Importance of seismic hydrodynamic pressure for design of bridge pier in deep water from a numerical case study

Haiming Liu¹, Xiaxin Tao²*, Zhengru Tao³, Shiwang Zhang³

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

*Corresponding author’s e-mail: taoxiaxin@aliyun.com

Abstract. The importance to take into account the hydrodynamic pressure on bridge pier in deep water for seismic design is dealt with in this paper from a numerical case study. In that study, a bridge pier in 54 m water is modeled as single pier, the interaction between soil-pile foundation system and pier is expressed by springs from M method and mechanical analysis, that between water and the pier is by added mass and damping of moving water from Morison equation. Seismic responses of the model in conditions with 6 water depths and without water are calculated respectively, with inputs of 12 ground motions for 4 fortification intensities. The maximum values of shear forces at the bottom of the pier are acquired from the corresponding response time histories, and compared with those without water. The result shows that the effect of the hydrodynamic pressure must be taken into account in design of bridge in deep water as it may be even larger than that of strong ground motion if water depth is larger than 50 m.

1. Introduction
The effect of hydrodynamic pressure on bridge pier is required to combined with those from ground motion, dead load, earth pressure and so on in seismic design according to the Guidelines for Seismic Design of Highway Bridges of China[1], as well in Japanese code[2] and European code[3]. However it is not stipulated in US codes[4, 5]. The difference means that the knowledge on the pressure is now not enough, its effect on seismic response must be dealt with further. In recent years, more and more bridges have been constructed in deep water, with water depth even more than 100 m, in China. A new pressing issue must be answered by scientists is that if the effect increases with water depth significantly and how fast it may increases. In this paper, the problem is dealt with from a numerical case study.

2. Modeling of bridge pier in deep water in the case study
The single pier model for the case study is built from a actual double tower and double cable plane cable-stayed bridge with total length 908 m and span combination 70m+160m+448m+160m+70m. The 5# pier at an end of the main span is chosen for the model, which is 54 m high and width 4 m and 3 m along longitudinal and transverse directions respectively. The materials are C40 and C30 concrete
for piers, cushion caps and piles with density 2500kg/m$^3$, elastic modulus $3 \times 10^{10}$Pa, Poisson ratio 0.2, and damping ratio 0.05.

The finite element model is built by means of the Midas/Civil software, the pier is discretized by 108 beam elements with height 0.5 m, as shown in figure 1 [7]. The upper load, such as the main beam and tower, is simplified by a vertical force 36840kN centered at the pier top. The interaction between soil and piles in group is expressed by lateral springs which are determined by “M” method and soil data from field survey. The interaction between the soil-pile foundation system and pier is expressed by springs for translational and rotational motions, which are determined by deformations from mechanic analysis.

![Figure 1. The diagrammatic sketch of the pier model (from [7])]({})

3. **Seismic response of the model in water with 6 depths**

As inputs, three ground motion time histories for each of the four fortification intensity VI, VII, VIII and IX are synthesized from the corresponding design spectra constructed according to the provision 5.2.3 of the design guidelines[1]. Four examples for each of the four intensities, (a) for VI, (b) VII, (c) VIII and (d) IX, are shown in figure 2.
Figure 2. Four examples of the input time histories for each of the four intensities

The water-pier dynamic interaction is expressed by the added mass and damping of moving water calculated by Morison equation. The values of them are listed in Table 1.

Table 1. Values of the added mass and damping adopted in the case study

| Added mass per unit height (kg/m) | Added damping per unit height (kN•s/m) |
|----------------------------------|----------------------------------------|
| Transverse                       | Longitudinal                           |
| 6.645                            | 8.034                                  |
| Transverse                       | Longitudinal                           |
| 2.870                            | 3.830                                  |

The response shear forces and bend moments at the pier bottom are calculated with water depth 5 m, 10 m, 20 m, 30 m, 40 m and 54 m, as well without water for comparison, respectively from each input of the twelve and along the longitudinal and transverse bridge directions.

4. The increasing of hydrodynamic pressure with water depth

The hydrodynamic pressure is acquire as the maximum absolute value of the time history of shear force difference between the forces at the bottom of the pier with a given water depth and without water. For comparison, a relative amplified coefficient is defined as in equation (1).

\[
A_{Qh} = \frac{\text{Max}\left|Q_h - Q_0\right|}{\text{Max}\left|Q_0\right|}
\]  

(1)

where \(Q_h\) and \(Q_0\) are the shear force amplitudes at the bottom of the pier with water depth \(h\) and without water respectively. It is obvious that there must be no amplification if the value of \(A_{Qh}\) equals 0.0, and amplification 100% if it equals 1.0, that means the response is doubled by hydrodynamic pressure.

The results of the relative amplified coefficients for the 6 water depths and the four intensities are calculated and plotted as shown in figure 3. In the figure, as same in figure 2, (a), (b), (c) and (d) are for intensity VI, VII, VIII and IX respectively. The small squares and triangles are for the results of along longitudinal and transverse bridge directions respectively.
One can find from the figure that the amplification by the hydrodynamic pressure increases obviously with water depth. The mean value of the coefficient is just several percent for 5 m water, and more than 20%, 50%, 70% and 100% at water depth 20 m, 30 m, 40 m, 50m respective. The maximum value more than 120% shows that the effect of hydrodynamic pressure on pier in deep water may be probably even larger than that of strong ground motion. There is no big difference among the results of four intensities.

5. Conclusion
The importance of hydrodynamic pressure on design of bridge pier in deep water is deal with from a case study, in which a single pier model is built from a real bridge, the interaction between the water and pier is expressed by the added mass and damping from Morison equation. Seismic responses of the pier model in conditions with 6 water depths and without water are calculated respectively, with inputs of 12 ground motions for 4 fortification intensities. The hydrodynamic pressure is acquired from the maximum absolute value of time history of difference between shear forces at the bottom of the pier with the given water depth and without water. A related amplified coefficient is defined as the ratio of pressure to the value of the corresponding shear force without water. The results show that the pressure increases with water depth obviously, and the effect of hydrodynamic pressure must be taken into account in design of bridge in deep water as it may be even larger than the that of strong ground motion if water depth larger than 50 m.

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] Ministry of Transport of the People's Republic of China (2008). Guidelines for Seismic Design of Highway Bridges (JTG/T B02-01-2008, in Chinese)

[2] Japan Road Association (2012). 2012 Design Specifications for Highway Bridges, Part V Seismic Design.

[3] Technical Committee CEN/TC250 (2011). Euro code 8: Design of structures for earthquake resistance – Part 2: Bridges.

[4] California Department of Transportation (2013). Caltrans, Seismic design criteria, Version 1.7..

[5] U.S. Department of Transportation Federal Highway Administration (2014). AASHTO Guide specifications for LRFD Seismic Bridge Design, 2nd Edition

[6] Morison J R (1950). The Force Exerted by Surface Waves on Piles[J]. Journal of Petroleum Technology, 189(5):149-154.

[7] Zhang S (2019). Seismic Hydrodynamic Pressure on Bridge Pier in Deep Water. Thesis for Master's Degree, Institute of Engineering Mechanics, China Earthquake Administration.