	12.95%	81.63	95.47	87.20	16.95%	6.82%
	Taft	3.46	4.11	3.87	18.77%	12.10%	60.10	65.29	61.67	8.64%	2.61%
P-4	ChiChi	14.73	21.07	17.65	43.07%	19.86%	294.43	371.74	388.24	26.26%	31.86%
	Taft	11.37	14.16	13.11	24.50%	15.29%	262.64	291.87	306.57	11.13%	16.73%
P-5	ChiChi	24.52	37.10	30.73	51.34%	25.35%	517.13	652.42	693.38	26.16%	34.08%
	Taft	28.35	36.63	31.67	29.18%	11.70%	656.51	752.37	814.41	14.60%	24.05%

3.2.2 Influence of the slenderness ratio on the accuracy of AM

The difference coefficients of relative displacement and acceleration of the pier top, shear force and bending moment of the pier bottom under different slenderness ratio are shown in Fig. 6. As shown in Fig. 6(a), the difference coefficients of relative displacement of the pier top are all negative, that is, the analysis results of AM are less than that of FSI. When the slenderness ratio is 80, the analysis results of AM are similar with that of FSI, the difference coefficients of relative displacement of the pier top are below 4%. The error of AM increases with the decrease of the slenderness ratio.

As shown in Fig. 6(b), the difference coefficients of pier top acceleration are all positive, it shows that AM is more conservative. The difference coefficients of pier top acceleration are below 10%. Results show that the accuracy of AM can satisfy the requirement of engineering calculation.

As shown in Fig. 6(c), when the height of pier is kept constant, the difference coefficients of shear force of pier bottom increase with the increasing of section size of pier., which is due to the increase of influence of hydrodynamic pressure on pier bottom shear force. The difference coefficients of P-5 under ChiChi and Taft earthquake motion are 17.18% and -13.53%, respectively. The error of AM is relatively high.

As shown in Fig. 6(d), the difference coefficients of bending moment of the pier bottom under different slenderness ratio are below 10%. The absolute value of difference coefficients decreases with the increase of the slenderness ratio. The slenderness ratio is 80, the difference coefficients under ChiChi and Taft earthquake motion are 3.13% and -2.67%, respectively. The analysis results of FSI are slightly higher than those of AM. When the section size of pier is kept constant, the difference coefficients are negative under different height, which shows that AM underestimates the influence of hydrodynamic pressure on the bending moment of pier bottom. But when the height of the pier is kept constant, the difference coefficient changes from negative to positive with the increase of section size of the pier. When the diameter of the cross section of the pier is 7m, the difference coefficients under ChiChi and Taft earthquake motion is 6.28% and 8.25%, respectively.

In conclusion, there are some differences between the analyses results of AM and FSI, and the analyses results of AM are not all conservative. As for the relative displacement of the pier top and the shear force of the pier bottom, the added-mass method will underestimate the effect of hydrodynamic pressure. And the accuracy of AM increase with the increasing of the slenderness ratio, the difference coefficients are less than 10% when the slenderness ratio is 53-80. But when the slenderness ratio is less than 53, the error of AM is large, the maximum errors of the relative displacement of the pier top and the shear force of the pier bottom is 17.25% and 17.18, respectively. As for pier top acceleration and the bending moment of pier bottom, the difference coefficients are less than 10%.

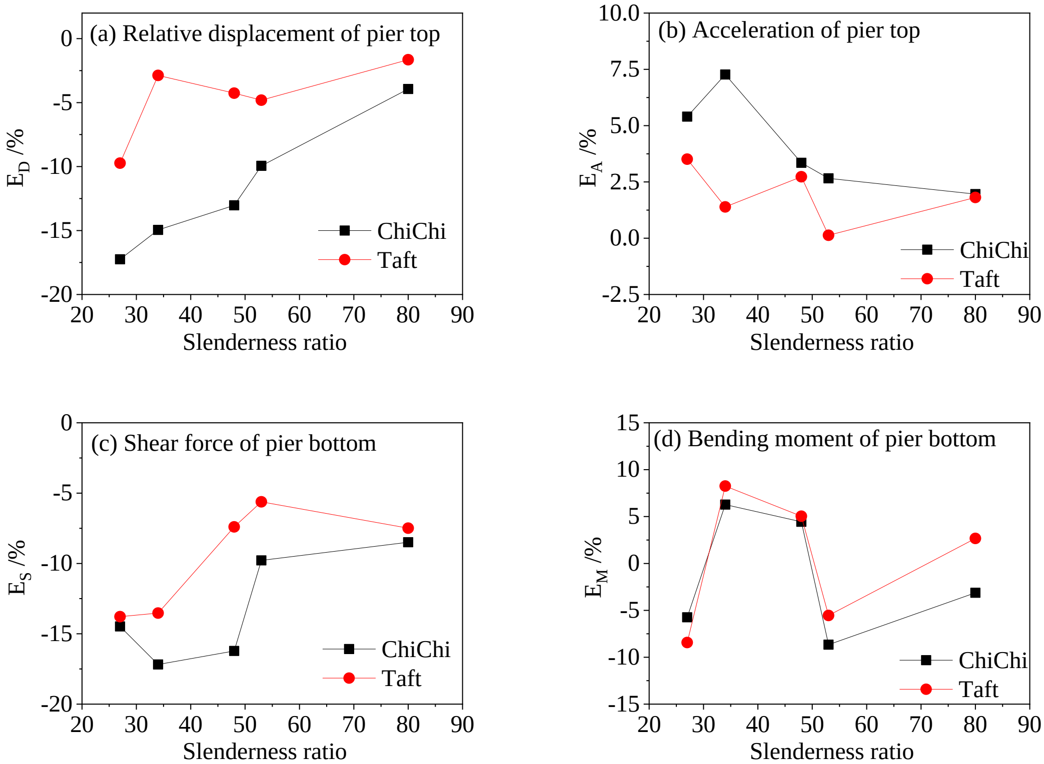

Fig. 6 – Difference coefficient of seismic response under different slenderness ratio

3.3 Influence of the water-depth ratio

In order to study the influence of the water-depth ratio on the seismic response of bridge pier and the accuracy of the simplified method of AM, nonlinear time-history analyses are performed of bridge pier of the five cases (P-1, P-6~P-8) defined in Table 1. The influence coefficient of hydrodynamic pressure under different water-depth ratio is shown in Fig. 7. The difference coefficient of seismic response under different slenderness ratio is shown in Fig. 8.

3.3.1 Influence of the water-depth ratio on seismic response of bridge pier

As shown in Fig. 7, the influence coefficients of seismic response are almost positive, this means that the hydrodynamic pressure increases the seismic response of deep-water bridge pier. The influence coefficients of the relative displacement of the pier top are shown in Fig. 7(a). When the water-depth ratio is less than 0.6, the influence coefficients are below 10%, and the difference of them under ChiChi and Taft earthquake motion is small. But the influence of hydrodynamic pressure is large when the water-depth ratio is greater than 0.6. Under the ChiChi earthquake motion, the influence coefficients of the relative displacement of the pier top increased with the increasing of water-depth ratio when the water-depth ratio is below 0.8, and that reaches the maximum when the water-depth ratio is 0.8. And then the influence coefficients decrease when the water-depth ratio increases to 1.0. Under Taft earthquake motion, the influence coefficients increase with the increase of water-depth, and reach the maximum when the water-depth ratio is 1.0.

The influence coefficients of pier top acceleration are shown in Fig. 7(b). With the increase of water-depth ratio, the acceleration of the pier top first increases and then decreases. The pier top acceleration under Taft earthquake motion is more affected by hydrodynamic pressure than that under ChiChi earthquake motion. Under Taft earthquake motion, the pier top acceleration increase with the increase of water-depth ratio when the water-depth ratio is less than 0.8, and reach the maximum when the water-depth is 0.8. Under ChiChi earthquake motion, the influence coefficient of pier top acceleration is positive when the water-depth ratio is between 0.4 and 0.8, which means that the hydrodynamic pressure increases the peak value of pier top acceleration; but when the water-depth ratio is 1.0, the influence coefficient is negative, which means that the hydrodynamic pressure decrease the peak value of pier top acceleration.

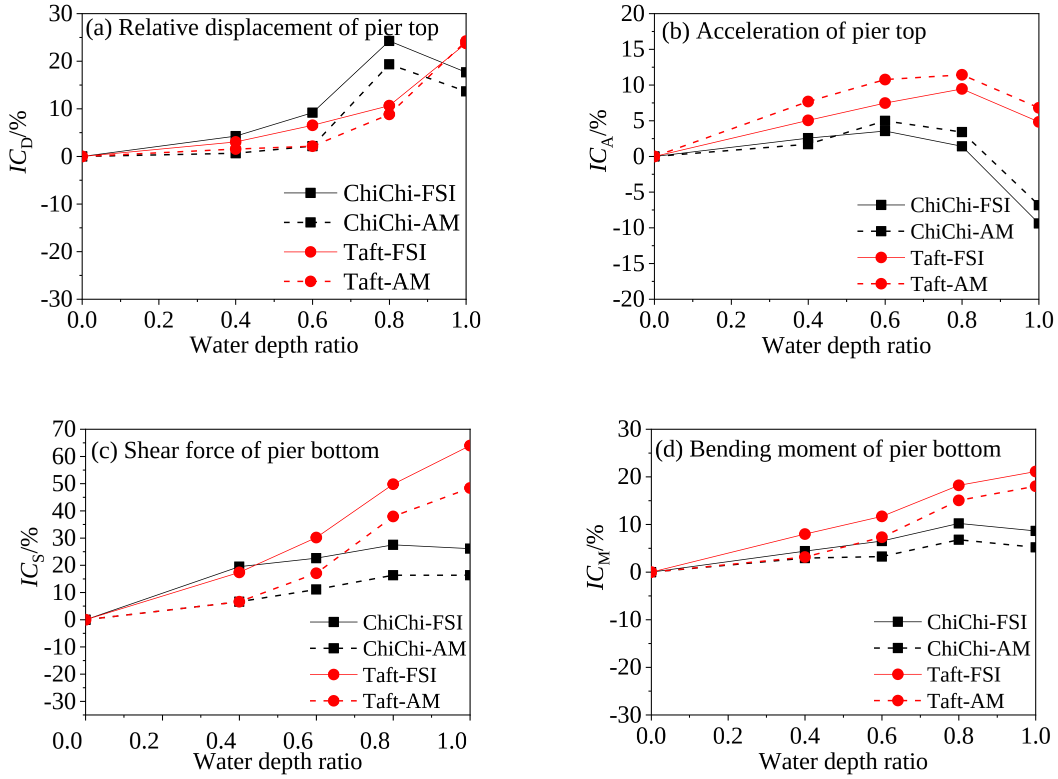

Fig. 7 –Influence coefficient of sesimic response under different water depth ratio

The influence coefficients of the shear force of the pier bottom are shown in Fig. 7(c). Under the ChiChi earthquake motion, the influence coefficients of the shear force of the pier bottom increased with the increasing of water-depth ratio when the water-depth ratio is below 0.8, and that reaches the maximum when the water-depth ratio is 0.8. And then the influence coefficients decrease when the water-depth ratio increases to 1.0. Under Taft earthquake motion, the influence coefficients increase with the increase of water-depth, and reach the maximum when the water-depth ratio is 1.0.

The influence coefficients of bending moments of pier bottom are shown in Fig. 7(d). The trend of the influence coefficients of bending moments of pier bottom is the same with that of pier bottom shear force.

In conclusion, with the increase of water-depth ratio, the influence coefficients of the relative displacement of the pier top, shear force and bending moments of the pier bottom increase, and reach the maximum value when the water-depth ratio is 0.8 or 1.0. When the water-depth ratio is 0.4, the influence coefficients of seismic response is large. Therefore, the effect of hydrodynamic pressure on the seismic response of deep-water bridge pier cannot be ignored.

3.3.2 Influence of the water-depth ratio on the accuracy of AM

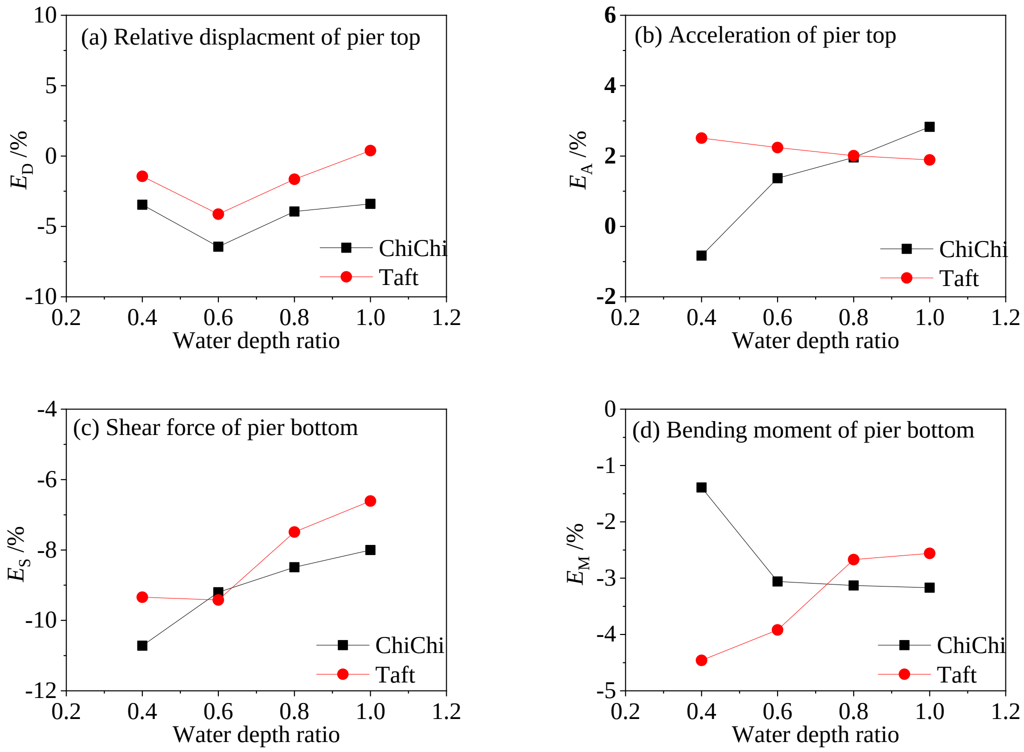

Fig. 8 – Difference coefficient of seismic response under different water-depth ratio

The difference coefficients of the relative displacement and acceleration of the pier top, shear force and bending moment of the pier bottom under different water-depth ratio is shown in Fig. 8. As shown in Fig. 8(a), the difference coefficients of relative displacement of pier top are all negative, that is, the analysis results of AM are less than that of FSI. The difference coefficients of the relative displacement of the pier top under ChiChi earthquake motion are larger than that under Taft earthquake motion.

As shown in Fig. 8(b), the variation trend of the difference coefficients of pier top acceleration is different under ChiChi and Taft earthquake motion. Generally, the difference coefficients of pier top acceleration are less than 3%. As shown in Fig. 8(c), the difference coefficients of the shear force of the pier bottom are all negative, that is, the added-mass method will underestimate the effect of hydrodynamic pressure on the shear force of the pier bottom. The absolute value of difference coefficients of the shear force of the pier bottom decreases with the increase of water-depth ratio, that is, the error of AM decreases gradually. As shown in Fig. 8(d), the variation trend of the difference coefficients of the bending moment of the pier bottom is different under ChiChi and Taft earthquake motion. The difference coefficients of the shear force of the pier bottom are all negative, that is, the added-mass method will underestimate the effect of hydrodynamic pressure on the bending moment of the pier bottom.

In conclusion, except the difference coefficients of shear force of pier bottom is -10.72% when the water-depth ratio is 0.4. The other difference coefficients of seismic response are all within 10%. Therefore, when the slenderness ratio of bridge pier is larger enough, the water-depth has little influence on the accuracy of add-mass method.

4. Conclusions

(1) The hydrodynamic pressure increases the seismic response of the deep-water bridge pier, and have great influence on the relative displacement of pier top, the shear force and bending moments of pier bottom, but have little influence on the acceleration of the pier top.

(2) With the increase of the slenderness ratio, the relative displacement of the pier top increase, but the acceleration of pier top decrease. The peak shear force of pier bottom is related to the size of the cross section. With the increase of diameter of cross section of bridge pier, the shear force of pier bottom increases obviously. The shear influence coefficient of high piers is larger, up to more than 40%. The higher the height and the larger the section size, the larger the interaction area between pier and fluid, and the greater the influence of hydrodynamic pressure.

(3) The accuracy of the added-mass method based on Morison equation is related to the slenderness ratio of pier, the larger the slenderness ratio is, the smaller the accuracy of the added-mass method is. When the slenderness ratio is greater than 53, the difference coefficient of seismic response is within 10%, the accuracy will satisfy the requirement of engineering.

(4) With the increase of water-depth ratio, the seismic response of deep-water composite bridge pier increase. When the water-depth ratio is 0.8 or 1.0, the influence of hydrodynamic pressure on seismic response is the largest. And when the water-depth ratio is more than 0.4, the influence of hydrodynamic pressure on seismic response is large, which cannot be ignored.

(5) The water-depth ratio has little influence on the accuracy of the added-mass method. When the slenderness ratio of pier meets the requirements, the added-mass method based can basically meet the requirements of engineering.

Acknowledgements

The authors gratefully acknowledge the financial supports for this research by the National Natural Science Foundation of China (NSFC) under grant number 51678406, 51878447

References

[1] Liu Minghu, Meng Fanchao, Li Guoliang, et al (2014). Design of the Qingzhou Ship Channel Bridge of Hong Kong-Zhuhai-Macao Bridge [J]. *Highway*. 01, 44-51. (in Chinese)

[2] Liu Minghu, Meng Fanchao, Li Guoliang, et al (2013). Engineering Characteristics and Key Techniques of Qingzhou Ship Channel Bridge of Hong Kong-Zhuhai-Macao Bridge. *Bridge Construction*, 43(4), 87-93. (in Chinese)

[3] Liu Zhenyu, Li Qiao, Zhao Canhui, et al (2009). Analysis of seismic responses of continuous rigid frame bridge in deep water. *Earthquake Engineering and Engineering Vibration*, 29(4), 119-124. (in Chinese)

[4] Yang, Wangli, Li, Qiao (2012). Effects of hydrodynamic pressure on seismic response of continuous rigid-framed bridge. *Journal of Southwest Jiaotong University*, 47(3), 373–378 (in Chinese).

[5] Gao Xuekui, Zhu Xi, Li Hui. (2006). Seismic response analysis of bridge pier in deep water excited by near-fault earthquakes. *Earthquake Resistant Engineering and Retrofitting*, 28(3), 83–87 (in Chinese).

[6] Yang Wangli, Li Qiao, Zhao Canhui, et al. (2012) Failure Mechanism Analysis of Main Bridge of Miaoziping Bridge and Seismic Design Measures. *6th National Symposium on Earthquake Prevention and Mitigation Engineering*, Harbin, China. (in Chinese)

[7] Liaw, C.Y., Chopra, Anil. K. (1974). Dynamics of towers surrounded by water. *Earthquake Engineering and Structural Dynamics*, 3, 33–49.

[8] Wang Zhihua, Cao Wei, Chen Guoxing (2010). Seismic Response Analysis of Deepwater Bridge Pier considering Close Fluid-structure Interaction Effects. *Journal of Disaster Prevention and Mitigation Engineering*, 30(5), 517-523. (in Chinese)

[9] Chen B F (2000). Dynamic responses of coastal structures during earthquakes including sediment-sea-structure interaction. *Soil Dynamics & Earthquake Engineering*, 20(5), 445~467.

[10] Chen B F. (1998). Hybrid three-dimensional finite-difference and finite-element analysis of seismic wave induced fluid-structure interaction of a vertical cylinder. *Ocean Engineering*, 25(8), 639~656

[11] Li, Qiao, Liu, Lang, Yang, Wangli (2016). Experimental and numerical investigation on pier-water coupling vibration of bridges in deepwater. *Engineering. Mechanics*, 33(7), 197–203 (in Chinese).

[12] Yang Wangli, Li Qiao, Yeh Harry (2017). Calculation Method of Hydrodynamic Forces on Circular Piers during Earthquakes. *Journal of Bridge Engineering*, 22(11),04107093.

[13] Du Xuli, Wang Piguang, Zhao Mi (2014). Simplified formula of hydrodynamic pressure on circular bridge piers in the time domain. Ocean Engineering, 85, 44-53.

[14] Li, Furong, Chen Xingguo, Wang Zhihua (2008). Seismic responses of single-column pier considering the effects of hydrodynamic pressure. *Journal of Earthquake Engineering and Engineering Vibration*, 28 (2), 114–121 (in Chinese).

[15] Gao, Xuekui, Zhu, Xi (2006). Hydrodynamic effect on seismic response of bridge pier in deep water. *Journal of Beijing Jiaotong University*. 30 (1), 55–58 (in Chinese)

[16] Li Yue, Song Bo (2010). Study of the effect of hydrodynamic force on cable-stayed bridges under earthquake. *China Civil Engineering Journal*, 43 (12), 94–99 (in Chinese).

[17] Morison JR, Obrien MP, Johnson JW, et al (1950). The Force Exerted by Surface Wave on Piles. *Journal of Petroleum Technology*, 2 (5), 149-154.

[18] Penzien J, Kaul MK (2010). Response of Offshore Towers to Strong Motion Earthquakes. *Earthquake Engineering & Structural Dynamics*, 1 (1), 55-68.

[19] Ministry of transport of the people's republic of China. Code of Hydrology for Sea Harbour (JTS 145-2-2013). Beijing: China Communications Press, 2013.

