13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3

THE EXPERIMENTAL STUDY OF THE HYDRODYNAMIC EFFECTS ON SEISMIC RESPONSE OF BRIDGES

Jun-jie Wang[1], Wei Lai[1], Zhi-qiang Wang[1], Xiao Wei[2], Shide Hu[1]

SUMMARY

A semi-analytical and semi-numerical approach for earthquake induced hydrodynamic pressure on pier was developed. Trefftz-complete functions were used to form the potential of rigid movement and that of elastic vibration. The coupling kinetic equations were solved by FEM with beam element. This method is a relatively simple and efficient approach, retaining the gravity waves on the water surface and the compressibility of the fluid. Examples were presented to discuss the influence of earthquake induced hydrodynamic pressure on pier and the accuracy of this method was illustrated. Based on the potential theory, hydrodynamic pressure on the side of circular pile cap was also investigated. An efficient semi-analytical and semi-numerical approach for harmonic earthquake induced hydrodynamic pressure on the side of circular pile cap was developed, as well as coefficient of added mass. This method is not only able to consider gravity waves on the water surface, but also able to be applied to pile cap in arbitrary depth of water. Results of analysis illustrated that for pile cap near the surface of water, surface wave would have significant effect on hydrodynamic pressure in the case of low frequency of movement, while there is little effect of surface wave induced by high frequency of movement. Besides, using coefficient of added mass in modified Morison equation will over-evaluate the hydrodynamic pressure on pile cap. To investigate the importance of hydrodynamic pressure on seismic response of bridge, shaking table tests of bridge models have been carried out.

INTRODUCTION

Some bridges crossing sea bays or sea straits have been constructed, or are in the design and planning stage in home and abroad, two examples are shown in Figure 1 and Figure2. The Bohai bay has a width of 145km, and a mean water depth of 40m; the Qiongzhou strait has a shortest width of 20km, and a mean water depth of 60m. Solutions of bridges and tunnels have been proposed. The earthquake-resistance of bridges surrounded by water requires special considerations, while it does not need such considerations for bridges on the land.

For decades, most of the researches on dynamics of structures surrounded by water has focused on dams[3-6], platforms[7-12], and tower structures[13-17], etc. For vibration of structures surrounded by water, various methods may be used, e.g., FEM, BEM, and analytical method. However, for complex cases, an analytical method is rather difficult to process mathematically. To solve such a problem numerically with FEM or BEM would involve a large

[1] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, PRC
[2] Department of Earthquake Hazard Prevention, Seismological Bureau of Shanghai, 200062, PRC

number of degrees of freedom and much computer time.

To the knowledge of the authors, there have been few research papers[18-22] that deal with the response characteristics of bridges surrounded by water up to now. Furthermore, in most papers about bridges, the pier was reduced to a cantilever beam in water. For a circular cylinder surrounded by water, [23-25] which has given analytical or semi-analytical solutions based on vibration equation and mode functions of cantilever beam in water. But those solutions are limited to single cylinder, being not convenient to be coupled with other parts of a structure for vibration analysis of the whole structure. To overcome the above problems, a semi-analytical and semi-numerical method is introduced herein based on Trefftz complete function and FEM. The gravity waves on the water surface and the compressibility are retained in the method for extremely low frequency and high frequency. The hydrodynamic pressure is expressed in the form of virtual mass as the Morison's equation does.

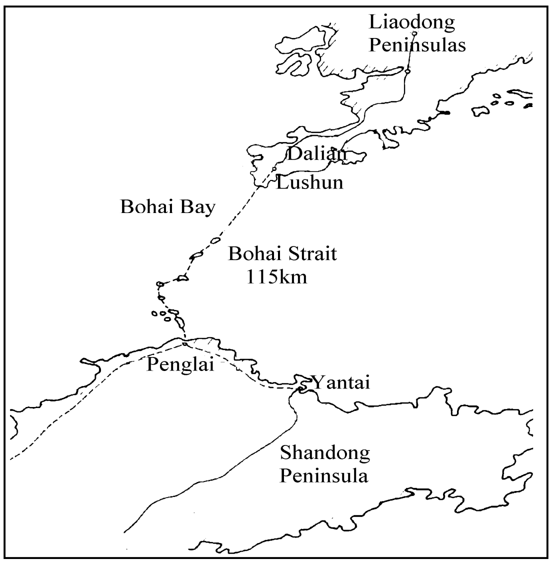


Figure 1. The Bohai Bay in China

Figure2 The Qiongzhou Strait

For pile foundation, Morison equation is preferable to calculate the added mass on piles with small radius. But for pile cap under free surface of water, regular coefficient of added mass in Morison equation is not suitable anymore. Thus in this paper, earthquake induced horizontal hydrodynamic pressure are also obtained for pile cap, as well as coefficient of added mass for pile cap.

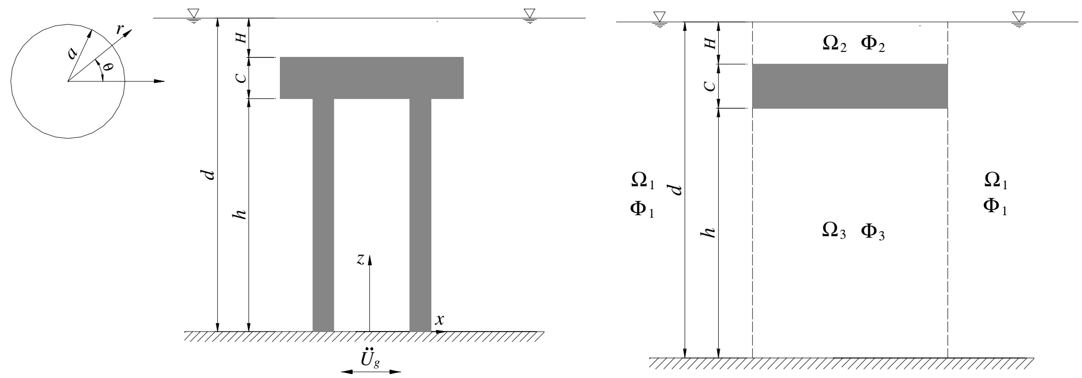
HYDRODYNAMIC PRESSURE ON PILE CAP DUE TO EARTHQUAKES

It is assumed that the global displacement motion of pile cap is $U(t)=u_0 e^{i\omega t}$, and then the hydrodynamic pressure along unit length of the pile cap is,

$$P(a,z,t)=\ddot{U}(t)\rho a\pi\Bigg[Z_0(z)\overline{H}_1(\lambda_0 a)\int_h^{C+h}Z_0(z)dz+\sum_{m=1}^{\infty}Z_m(z)\overline{K}_1(\lambda_m a)\int_h^{C+h}Z_m(z)dz$$
$$+Z_0(z)\overline{H}_1(\lambda_0 a)\left(\sum_{n=0}^{\infty}\dot{\overline{V}}_{1n}P_{0n}^{(1)}+\sum_{s=0}^{\infty}\dot{\overline{V}}_{2s}P_{0s}^{(2)}\right)+\sum_{m=1}^{\infty}Z_m(z)\overline{K}_1(\lambda_m a)\left(\sum_{n=0}^{\infty}\dot{\overline{V}}_{1n}P_{mn}^{(1)}+\sum_{s=0}^{\infty}\dot{\overline{V}}_{2s}P_{ms}^{(2)}\right)\Bigg] \quad (1)$$

in which

$$\overline{H}_1(ka)=\frac{H_1^{(2)}(ka)}{kH_1^{(2)'}(ka)},\quad \overline{K}_1(ka)=\frac{K_1(ka)}{kK_1^{'}(ka)} \quad (2)$$



(a) the pile foundation (b) the domains of fluid

Figure 3 Model for Analysis of Hydrodynamic Pressure of Pile Cap

$$Z_0(z)=\frac{\sqrt{2}\cosh(\lambda_0 z)}{\sqrt{d+\sigma^{-1}\sinh^2(\lambda_0 d)}},\quad Z_m(z)=\frac{\sqrt{2}\cos(\lambda_m z)}{\sqrt{d-\sigma^{-1}\sin^2(\lambda_m d)}}\quad m=1,2,\ldots\quad 0<z<d \tag{3}$$

where $\dot{\bar{V}}_{1n}$ and $\dot{\bar{V}}_{2s}$ are constants to be decided by the continuous conditions among velocity potentials of different fluid domain, other symbols have the same meaning as before. Constants of $P_{ij}^{(1)}$ and $P_{ij}^{(2)}$ are calculated respectively,

$$P_{ij}^{(1)}=\int_{C+h}^{d} Z_i(z)F_j(z)dz \quad i,j=0,1,2\cdots \tag{4a}$$

$$P_{ij}^{(2)}=\int_{0}^{h} Z_i(z)f_j(z)dz \quad i,j=0,1,2\cdots \tag{4b}$$

where,

$$\begin{cases} F_0(z)=\dfrac{\sqrt{2}\cosh[\partial_0(z-C-h)]}{\sqrt{H+\sigma^{-1}\sinh^2(\partial_0 H)}} \\ F_m(z)=\dfrac{\sqrt{2}\cos[\partial_m(z-C-h)]}{\sqrt{H-\sigma^{-1}\sin^2(\partial_m H)}} \quad m=1,2,\ldots \end{cases} \quad C+h<z<d \tag{5}$$

$$\begin{cases} f_0(z)=1/\sqrt{h} \\ f_m(z)=\sqrt{\dfrac{2}{h}}\cos\left(\dfrac{m\pi z}{h}\right) \quad m=1,2,\ldots \end{cases} \quad 0<z<h \tag{6}$$

in which, H is the displacement from the surface of cap to the water surface, ∂_0 and ∂_m are the solution of the following dispersion relation equations,

$$\begin{cases} \tanh(\partial_0 H)=\dfrac{\omega^2}{g\partial_0} \\ \tan(\partial_m H)=-\dfrac{\omega^2}{g\partial_m} \end{cases} \tag{7}$$

Finish the integral of $P(r,z,t)\big|_{r=a}$ along cap in z-direction, the horizontal hydrodynamic force F_a can be obtained,

$$F_a = \ddot{U}(t)\rho a\pi\Bigg[\overline{H}_1(\lambda_0 a)\left(\int_h^{C+h} Z_0(z)dz\right)^2 + \sum_{m=1}^{\infty}\overline{K}_1(\lambda_m a)\left(\int_h^{C+h} Z_m(z)dz\right)^2$$
$$+\overline{H}_1(\lambda_0 a)\left(\sum_{n=0}^{\infty}\bar{\dot{V}}_{1n}P_{0n}^{(1)} + \sum_{s=0}^{\infty}\bar{\dot{V}}_{2s}P_{0s}^{(2)}\right)\int_h^{C+h} Z_0(z)dz + \sum_{m=1}^{\infty}\overline{K}_1(\lambda_m a)\left(\sum_{n=0}^{\infty}\bar{\dot{V}}_{1n}P_{mn}^{(1)} + \sum_{s=0}^{\infty}\bar{\dot{V}}_{2s}P_{ms}^{(2)}\right)\int_h^{C+h} Z_m(z)dz\Bigg] \tag{8}$$

denote,

$$\mathrm{m}_a = -\rho a\pi\Bigg[\overline{H}_1(\lambda_0 a)\left(\int_h^{C+h} Z_0(z)dz\right)^2 + \sum_{m=1}^{\infty}\overline{K}_1(\lambda_m a)\left(\int_h^{C+h} Z_m(z)dz\right)^2$$
$$+\overline{H}_1(\lambda_0 a)\left(\sum_{n=0}^{\infty}\bar{\dot{V}}_{1n}P_{0n}^{(1)} + \sum_{s=0}^{\infty}\bar{\dot{V}}_{2s}P_{0s}^{(2)}\right)\int_h^{C+h} Z_0(z)dz$$
$$+\sum_{m=1}^{\infty}\overline{K}_1(\lambda_m a)\left(\sum_{n=0}^{\infty}\bar{\dot{V}}_{1n}P_{mn}^{(1)} + \sum_{s=0}^{\infty}\bar{\dot{V}}_{2s}P_{ms}^{(2)}\right)\int_h^{C+h} Z_m(z)dz\Bigg] \tag{9}$$

then equation (21) can be written as,

$$F_a = -m_a\ddot{U}(t) \tag{10}$$

in which m_a is the added hydrodynamic mass on the cap in horizontal direction. Then the added hydrodynamic mass factor $C_a^{'}$ is,

$$C_a^{'} = m_a / C\rho\pi a^2 \tag{11}$$

From the above analysis, with the consideration of surface waves, $C_a^{'}$ is related to frequency ω, then the dynamic equation of bridge under seismic action should be written in frequency domain,

$$\left(\mathbf{K} + i\omega\mathbf{C} - \omega^2\mathbf{M}\right)\mathbf{u}_s(\omega) = -\mathbf{M}\ddot{\mathbf{u}}_g(\omega) - \mathbf{M}_a\left(\ddot{\mathbf{u}}_g(\omega) - \omega^2\mathbf{u}_s(\omega)\right) \tag{12a}$$

$$\left(\mathbf{K} + i\omega\mathbf{C} - \omega^2(\mathbf{M} + \mathbf{M}_a)\right)\mathbf{u}_s(\omega) = -(\mathbf{M} + \mathbf{M}_a)\ddot{\mathbf{u}}_g(\omega) \tag{12b}$$

where $\mathbf{K}$, $\mathbf{C}$ and $\mathbf{M}$ are the stiffness matrix, damping matrix and mass matrix of bridge respectively. $\ddot{\mathbf{u}}_g(\omega)$ is defined in equation (10), $\left[\ddot{\mathbf{u}}_g(\omega) - \omega^2\mathbf{u}_s(\omega)\right]$ is the absolute acceleration vector of bridge structure, $\mathbf{M}_a$ is the matrix of added hydrodynamic mass, which diagonal elements correspond to the part of bridge in water and zero elements correspond to other parts of bridge.

When the effects of surface waves are neglected, we have $\sigma^{-1} = g/\omega^2 = 0$, and λ_0 and ∂_0 do not exist, $\lambda_m = \dfrac{(2m-1)\pi}{2d}$, $Z_m(z) = \sqrt{\dfrac{2}{d}}\cos(\lambda_m z)$, $\partial_m = \dfrac{(2m-1)\pi}{2H}$, $F_m(z) = \sqrt{\dfrac{2}{H}}\cos(\partial_m z)$, meanwhile $\bar{\dot{V}}_{1n}$ and $\bar{\dot{V}}_{2s}$ are not related to ω, thus the added hydrodynamic mass is not related to ω. Then equation (12b) can be written in time domain,

$$(\mathbf{M} + \mathbf{M}_a)\ddot{\mathbf{u}}_s(t) + \mathbf{C}\dot{u}_s(t) + \mathbf{K}u_s(t) = -(\mathbf{M} + \mathbf{M}_a)\ddot{\mathbf{u}}_g(t) \tag{13}$$

As an example, assume the pile cap moves in an harmonic way, and $d = 30m$, $a = 6m$, $C = 3m$, $\theta = 0^{\circ}$. The results are shown in Figure 4 and 5. It is observed that the added mass factor is significantly increased or decreased by the surface waves in the range of lower frequency, and with the increase of ω, the contribution of surface waves to $C_a^{'}$ decreases, finally reach the value without consideration of the effects of surface waves. From Figure 5, $C_a^{'}$ is related to the position of the cap in the water. Figure 6 gives the relationship between $C_a^{'}$ and d . It can be seen from Figure 6 that the depth of water d has an insignificant effect on $C_a^{'}$.

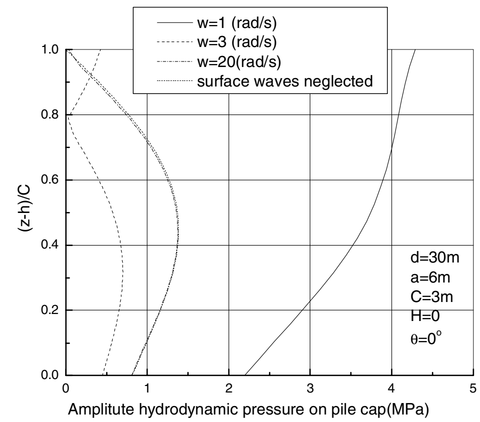


Figure 4 The Amplitute of Hydrodynamic Pressure on The lateral Side of The Pile Cap

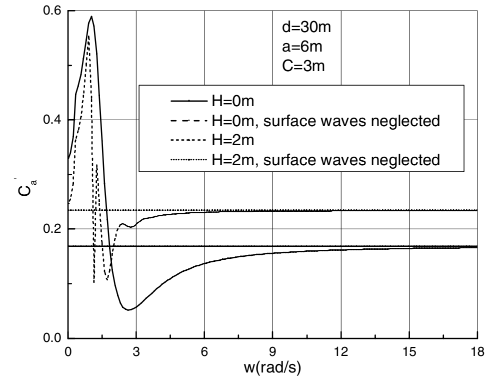


Figure 5 The Added mass Factor

Figure 7 gives the relationship between $C_a^{'}$ and C/d . Figure 7(a) is for $d = 20m$, and (b) is for $d = 40m$. It is observed that $C_a^{'}$ increases with C (the thickness of the cap) when d is a constant. One can see that $C_a^{'}$ vary with frequency ω , and reaches a peak at a frequency range of 0.5-1.5rad/s. It means that fluid motion with low frequency may lead to large hydrodynamic pressure.

Figure 8 demonstrates that $C_a^{'}$ gets larger with the value of radius a. But $C_a^{'}$ is not more than 1. According to the modified Morison equation, the added mass factor for a circular cylinder with relative minor radius to water depth is $C_a = 1.0$. The results shown in Figure 8 mean that the Morison's equation would exaggerate the added hydrodynamic mass on the cap in horizontal direction.

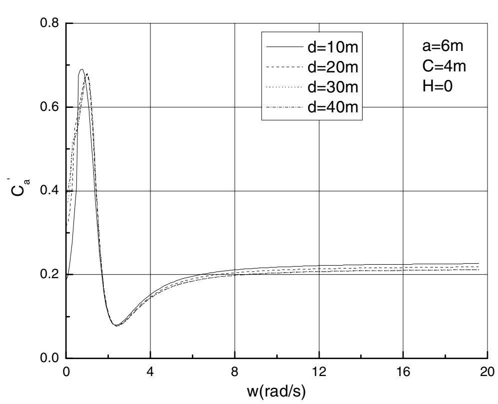


Figure 6 Relationship Between $C_a^{'}$ and d

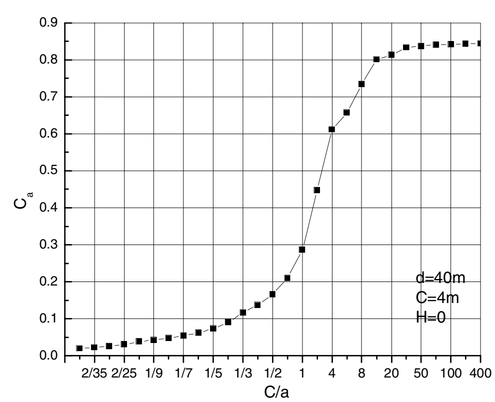
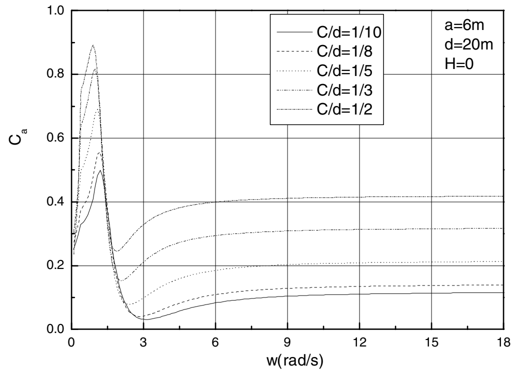
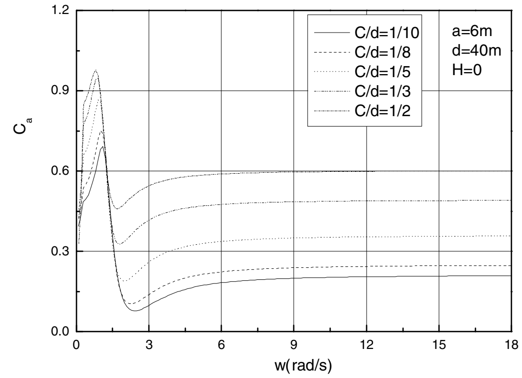


Figure 8 Relationship Between $C_a^{'}$ and a





(a) d=20m (b) d=40m

Figure 7 Relationship Between $C_a^{'}$ and C/d

SHAKING TABLE TESTS OF MODEL PIERS OF BRIDGE

To investigate the importance of hydrodynamic pressure on seismic response of bridge, and to verify the formulas derived in this paper, shaking table tests of model bridge piers were carried out. Two model bridge piers were designed. The first is a model of Pingtan Bridge(in Fujian province, China, see Figure 9) following the similarity laws，and the second one is an ideal model, which is the same in configuration, but with different mass density and different stiffness. The configurations of the model bridge pier are shown in Figure 10. Figure 11 shows the pictures of the model bridge piers.

Some results of the shaking table tests for harmonic excitations are shown in Figure 12-18. What one can observe from Figure 12-18 tell us that the hydrodynamic fluid pressures enlarge the seismic responses of the model bridges. Not much enlargement is observed in Figure 13 and 14 for model of Pingtan Bridge. But large enlargement for ideal model bridge is observed.

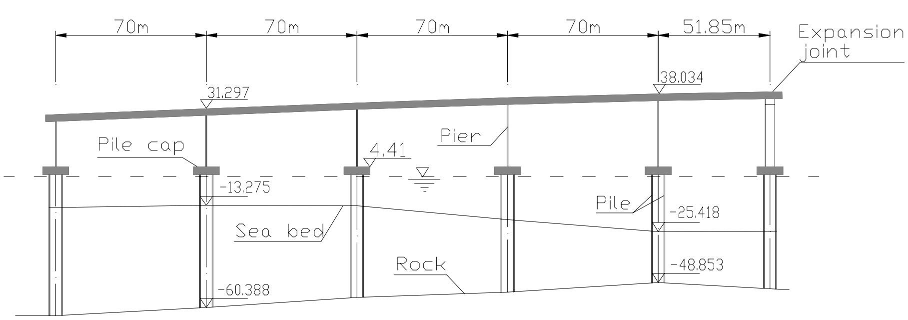


Figure 9 The Pingtan Bridge(approach spans)

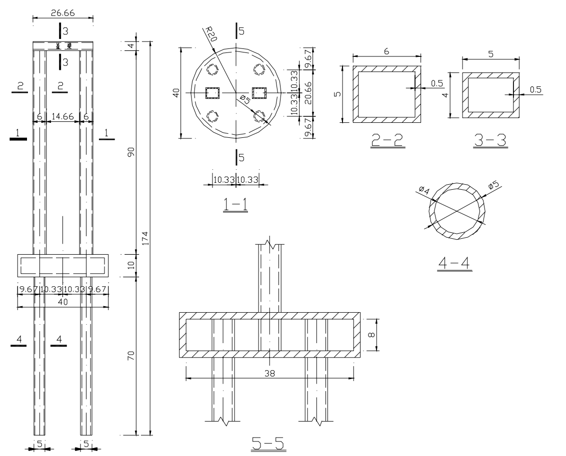


Figure 10 The Configuration of The Tested Model Bridge Piers

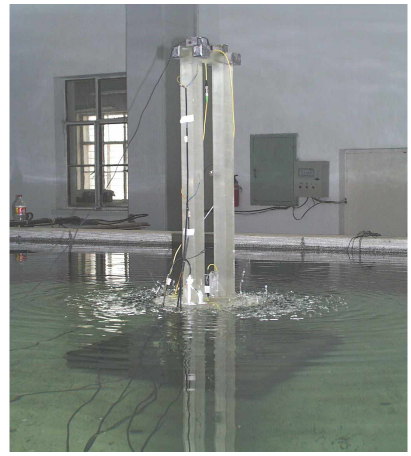


Figure 11 Example Photos of Bridge Models in Testing

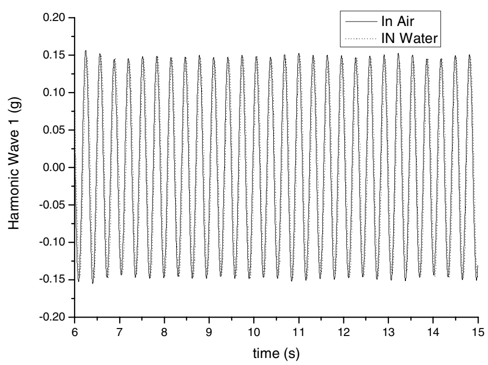


Figure 12 Harmonic Excitations (3.13Hz) For Model of Pingtan Bridge

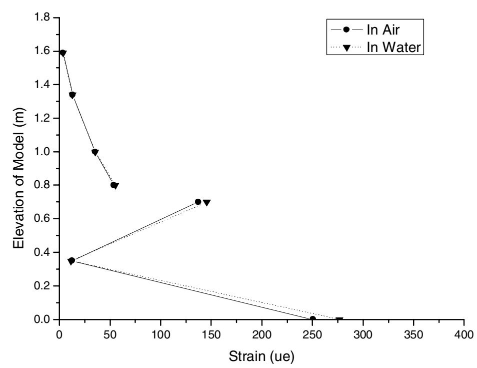
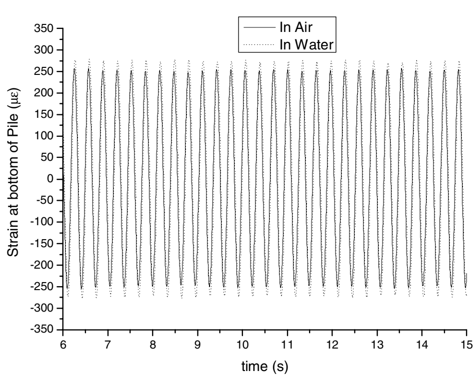


Figure 13 Strain envelope along the elevation For Model of Pingtan Bridge



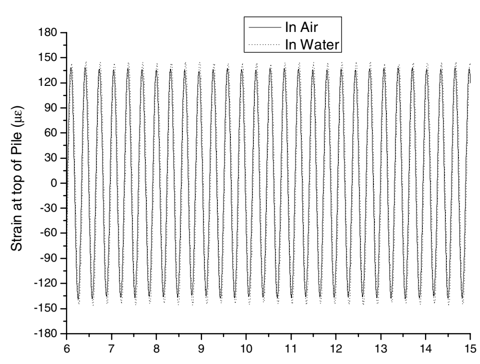
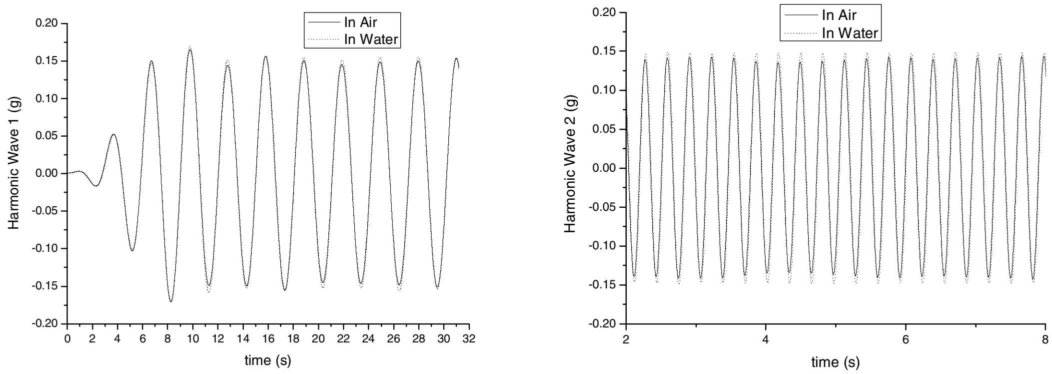
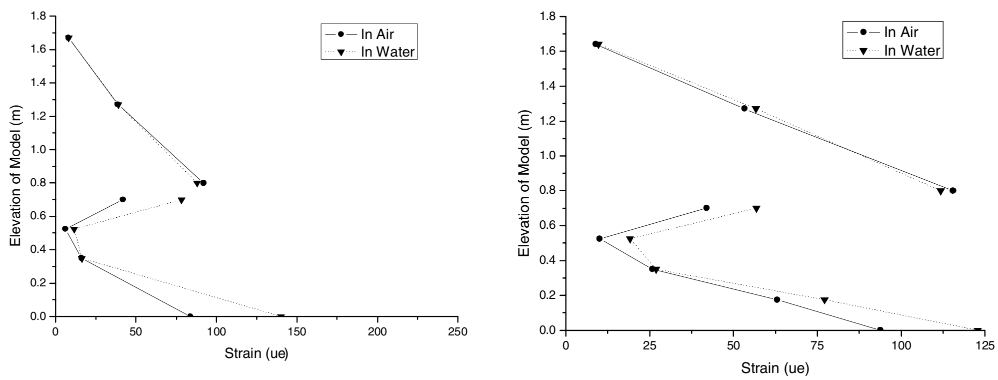


Figure 14 Time History of Strains(3.13Hz Harmonic excitation) For Model of Pingtan Bridge



(a) 0.313Hz (b) 3.13Hz

Figure 15 Harmonic Excitations for Ideal Model Bridge



0.313Hz 3.13Hz

Figure 16 Strain envelope along the elevation for Ideal Model Bridge

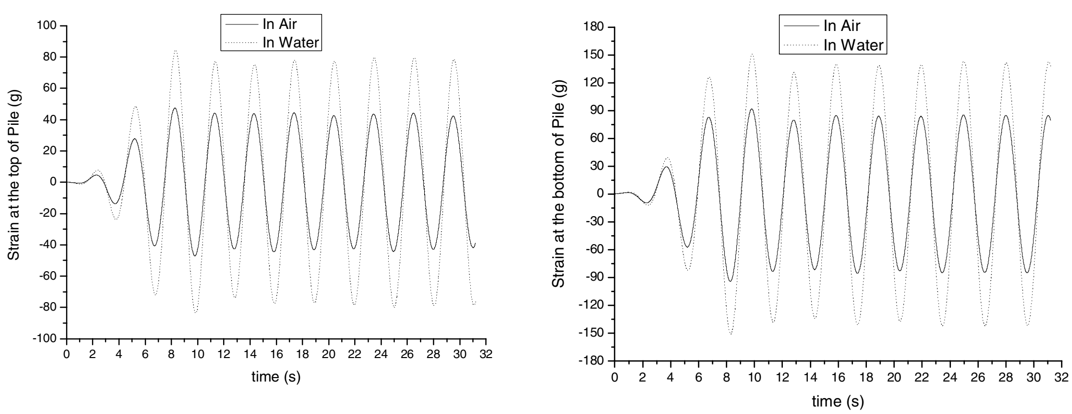


Figure 17 Time History of Strains(0.313Hz) for Ideal Model Bridge

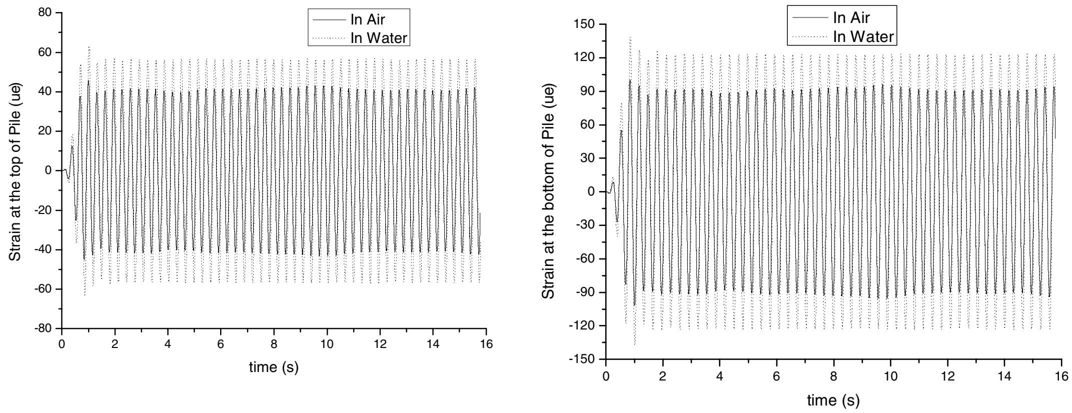
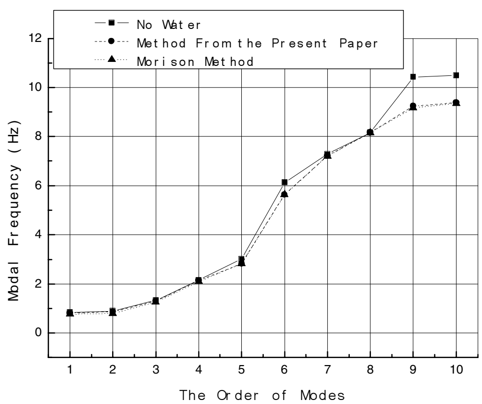


Figure 18 Time History of Strains(3.13Hz) for Ideal Model Bridge

DISCUSSIONS

A example is computed in this section. The example is the prototype of the Pingtan Bridge shown in figure 9. The calculated results are shown in Figure 19-24.



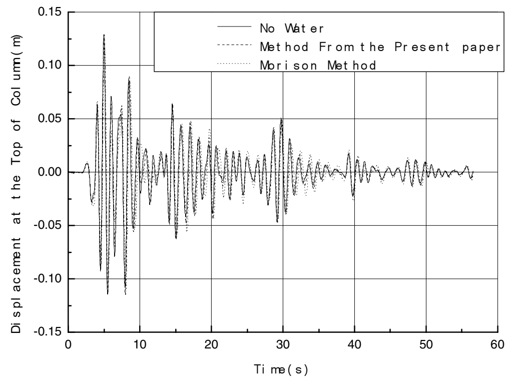
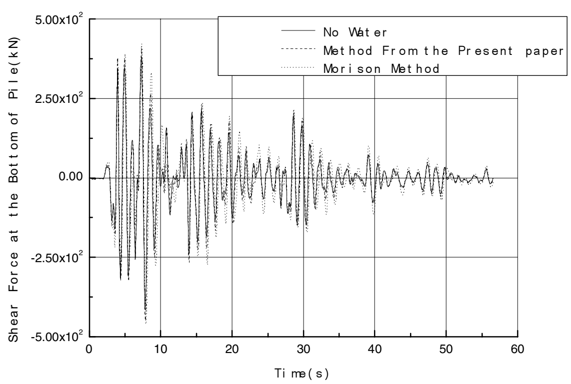


Figure 19 The First Lowest Modal Frequency Figure 20 Displacement at Top of Pier



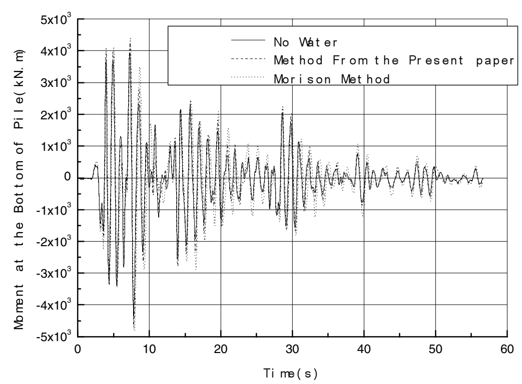
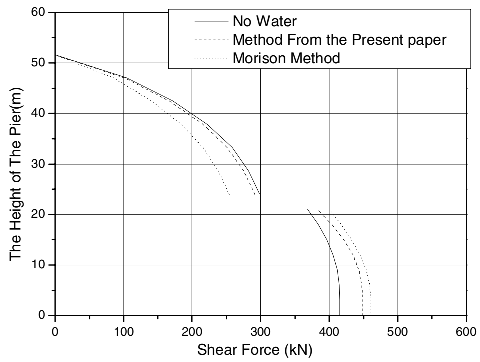


Figure 21 Shear Force at bottom of Pile Figure 22 Displacement at Top of Pile



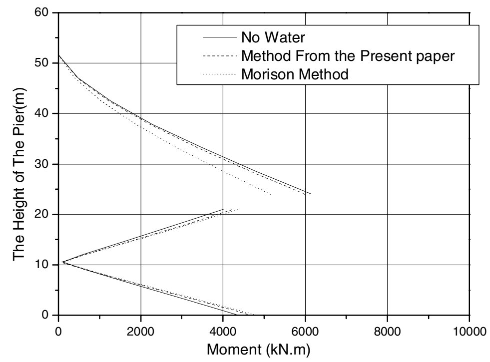


Figure 23 Envelope Shear Force

Figure 24 Envelope Moment

Figure 19 gives the first ten modal frequencies of pier vibrating in air and water. In figure, the lowest four modal frequencies of pier vibrating in water are almost the same as those in air. Moreover the results by two methods have minor difference. The dynamic responses of pier vibrating in air and water are compared in figure 20-24. Differences between the dynamic responses of pier vibrating in water and in air are observed, but the differences are not significant, not more than 10%. The reason is that the added masses for pile cap obtained by two methods are quite small with regard to the mass of pile cap. Accordingly, the effect of hydrodynamic pressures on dynamic characteristics of the computed pier is not obvious.

CONCLUSIONS

To estimate the seismic responses of bridges surrounded by water, a semi-analytical and semi-numerical approach for earthquake induced hydrodynamic pressure on pier was developed and shaking table tests of model bridge piers were finished. The following conclusions can be reached.

The methods developed in this paper can easily be combined with FEM method, and then make it convenient to estimate the seismic responses of bridges surrounded by water;

Hydrodynamic pressure may largely change the seismic responses of bridges which are of low modal frequencies or bridges which consist of thin-wall column piers;

The results from shaking table tests show that hydrodynamic pressure may be important to seismic responses of some types of bridges surrounded by water. This conclusion agrees to that obtained by theoretical computation.

ACKNOWLEDGEMENT

This research is supported by the National Science Foundation of China at granted No. 40072088.

REFERENCES

1. Bridge and Offshore Engineering Association, Sea Strait Crossing, Vol.13, 47-53, 1998.
2. Fujian Highway Design Institute, The Pre-feasibility Study of Pingtan Bridge, 1999.
3. Chopra, A. K.; Gupta, S., Hydrodynamic and foundation interaction effects in frequency response functions for concrete gravity dams, Earthquake Engineering & Structural Dynamics, 10, 1, Jan.-Feb. 1982, pages 89-106.
4. Fahjan, Y.M., Borekci, O.S., And Erdik, M, Earthquake-induced hydrodynamic pressures on a 3D rigid dam-reservoir system using DRBEM and a radiation matrix, Int. J. for Numerical Methods in Engineering, Vol.56, No.10, 2003, 1511-1532.

5. Madabhushi, S. P. Gopal, Seismic behaviour of dams subjected to earthquake induced hydro-dynamic forces, Earthquake Geotechnical Engineering, Proceedings of the Second International Conference on, A.A. Balkema, Rotterdam, Vol. 2, 1999, pages 649-654.
6. Proulx, Jean; et al., An experimental investigation of water level effects on the dynamic behaviour of a large arch dam, Earthquake Engineering & Structural Dynamics, 30, 8, 2001, 1147-1166.
7. Aviles, Javier; Li, Xiangyue, Hydrodynamic pressures on axisymmetric offshore structures considering seabed flexibility, Computers & Structures, 79, 29-30, Nov. 2001, pages 2595-2606.
8. Chen, Bang-Fuh, Dynamic responses of coastal structures during earthquakes including sediment-sea-structure interaction, Soil Dynamics and Earthquake Engineering, 20, 5-8, Dec. 2000, pages 445-467.
9. Chen, B.-F., 3D nonlinear hydrodynamic analysis of vertical cylinder during earthquakes. I: rigid motion, Journal of Engineering Mechanics, 123, 5, May 1997, pages 458-465.
10. Hu, Yuxia; Randolph, Mark F., Bearing capacity of caisson foundations on normally consolidated clay, Soils and Foundations, 42, 5, Oct. 2002, pages 71-77.
11. Sun, K.; Nogami, T. 1991. Earthquake induced hydrodynamic pressure on axisymmetric offshore structures, Earthquake Engineering & Structural Dynamics, 20, 5, May, pages 429-440.
12. Yamada, Y.; et al. 1989. Seismic response of offshore structures in random seas, Earthquake Engineering & Structural Dynamics, 18, 7, Oct, pages 965-981.
13. Chopra A. K., Goyal, A. 1991. Simplified earthquake analysis of intake-outlet towers, Journal of Structural Engineering, 117, 3, Mar, pages 767-788.
14. Liaw, C.-Y., and Chopra, A.K., Dynamics of towers surrounded by water, Earthquake Engineering & Structural Dynamics, Vol.3, No.1, 1974, 33-49.
15. Goyal, A.; Chopra, A. K. 1989. Hydrodynamic and foundation interation effects in dynamics of intake towers:earthquake responses, Journal of Structural Engineering, 115, 6, June, 1386-1395.
16. Goyal A., Chopra, A. K. 1989. Earthquake response spectrum analysis of intake-outlet towers, Journal of Engineering Mechanics, 115, 7, July, pages 1413-1433.
17. Spyrakos, C. C.; Xu, C., Soil-structure-water interaction of intake-outlet towers allowed to uplift, Soil Dynamics and Earthquake Engineering, 16, 2, 1997, 151-159.
18. Akkas, Demirci, Y., Dynamic response of a bridge pier within a fluid medium, Proceedings of the 8th European conference on Earthquake Engineering, Lab. Nacional de Engenharia Civil, Lisbon, 1986, 6.9/33-39, Vol.3.
19. H. Goto and K. Toki. 1965. Vibration Characteristics and Aseismic Design of Submerged Bridge Piers, Proc. Third World Conf. On Earthq. Eng, Auckland, Welligton, New Zealand.
20. Kotsubo,S., and Takanoshi, T., Analysis of Hydrodynamic pressure on multi-piles foundation during earthquakes, (in Japanese) Proceedings of Japan Society of Civil Engineers, 276, 1978, 1-12.
21. Rao, P.V., Hydrodynamic Earthquake Coefficients of Bridge Piers, Bulletin of the Indian Society of Earthquake Technology, Vol.8, No.4, 1971, 188-194.
22. S.Kotsubo. 1965. Seismic force effect on submerged bridge piers with elliptic cross-section, Proc. Third World Conf. On Earthq. Eng., Auckland, Welligton, New Zealand.
23. Anthony N.Willians. 1986.Earthquake response of submerged circular cylinder. Ocean Engng, Vol.13.No.6,pp.569-585.
24. Keming Sun and Toyoaki Nogami, 1991, Earthquake induced hydrodynamic pressure on axisymmetric offshore structures., J.Earthquake Engng struct.Dynamics 20, pp.429-440.
25. Yoshihiro Tanaka and Robert T.Hudspeth. 1988. Restoring forces on vertical circular cylinders forced by earthquakes. Earthquake Engng and Struc Dynamics, Vol.16.99-119.