A Numerical Case Study on Pier Shape Coefficient of Seismic Hydrodynamic Pressure in Design Codes

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Abstract. To study the pier shape coefficient of seismic hydrodynamic pressure, three water-pier coupling finite element models of piers with circular, rectangular and elliptical sections are built. The results numerically calculated with the same input ground motion show that the horizontally distributions of the hydrodynamic pressures from the vertical central lines to the edges of the three types of piers at a given depth are almost the same, the difference among the pressures on the three piers is mainly from the decreasing rate from the central line to the edge. The pressures decrease with the input direction from perpendicular to parallel. The result values of shape coefficients are close to the provisions in Japanese code, and those for circular and elliptical piers are slightly less than that stipulated in the code; and the coefficient values for rectangular pier are less than that in Euro code 8 and those for elliptical pier are in the range of the code.

1. Introduction
To improve the provision on hydrodynamic pressure in the Guidelines for seismic design of highway bridges of China [1], two authors of this paper reviewed the corresponding provisions in two main seismic design codes for highway bridges in the world, Design specifications for highway bridges of Japan (in brief, called as Japanese code below) [2] and Euro code 8 [3]. They pointed out the difference between the provisions and the theoretical bases, and compared numerical values of the pier shape coefficients [4]. They concluded that the shape coefficients in the both codes are not very different for pier with rectangular section, but quite different for those with elliptical section, and then suggested some further studies on this issue. Afterwards, the authors of this paper developed a feasible numerical procedure to calculate seismic response of bridge pier in deep water with considering the water-pier interaction [5, 6], and validated it by a series of shaking table tests. In this paper, the values of shape coefficients for bridge piers with circular, rectangular and elliptical sections are calculated by this procedure in a case study, and are compared with the provisions in the two codes.

2. The finite element models and their boundary condition
The three water-pier coupling finite element models in the case study are all consist of two parts, fluid part for water and solid part for pier. The pier with rectangular section 0.500 m × 0.300 m, that with
circular radius 0.300 m and with elliptic section 0.484 m (in long axis) × 0.310 m (in short axis) are all discretized by 20-node 3D solid element with maximum size 0.050 m. The surrounding water in 3 m × 2 m × 1.6 m is discretized by 20-node 3D potential-based fluid element with maximum element size 0.020 m. The material parameters of the piers and water are the same as in [6]. The four lateral sides of the fluid domain are coupled with 20-node shell elements, the top boundary of the water is set as free surface, and the bottom of the whole finite element model is constrained without vertical movement. Modelling of the interaction of water and pier is the key step to simulate the seismic response of bridge pier in deep water. The fluid – pier interface boundary is adopted. The equations for the fluid-structure boundary, the infinite-region boundary, the rigid boundary and the free-surface boundary are listed in equation (1) to equation (5) respectively.

\[
\frac{\partial \phi}{\partial t} = \frac{\partial u}{\partial t} n \quad (1)
\]

\[
\frac{\partial \phi}{\partial t} = p_\infty, \quad \frac{\partial \phi}{\partial n} = \frac{\partial u_\infty}{\partial t} n \quad (2)
\]

\[
\frac{\partial \phi}{\partial n} = 0, \quad \phi = 0 \quad (3)
\]

\[
\frac{\partial \phi}{\partial z} - \frac{\partial u}{\partial t} = 0 \quad (4)
\]

\[
\frac{\partial \phi}{\partial t} + gu = 0 \quad (5)
\]

where \( \phi \) is the velocity potential, \( u \) is the displacement of pier, \( n \) is the direction vector, \( p_\infty \) and \( \frac{\partial u_\infty}{\partial t} \) are corresponding pressure and normal velocity at the infinity region, \( z \) is the submerged depth, \( g \) is gravity acceleration, respectively.

In the fluid velocity potential, the total water pressure can be expressed by the principle of Bernoulli, as following equations [7].

\[
p = \rho_w \cdot \left( -\frac{\partial \phi}{\partial t} - \frac{1}{2}(\nabla \phi) \cdot (\nabla \phi) \right) + \rho_w \cdot g \cdot z \quad (6)
\]

where \( p \) is the fluid total pressures, \( \rho_w \) is mass density of water, \( \rho_w \cdot g \cdot z \) is the expression of hydrostatic pressure at the depth \( z \). The hydrodynamic pressure \( p_D \) can be obtained through the following equation [8]

\[
p_D = \rho_w \cdot \left( -\frac{\partial \phi}{\partial t} - \frac{1}{2}(\nabla \phi) \cdot (\nabla \phi) \right) \quad (7)
\]

The dynamic water pressure at any point can be given finally by the following formula [9]

\[
p_D = -\rho_w \frac{\partial \phi}{\partial t} \quad (8)
\]

3. Numerical results of the hydrodynamic pressures on upstream faces of the piers

Acceleration time history of ground motion with peak value 0.265 g, as the same of E1 in [6], are input horizontally perpendicular to the upstream face of the pier, with vertical component 0.177 g conjugately, at the bottom of each of the finite element models. The time histories of hydrodynamic water pressures at selected node points on upstream faces of the piers are output. They show that the peak times of waveforms are all the same, without any phase difference, so the absolute maximum values are chosen as the representative values of the pressures on unit area of the upstream faces. Figure 1 shows the horizontally distributions of the pressures from the vertical central lines to the edges at 8 submerged depths for the three types of piers, rectangular, circular and elliptical. One can see from the figure that
the pressures on the vertical central lines of the three piers are almost the same, the difference among the pressures on the three piers is mainly from the decreasing rate from the central line to the edge.

Figure 1. Horizontal distributions of the hydrodynamic pressures at 8 depths on three piers.

The unit-height pressures (per 0.020 m) at each submerged depth are integrated horizontally from the above distributions, the results at 8 depths for the three piers are listed in table 1, as those values at left of the first / in each column. Furthermore, the total hydrodynamic pressures on the whole upstream faces of the three piers are obtained by secondary integral vertically, and also listed at the bottom of table 1.

Table 1. The hydrodynamic pressures (KN) on upstream faces of the three piers.

| Piers       | Rectangular | Circular | Elliptical |
|-------------|-------------|----------|------------|
| Unit-height pressure at 0.070 m | 0.033/0.028/0.025 | 0.020/0.017/0.017 | 0.019/0.016/0.016 |
| Unit-height pressure at 0.200 m | 0.089/0.081/0.074 | 0.061/0.055/0.054 | 0.062/0.054/0.051 |
| Unit-height pressure at 0.363 m | 0.161/0.145/0.135 | 0.122/0.111/0.109 | 0.113/0.099/0.099 |
| Unit-height pressure at 0.505 m | 0.195/0.185/0.165 | 0.156/0.145/0.144 | 0.158/0.135/0.125 |
| Unit-height pressure at 0.685 m | 0.277/0.253/0.234 | 0.205/0.193/0.193 | 0.201/0.182/0.162 |
| Unit-height pressure at 0.815 m | 0.312/0.291/0.266 | 0.228/0.223/0.217 | 0.232/0.202/0.189 |
| Unit-height pressure at 1.005 m | 0.338/0.323/0.293 | 0.263/0.267/0.251 | 0.273/0.234/0.224 |
| Unit-height pressure at 1.120 m | 0.351/0.335/0.307 | 0.275/0.271/0.268 | 0.295/0.256/0.238 |
| Total hydrodynamic pressure | 0.414/0.390/0.372 | 0.317/0.307/0.302 | 0.325/0.284/0.266 |

One can see from the table 1 that the unit-height pressure is getting larger as the depth increase, and the pressures on rectangular pier is larger than those on the other two piers in general.

To see the effect of input direction on the pressure that is emphasized in Euro code 8, the pier responses from inputs in 0° and 45° directions to the pier upstream face are calculated respectively, and horizontal distributions of the pressures are shown in figure 2 and figure 3.

Figure 2. Horizontal distributions of the hydrodynamic pressures at 8 depths on the three piers from 45° input.
One can see from the figures that the pressures on the central lines of the three piers are not the same in these situations. The unit-height pressures at 8 depths and the total hydrodynamic pressures on the three piers from these two inputs are also listed in Table 1. In the table, the values between the two '/' and those at right in each column are from 45° input and 0° input respectively. One can see from the figures and the table that the pressures decrease with the input direction from 90° to 0°, and the pressures decrease from the central line to the edge from inputs 90° and 45°, but increase from 0° input.

4. Comparison of the result shape parameters to the provisions in the two codes

The shape coefficient in Japanese code [2] is stipulated as the ratio of total hydrodynamic pressure on the upstream face of a pier with other section to that on the rectangular pier with the same width and height of upstream face, and the results are listed at the bottom of the table 2. In Euro code 8 [1], it is defined as the ratio of the unit-height pressure on a pier with other section to that on the circular pier with the same upstream face size at the same depth, the results are listed also in table 2 with the corresponding depths.

| Piers                | Rectangular | Circular | Elliptical |
|----------------------|-------------|----------|------------|
| Shape coefficient at 0.070 m | 1.64/1.60/1.48 | 1.00/1.00/1.00 | 0.97/0.93/0.93 |
| Shape coefficient at 0.200 m | 1.46/1.48/1.38 | 1.00/1.00/1.00 | 1.02/0.98/0.95 |
| Shape coefficient at 0.363 m | 1.32/1.31/1.24 | 1.00/1.00/1.00 | 0.93/0.89/0.90 |
| Shape coefficient at 0.505 m | 1.24/1.28/1.14 | 1.00/1.00/1.00 | 1.01/0.93/0.87 |
| Shape coefficient at 0.685 m | 1.35/1.31/1.22 | 1.00/1.00/1.00 | 0.98/0.94/0.84 |
| Shape coefficient at 0.815 m | 1.37/1.30/1.22 | 1.00/1.00/1.00 | 1.02/0.91/0.87 |
| Shape coefficient at 1.005 m | 1.28/1.21/1.17 | 1.00/1.00/1.00 | 1.04/0.88/0.89 |
| Shape coefficient at 1.120 m | 1.28/1.24/1.14 | 1.00/1.00/1.00 | 1.07/0.94/0.89 |
| Mean value            | 1.37/1.34/1.25 | 1.00/1.00/1.00 | 1.00/0.92/0.89 |
| Shape coefficient from total hydrodynamic pressure | 1.00/1.00/1.00 | 0.77/0.74/0.73 | 0.79/0.69/0.64 |

The results of this paper are be compared with the corresponding values of the coefficient in the two codes respectively, as shown in figure 4. In the figure, the small triangles, circles and squares are the results of elliptical, circular and rectangular piers by this paper, and the solid and broken curves are from the provisions in Japanese code (left) and in Euro code 8 (right).

One can see from the figure that the result values of shape coefficients of this paper are close to the provisions in Japanese code, and those for circular and elliptical piers are slightly less than that stipulated in the code; and the coefficient values for rectangular pier are less than that in Euro code 8 and those for elliptical pier are in the range by the code.
5. Conclusion

A numerical case study to discuss the pier shape coefficient of seismic hydrodynamic pressure is introduced in this paper. Three water-pier coupling finite element models of piers with circular, rectangular and elliptical sections and the surrounding water are built with 20-node 3D solid elements and potential-based fluid elements. The boundary conditions are free surface for water top, rigid boundary for the bottom, elastic boundary for the four lateral sides, and fluid-structure interface boundary for the interaction between water and pier. Ground motions with PGA 0.265 g and 0.177 g are input along horizontal and vertical directions to the models one by one. The absolute maximum values of the result pressure time histories show that the horizontal distributions of the pressures from the vertical central line to the edge at 8 submerged depths for the three types of piers, rectangular, circular and elliptical are almost the same, the difference among the pressures on the three piers is mainly from the decreasing rate from the central line to the edge. The unit-height pressures are getting large as the depth increase, and the pressure on rectangular pier is larger than those on the other two piers in general. The pressures decrease with the input direction from perpendicular to parallel. The result values of shape coefficients of this paper are close to the provisions in Japanese code, and those for circular and elliptical piers are slightly less than that stipulated in the code; and the coefficient values for rectangular pier are less than that in Euro code 8 and those for elliptical pier are in the range of the code.

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