A Numerical Case Study on Boundary Effect in Test and Simulation of Seismic Hydrodynamic Pressure on Pier

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Abstract. Total 12 finite element models are built for piers of rectangular and elliptical sections in water with infinite boundary condition or with elastic boundaries and longitudinal size 3 m, 5 m, 7.5 m, 10 m and 15 m respectively. Responses of the models are calculated by numerical water-pier interaction coupling procedure. The result hydrodynamic pressures of nodes on the central line of the pier upstream faces at 8 depths show that the pressures on models with elastic boundaries are getting close to that with infinite boundary as the longitudinal size increasing, and the 15 m length is long enough for tank in shaking table test to prevent the disturbance of boundary wave on the maximum absolute value of hydrodynamic pressure.

1. Introduction
There are two ways to improve the understanding of hydrodynamic pressure on pier during earthquake, model test on shaking table and numerical simulation. The former could reveal the dynamic interaction nature between water and pier during ground motion, but is expensive and time consuming. The latter is cheap and fast, but is limited to the dynamic mechanism adopted in the calculation. A feasible approach is to combine the two. To study the variation of seismic hydrodynamic pressure on bridge pier with submerged depth in deep water, a series of shaking table model tests were carried out recently [1, 2]. Conjugately, a set of finite element calculations are completed with the same conditions of the test afterwards [3, 4]. The results of the hydrodynamic pressures at seven submerged depths from the same inputs by the two ways show that the numerical procedure is feasible to take into account the water-pier interaction, and the test results could be validated by the simulation too. The comparison of the numerical simulation results with rigid and infinite side boundaries for the situations with and without boundary wave (in some references it is called as reflected wave) shows that the pressures with boundary wave are obviously different from those without the wave. It means that the boundary effect is noticeable on the hydrodynamic pressure on bridge pier, and the fact that the test results with and without wave absorbing stuff on the tank side walls in the shaking table test are similar, must come from the lack of effectivity of the stuff or the shortness of longitudinal size of the tank. A further study is presented in this paper, to see if the stuff is really feeble and how long of the tank is enough to eliminate the effect of potential boundary wave by a set of numerical simulations.
2. The test models and the finite element models

In the shaking table tests mentioned above, a rectangular steel water tank 3 m × 2 m × 2 m was built and fixed on the shaking table, the models were fixed on the bottom of the tank and submerged in 1.6m water. The size of pier with rectangular cross-section is 0.500 m × 0.300 m and height of 2.890 m, and the major and minor axes of the ellipse cross-section are 0.484 m and 0.310 m with height of 2.870 m. The pier models are made of C50 concrete and HRB 400 rebar, and their elastic modulus, Poisson’s ratio, and mass density are 34.5 GPa, 0.2 and 2500 kg/m³, and 210 GPa, 0.2 and 7850 kg/m³, respectively. Some wave absorbing stuffs were installed on the walls of water tank. Two pictures of a model and the tank are shown in figure 1.

Two sets of the finite element models are constructed for piers with the two sections in surrounding water, with total sizes of width 2 m, height 1.6 m, and five lengths 3m, 5m, 7.5m, 10m and 15m respectively. The pier models are discretized by 20-node 3D solid elements with maximum size 0.050 m and the same material parameters in the test. The water domain is discretized by 20-node 3D potential-based fluid elements with maximum element size 0.020 m and mass density of 1000 kg/m³, Young’s modulus of 2.2 GPa. The four lateral sides of the fluid domain are coupled with 20-node shell elements for the steel plates of water tank with Young’s modulus of 206 GPa, density of 8000 kg/m³ and thickness of 0.13 m. The water element connecting to shell element is slide free in tangential direction and velocity of the water element is the same as that of the shell element in normal direction, as shown in figure 2.

Figure 1. The pier model in water (left) and the water tank on shaking table (right).

Figure 2. The slide free boundary conditions on the numerical steel plates.

The top boundary of the water domain is set as free surface, the water – pier interface boundary is set as fluid-structure-interaction boundary, and the rigid bottom boundary of the whole finite element model is constrained without vertical movement. The boundaries of the two longitudinal sides are
substituted by infinite boundary for the cases without boundary wave. As an example, the finite element models 5 m × 2 m×1.6m are shown in figures 3.

![3D view of two finite element models for elliptical (left) and rectangular (right) piers](image)

Figure 3. 3D view of two finite element models for elliptical (left) and rectangular (right) piers. The flowchart of the calculations is shown in figure 4 without specification of details since the limited space.

![Flowchart of the calculation](image)

Figure 4. The general flowchart of the calculation.

**3. Results of the hydrodynamic pressures on upstream face of the pier models**

Ground motions with peak accelerations 0.265 g and 0.177 g are input simultaneously in X and Z directions with duration up to 6 seconds, to bottoms of the 10 models one by one. The hydrodynamic pressures at some given nodes on upstream faces of each pier are calculated by the above mentioned procedure.

As an example, the time histories of pressures at 8 depths from the water surface to the bottom on nodes of central lines of the rectangular and elliptical piers from the models in figure 3, are shown in figure 5. One can see from the figure that the time histories of hydrodynamic pressures at the 8 depths have quite similar waveform for each pier, even with no any phase difference. The hydrodynamic pressure of each time history reaches its peak at almost the same time, about 1.7248 s. Maximum
absolute values are read from each of the time histories as the representative hydrodynamic pressures in this paper.

![Figure 5](image_url)  

Figure 5. Time histories of the hydrodynamic pressures on rectangular (left) and elliptical (right) piers at 8 submerged depths.

Figure 6 presents the results of the pressures at 8 depths on the 6 models for each of the two piers respectively. In the figures, the solid curves are the result without boundary wave, i.e. result from infinite boundary, the broken curves are results of the pressures of the models with elastic boundaries.
of the shell elements at the two longitudinal sides, and symbols +, *, ×, ● and ▲ represent respectively the results of the models with longitudinal sizes 3 m, 5 m, 7.5m, 10 m and 15 m.

Figure 6. The hydrodynamic pressures on the rectangular (left) and elliptical (right) piers with submerged depth.

One can see from the figure that the results from models with elastic boundaries are getting close to that with infinite boundary as the longitudinal size increasing. It means that the stuff adopted in the shaking table test is really feeble and the 15 m length is long enough to prevent the disturbance of boundary wave on the maximum absolute hydrodynamic pressure. It is clear that the superposition effect of the boundary wave controlled by its arrival time, the effect must be negligible if the boundary wave arrivals long enough after the corresponding time of pressure peak and the longer the longitudinal size of model is, the longer time of the boundary wave getting the pier upstream face must be. The feasible longitudinal size of test or simulation model, 15 m in this paper, needs further study to see if it depends on the size of the pier section and the intensity of ground motion input.

4. Conclusion
To see how long of the tank in shaking table model test of hydrodynamic pressure on pier is enough to eliminate the effect of potential boundary wave, 12 finite element models with water-pier interaction coupling are built for piers of rectangular and elliptical sections, and with infinite boundary condition or with the longitudinal size 3 m, 5 m, 7.5 m, 10 m and 15 m respectively. The responses of the 12 models are calculated from acceleration time history inputs with PGA 0.265 g and 0.177 g in horizontal and vertical directions conjugately, by numerical procedure developed by the authors. The hydrodynamic pressures on nodes at 8 submerged depths on the central line of the pier upstream faces are output. By comparing the pressures on the two piers with 5 longitudinal sizes to that with infinite boundary conditions, it could be concluded that the hydrodynamic pressures on the models with elastic boundaries are getting closer to that with infinite boundary as the longitudinal size increasing, and the 15 m length is long enough for tank in shaking table test to prevent the disturbance of boundary wave on the maximum absolute hydrodynamic pressure. The stuff adopted in the shaking table test is really feeble. This conclusion on the feasible longitudinal size, of course needs further study to see if it depends on the size of the pier section and the intensity of ground motion input.

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