Numerical Simulation of Hydrodynamic Pressure on Bridge Pier in Water for a Model Test

Yifang Qin\textsuperscript{1}, Xiaxin Tao\textsuperscript{2,*}, Zhengru Tao\textsuperscript{1} and Haiming Liu\textsuperscript{3}

\textsuperscript{1}Institute of Engineering Mechanics, CEA, Harbin, Heilongjiang, 150080, China
\textsuperscript{2}School of Civil Engineering, Harbin Institute of Technology, Harbin, Heilongjiang, 150036, China
\textsuperscript{3}State Key Laboratory of Bridge Engineering Structural Dynamics, China Merchants Chongqing Communication Research & Design Institute Co., Ltd, Chongqing, 400067, China

\textsuperscript{*}Corresponding author

Abstract. Finite element model with considering the fluid and structure interaction is built by software ADINA with the same conditions of a shaking table model test in this paper. The hydrodynamic pressures at 7 submerged depths on the water-pier interfaces, as the same positions the sensors fixed in the test, are calculated from motion inputs E1 with PGA of 0.2651g and E2 with PGA of 0.51g numerically in two direction combinations. The result shows that the pressures from the simulation and the test are close to each other, and means that the numerical procedure adopted in this paper is feasible to take into account the water-pier interaction, while the test results are also validated by the simulation.

Keywords: Hydrodynamic Pressure; Potential-based fluid element; Fluid-structure interactions; Shaking table model test.

1. Introduction

To study the variation of seismic hydrodynamic pressure on bridge pier with submerged depth in water, a shaking table model test was carried out recently [1]. To develop a feasible numerical analysis procedure for seismic response of bridge pier in deep water from the test results, a finite element model is built by means of finite element software ADINA with the same conditions of the model test, and the hydrodynamic pressures at different depths are simulated from the same inputs in this paper numerically. The results of hydrodynamic pressure at seven submerged depths from the simulation are presented. The comparison between the results with those of the experiment shows that the numerical procedure adopted in this paper is feasible to take into account the water-pier interaction, while the test results are also validated by the simulation.

2. Numerical Simulation of Fluid and Structure Interaction by Means of ADINA

Modeling of fluid and structure interaction is the key step to simulate the seismic response of bridge pier in deep water. Most of the finite element software packages adopted in calculation of the response just consider the fluid effect on structure as the load or additional mass and damping. For example, Spirakos et al. proposed the concise added masses and applied to a finite element model of a tower structure [2]. Yang expressed the effect of hydrodynamic pressure in the form of additional mass and additional damping and applied to numerical model of structure to simulate fluid-structure interaction [3]. Song et al. proposed a simplified added mass of hydrodynamic added inertial, with distributing along the height.
of slender structures [5]. With the development of finite element and boundary element methods, the finite element methods for strongly coupled fluid-solid interaction are recently adopted in research. Chen et al. proposed the contact condition in fluid-solid interface and studied the problem of grid technology in the coupled simulation of convection field and fluid structure [6]. Wei et al. conducted a shaking table test and corresponding potential-based fluid-element analyses, and their simulations were in agreement with the test results [7]. Kwang-Jun et al. studied the fluid-solid coupling of elastic cylinder in sloshing flume, and proposed a nonlinear finite element method which could solve the large deformation and free surface for the problem of fluid-structure coupling[8]. In this paper, hydrodynamic pressure on bridge pier from the test is simulated numerically with considering the fluid-solid interaction by means of ADINA software, which is widely adopted in multi-field coupling problem [9].

The basic conditions on the fluid-structure interfaces are the displacement compatibility as in equation (1),

\[ d_f = d_s \]  \hspace{1cm} (1)

with traction equilibrium defined in equation (2).

\[ n \cdot \sigma_f = n \cdot \sigma_s \] \hspace{1cm} (2)

where \( d_f \) and \( d_s \) are the fluid and solid displacements respectively, and \( \sigma_f \) and \( \sigma_s \) are the fluid and solid stresses, respectively.

According to dynamic conditions, the fluid traction is integrated for the fluid force along fluid-structure interfaces and exerted onto the structure node, as shown in equation (3).

\[ F(t) = \int h^d \sigma_f \cdot dS \] \hspace{1cm} (3)

where \( h^d \) is the virtual quantity of the solid displacement, \( S \) is the fluid-structure interfaces, \( F(t) \) is fluid force. Note that the fluid stress is the sum of the fluid pressure and the shear stress, the fluid pressure should be obtained from the potential function \( \Phi \) of the fluid element node, which can be obtained from finite element equations of the coupled system, as in equation (4).

\[ F[X] = \begin{bmatrix} F_f[X_f, d_f(X_s)] \\ F_s[X_s, \tau_s(X_s)] \end{bmatrix} = 0 \] \hspace{1cm} (4)

where \( X_f \) and \( X_s \) are the fluid and solid solution vectors at the nodes on fluid and solid interface respectively. \( F_f \) and \( F_s \) are the fluid equations and the solid equations respectively.

Fluid-structure elements are adopted in the simulation and illustrated in figure 1 [10]. In order to avoid discrepancies of force and displacement at the fluid-structure interface, the nodes there of the two parts must be the same, as illustrated in figure 1.
Figure 1. Fluid-structure interaction elements.
On the interface, the force and displacements at solid nodes 1, 2, 3 and 4 must equal to those at the fluid nodes 1, 2, 3 and 4, respectively. The potential function $\Phi$ and the structural motion parameters $u$ are obtained from equation (4). The ADINA software select the above formulas by default for simulation of the coupled dynamic system.

ADINA software is adopted to simulate the seismic response of the pier model in the shaking table test in this paper, the overall process of the numerical simulation is shown in figure 2.

Figure 2. The general flowchart of the response analysis by ADINA software.

3. The Finite Element Model for the Simulation from the Test Model
The model in the experiment is fixed at the bottom of the tank on shaking table. The total height of the model is 4.54 m with pier of 1.5 m. There are two main elements groups, 20-node 3D potential-based
fluid element for water domain, 8-node shell elements for the structure. The water part is modeled by the cube element with size no larger than 0.04 m and mass density of 1,000 kg/m³. The structure part of the model is modeled as the shell elements for the thin-wall hollow pier and the pylon limbs, with the sizes of the shell elements similar to the water, the thicknesses 0.03 m for the former, and 0.016 m, 0.018 m, 0.020 m and 0.024 m for latter. For the material properties of the shell elements, the Young’s modulus is taken as 3.11 GPa, density is 1200 kg/m³. The function of glue mesh by ADINA is adopted to constrain the connection between pylon limbs and pier, by setting the master surfaces and slave lines of shell elements. Total additional weight 2.93 kg×93 is added into dead loads, as 2672.31 KN on element group of structure. Dead loads are acted on the model before the seismic motion inputs in two levels, E1 with PGA of 0.2651 g and E2 with PGA of 0.51 g. As the same as in the test, the duration of the inputs are up to 6 seconds, and the inputs are in two direction combinations, X and Z, Y and Z respectively.

Figures 3 shows the finite element model built for the simulation of response of pier in 1.5 m water with
input motion in X+Z direction.

4. The Results of the Simulation and Comparison with Those of the Test

The fluid pressure could be calculated from the fluid velocity potential by equation (5).

\[ p = \rho_w \cdot (-\frac{\partial \phi}{\partial t} - \frac{1}{2}(\nabla \phi) \cdot (\nabla \phi)) + \rho_w \cdot g \cdot z \]

where \( p \) is the total fluid pressure, \( \rho_w \) is mass density of the fluid, \( \phi \) is the velocity potential of the fluid domain, \( g \) is gravitational acceleration. The second term at the right side of the equation (5) is for the hydro-static pressure at the depth \( z \), while the first term is for the hydrodynamic pressures. It could be simplified by Bernoulli formula, as shown in equation (6) [7, 11].

\[ p_o = -\rho_w \frac{\partial \phi}{\partial t} \]

The hydrodynamic pressures at seven positions on the water-pier interfaces, as the same positions the sensors fixed in the test, are calculated, as shown in figure 4. In the figure, the hydrodynamic pressures
are plotted with those from the test together for inputs E1 and E2 with direction combinations X+Z and Y+Z in (a), (b), (c) and (d) respectively for comparison. One can see from the figures that the simulation results are comparable with those of the test. The pressures from the simulation and the test for the same depth and the same input, are close to each other, except those at depth larger than 1.2 m with relative differences between 10 % and 15 %, also in an acceptable range [12].

![Figures 4](image)

(a) Pressure with depth from E1 and X+Z.
(b) Pressure with depth from E1 and Y+Z.
(c) Pressure with depth from E2 and X+Z.
(d) Pressure with depth from E2 and Y+Z.

**Figures 4** The simulation results with those of the experiment.

5. Conclusion

To develop feasible numerical analysis procedure for seismic response of bridge pier in deep water, finite element model is built by software ADINA with the same conditions of a shaking table model test in this paper. For modeling of fluid and structure interaction, the key step in multi-field coupling problem, glue mesh by ADINA is adopted to constrain the connection between forces and displacements in the two parts. The hydrodynamic pressures at 7 depths on the water-pier interfaces, as the same positions the sensors fixed in the test, are simulated from motion inputs in two levels, E1 with PGA of 0.2651g and E2 with PGA of 0.51g numerically in two direction combinations, X and Z, Y and Z. The results of hydrodynamic pressure at seven submerged depths from the simulation show that the simulation results are comparable with those of the test, the pressures from the simulation and the test for the same depth and the same input, are close to each other, except those at depth larger than 1.2 m with relative differences between 10 % and 15 %, also in an acceptable range, that means that the numerical procedure adopted in this paper is feasible to take into account the water-pier interaction, while the test results are also validated by the simulation.

Acknowledgement

This work was financially supported by grant 201701 of open funds of State Key Laboratory of Bridge Engineering Structural Dynamics and Key Laboratory of Bridge Earthquake Resistance Technology, Ministry of Communications, PRC, 51678540 and 51778197 of National Nature Science Foundation of China.
References

[1] Liu H, Tao X, Tao Z and Qin Y. 2019. Preliminary result of seismic hydrodynamic pressure on bridge pier with depth in water from a shaking table test (submitted).

[2] Spyrokos C and Xu C. 1997. Soil-structure-water interaction of intake-outlet towers allowed to uplift. Soil Dynamics and Earthquake Engineering.

[3] Yang W. 2010. Hydrodynamic stress on non-vertical surface of pier under earthquakes. China Civil Engineering Journal, 43, 72-76.

[4] Morison J R, Johnson J W, and Schaaf S A. 1950. The force exerted by surface waves on piles. J. Petrol. Technol., 2(5), 149–154.

[5] Song B, Zheng F, and Li Y. 2013. Study on a simplified calculation method for hydrodynamic pressure to slender structures under earthquakes. Journal of Earthquake Engineering, 17(5), 720-735.

[6] Chen G, Xi R and Wang Z. 2010. Dynamic response method of bridge piers under earthquake excitation considering fluid-structure interaction. Journal of Disaster Prevention and Mitigation Engineering.

[7] Wei K, W Yuan and N Bouanani. 2013. Experimental and Numerical Assessment of the Three-Dimensional Modal Dynamic Response of Bridge Pile Foundations Submerged in Water. Journal of Bridge Engineering 18(10): 1032-1041.

[8] Kwang-Jun, Paik, Pablo M, and Carrica. 2014. Fluid-structure interaction for an elastic structure interacting with free surface in a rolling tank. Ocean Engineering.

[9] Theory and Modeling Guide, Volume III: ADINA. 2012. ADINA R&D, Inc.

[10] Sussman T, Sundqvist J. 2003. Fluid-structure interaction analysis with a subsonic potential-based fluid formulation. Computers & Structures, 81(3-11):949-962.

[11] Olson L G and K J Bathe. 1985. Analysis of fluid-structure interactions: a direct symmetric coupled formulation based on the fluid velocity potential. Comput. Struct. 21 (1–2): 21–32.

[12] Zhang Z, Li X, Lan R and Song C. Shaking table tests and numerical simulations of a small radius curved bridge considering ssi effect. Soil Dynamics and Earthquake Engineering, 118, 1-18.