Numerical Simulation of Hydrodynamic Pressure on Concrete Bridge Pier in Water from a Series of Model Tests

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Abstract. To develop numerical procedure to simulate hydrodynamic pressure on concrete bridge pier in water, finite element models are built by software ADINA with the same sizes and material properties in a set of shaking table tests in this paper. The results our numerical simulations show that the all pressures on the three piers decrease with the submerged depth at the similar rate as test data shows, and the mean values of the ratios of numerical results to the test data are mainly from 0.8 to 1.0. The pressures on piers with different section shapes at same depth are varied and the relative order is not stable. The finding is similar to that from the test data, but different to the shape coefficient values provided in some seismic design codes of highway bridges. It suggests to check what kind of horizontal variation of hydrodynamic pressures at same depth level is there from the center to the edges. The pressures with reflected wave are approximately half to two third of those without reflected wave. It means that the reflection effect reduce the hydrodynamic pressure on bridge pier obviously. The effectivity of the absorbing stuff on the side walls of the tank in the tests must be improved, or a new way to replace this kind of measure must be worked out.

Keywords: Numerical simulation; Seismic hydrodynamic pressure; Concrete bridge pier.

1. Introduction
The effect of hydrodynamic pressure on bridge pier in water during earthquake should be taken into account in design according to the provision of seismic design code of bridges in many countries, such as China, Japan and so on [1~3]. The formula in the code is simplified from series solution of three dimensional dynamic analysis by a shape function of the pressure distribution with the submerged depth, e.g. in the classical funding paper [4, 5]. In these years, papers on the pressure have been published more than a hundred, since more and more bridges are constructed in deep water. Therefore, to study the distribution of hydrodynamic pressure is very important in improvement of the formula. However, that distribution of pressure on pier could not be revealed theoretically [6]. To develop a feasible numerical analysis procedure for seismic response of bridge pier in deep water, a finite element model was built by means of software ADINA with the same conditions of the a model test of a Perspex rectangular pier [7], and the hydrodynamic pressures at different depths were simulated from the same inputs numerically by the authors of this paper last year [8]. The comparison between the results and those of the experiment
showed that the numerical procedure adopted in that paper was feasible to take the water-pier interaction into account. To study the variation of seismic hydrodynamic pressure on concrete bridge pier with submerged depth in water, a set of shaking table model test is carried out recently [9], and provides more valuable data. In this paper, the authors will study the variation of the hydrodynamic pressure with submerged depth, and the influence of section shape of pier, effect of absorbing stuff for potential reflection wave on the pressure distribution by means of the numerical procedure with the test data.

2. The Numerical Procedure of Fluid and Structure Interaction

The many fluid–structure interaction analyses, the water domain were considered as the potential-based fluid with the properties of no heat transfer, viscosity, vortex, and non-compressibility [10]. The ADINA software has been adopted to solve the coupling problem in different fluid type these years [11], with a wide range of fluid flows, such as slightly compressible or low-speed compressible flows and potential-based fluid mentioned above. The procedure was validated by some relevant analytical or classical methods for fluid-structure coupling problem in civil engineering [10~11], and by the comparison of the numerical result with a test data of seismic hydrodynamic pressure on bridge pier [8]. The potential-based fluid-element (PBFE) provided by the ADINA software is adopted here as the same in [8], as well as the following boundary conditions.

(I) at the free surface boundary [7]

\[ \frac{\partial \phi}{\partial t} + gu = 0, \quad \frac{\partial \phi}{\partial z} \frac{\partial u}{\partial t} = 0 \]  

(II) at the fluid-structure boundary

\[ \frac{\partial \phi}{\partial n} = \frac{\partial u}{\partial t} \]  

(III) at the Infinite boundary:

\[ \frac{\partial \phi}{\partial t} = p_\infty, \quad \frac{\partial \phi}{\partial n} = \frac{\partial u_\infty}{\partial t} \]  

(IV) at the rigid boundary:

\[ \frac{\partial \phi}{\partial n} = 0, \quad \phi = 0 \]

where \( u \) is the displacement of pier, \( p_\infty \) and \( \partial u_\infty / \partial t \) are corresponding pressure and normal velocity at the infinity region respectively.

The free surface boundary is adopted to the water surface as in Eq. 1. All the contact surfaces of pier and water are set to be the fluid-structure boundary in Eq. 2. The bottom of water domain is set by the rigid boundary in Eq. 4 to simulate the bottom of the tank fixed on shaking table in the test. To simulate the conditions without or with reflected wave from the tank walls by the absorbing stuff in the test, the four sides of fluid domain are set by infinite boundaries in Eq. 3, or by the rigid boundaries in Eq. 4.

3. The Finite Element Models of the Test Models

There are three kinds of concrete bridge pier models in the tests with cross-sections of rectangular, elliptic and variable rectangular respectively [1], and the corresponding heights of the models are 2.890 m, 2.870 m and 3.190 m, the dimension of the rectangular section is 0.300 m × 0.500 m, the major and minor axis of the ellipse section are 0.484 m and 0.310 m, the dimension of the variable section changes from 0.302 m × 0.310 m at top to 0.302 m × 0.615 m at the bottom. The pier models are fixed in a rectangular tank with a dimension of 2.000 m × 3.000 m × 2.000 m and submerged in 1.1 m and 1.6 m water in the two sets of tests. The piers are made of C50 concrete and HRB 400 rebar. The elastic modulus, Poisson’s ratio, and mass density of the concrete are 34.5 GPa, 0.2 and 2,500 kg/m³, respectively. The elastic modulus and mass density of the rebar are 210 GPa and 7,850 kg/m³,
respectively. The finite element models for these three piers are built with 8-node solid elements, with the same sizes and maximum element size 0.065 m. The 20-node 3D potential-based fluid element are adopted for the water domain and the maximum element size 0.070 m. The Young’s modulus is taken as 2.2 GPa, density as 1000 kg/m³ for water. The lateral boundaries of the water domain are built by infinite boundary for the situation without reflected wave, or by rigid wall boundary for that with reflected wave.

As the same as in the tests [7, 9], the seismic motion inputs are in two levels, E1 with PGA of 0.2651 g and E2 with PGA of 0.51 g, with the corresponding duration up to 6 seconds, and in two direction combinations, X and Z, Y and Z, respectively. The gravity loads are acted on the model before the input. The finite element models for the three kinds of piers in 1.6 m water with input motion in X+Z direction, are shown in Fig. 1, Fig. 2 and Fig. 3.

![Figure 1. Details (left) and 3D view (right) of the finite element model of the rectangular section pier.](image)

![Figure 2. Details (left) and 3D view (right) of the finite element model of the elliptic section pier.](image)
Figure 3. Details (left) and 3D view (right) of the finite element model of the variable rectangular section pier.

4. The Results of the Simulation and Comparison with those of the Tests

The fluid pressure could be calculated from the fluid velocity potential by Eq. 5 [15].

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

(5)

where \( p \) is the total fluid pressures, \( \rho_w \) 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 Eq. 5 is for the hydrostatic pressure at the depth \( z \), while the first term is for the hydrodynamic pressures. It could be simplified by Bernoulli formula, as shown in Eq. 6 [13].

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

(6)

The hydrodynamic pressures on the water-pier interfaces in 1.1m and 1.6m, are calculated at 4 and 8 output positions, as the same as the sensors fixed in the test.

5. Hydrodynamic Pressures on the Pier Models with Submerged Depth

As examples, Fig. 4 presents the numerical results of the pressures on piers from input E1 in tests without absorbing stuff. The solid and broken curves link the hydrodynamic pressures at the 4 or 8 submerged depths in 1.1m and 1.6m water respectively. The small square, circle and triangle are for the pressures on piers with rectangular, elliptic, and variable rectangular (in brief variable, below) cross-section, respectively.

One can see from the Fig. 4 that the all pressures on the three piers in the two total water depths and from the two input bi-directions decrease with the submerged depth at the similar rate as test data shows [9]. The differences among the pressures on the three models with different section shapes at the same test situation are smaller than those showed in the test data.

Figure 4. The hydrodynamic pressures on the piers from E1 inputs in X+Z (left) and Y+Z (right).
The ratios of numerical results of the models in 1.1 m and 1.6 m water from input E1 to the corresponding test pressure values in tests without absorbing stuff [9] are presented in Fig. 5, there all symbols are the same as in Fig. 5.

It is clear that the pressures by the numerical simulation are similar with the test data, since the mean ratio values are mainly from 0.8 to 1.0, with a mean about 0.9. It shows that the numerical results are always slightly smaller than test data.

6. Influence of Section Shapes of the Pier Models on the Pressure Distribution

The comparison of the numerically calculated pressures on piers with the three kinds of sections in 1.1 m and 1.6 m water are shown in Fig. 6(a) and Fig. 6(b), respectively. In the figure, all the symbols are the same as in the Fig. 4, but the solid and broken curves are for the results from inputs E1 and E2.

One can see from the figures that the pressures on piers with different section shapes at same depth from both E1 and E2 are varied, and the relative order is not stable. The finding is similar to that from the test data [9], but different to the shape coefficient values provided in some seismic design codes of highway bridges [15~ 17]. It suggests further numerical simulations of hydrodynamic pressures at same depth level not only on the center but also on the edges of the upstream water-pier interfaces to see if there is a horizontal variation of pressure.
7. Effect of the Reflected Wave on the Pressure Distribution
The test data shows that the absorbing stuff put on the tank side walls to reduce potential reflected wave does not work well. In the numerical simulations of this paper, the rigid and infinite side boundaries are adopted for the situation with and without reflected wave respectively. The ratios of pressures numerically calculated with the rigid side boundaries to those with the infinite side boundaries are shown in Fig. 7(a) and Fig. 7(b). In the figures, the symbols are the same as in Fig. 4, and the solid curves and the broken curves link the mean ratios from E1 and E2 inputs respectively.

One can see from the figures that the pressures with reflected wave are approximately half and two third of those without reflected wave. It means that the reflection effect reduce the hydrodynamic pressure on bridge pier obviously. The similarity of results with and without absorbing stuff on the tank side walls come from the lack of effectivity of the stuff or the shortness of longitudinal size of the tank.

8. Conclusion
To develop feasible numerical analysis procedure to simulate hydrodynamic pressure bridge pier in water, finite element models are built by software ADINA with the same sizes and material properties in a set of shaking table tests in this paper. The water domain is modeled by the potential-based elements in this paper. The 20-node 3D potential-based fluid element and 8-node solid elements are adopted for the water domain and the piers with the maximum element sizes 0.070 m and 0.065 m, respectively. The side boundaries of the water domain are built in two schemes, by infinite boundary for situation without...

Figure 6. (b) Hydrodynamic pressures on the three piers in 1.6 m water with E1 inputs in X+Z (left) and Y+Z (right).

Figure 7. (a) Ratio of the pressures on the piers in 1.1 m water with inputs E1 and E2 in X+Z (left) and Y+Z (right).

Figure 7. (b) Ratio of the pressures on the piers in 1.6 m water with inputs E1 in X+Z (left) and Y+Z (right).
reflected wave, and by rigid wall boundary for with reflected wave. The rigid side walls with 10 cm thickness are built with eight-node 2D-solid plate elements, coupling with four sides of water domain. The hydrodynamic pressures on the upstream faces of the piers in 1.1m and 1.6 m water, are calculated at 4 and 8 output positions, as the same as the sensors fixed in the test, from motion inputs E1 with PGA 0.2651 g and E2 with PGA 0.51 g and 6 second duration, in two direction combinations, X and Z, Y and Z, respectively.

The results of our numerical simulations show that the all pressures on the three piers decrease with the submerged depth at the similar rate as test data shows, and the mean values of the ratios of numerical results to the test data are mainly from 0.8 to 1.0, with a mean about 0.9. The pressures on piers with different section shapes at same depth from are varied and the relative order is not stable. The finding is similar to that from the test data, but different to the shape coefficient values provided in some seismic design codes of highway bridges. It suggests a check if the horizontal variation of hydrodynamic pressures at same depth level from the center to the edges. The pressures with reflected wave are approximately half and two third of those without reflected wave. It means that the reflection effect reduce the hydrodynamic pressure on bridge pier obviously. The effectivity of the absorbing stuff on the side walls of the tank in the tests must be improved or to work out a new way to replace this kind of measure.

Acknowledgement
This work was financially supported by grants of national key research and development plan 2017YFC0806009, 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.

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