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Preliminary Result of Seismic Hydrodynamic Pressure on Bridge Pier with Submerged Depth from a Shaking Table Model Test

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Abstract. To deal with the hydrodynamic pressure on bridge pier with submerged depth in water, a shaking table model test is reported in this paper. The model is designed and built for a pier of cable-stayed bridge submerged in 1.5 m water with a scale of 1/50. Two sets of motions, for E1 and E2 levels are input in two bi-directions, transverse and vertical, and longitudinal and vertical. The results show that the hydrodynamic pressure is getting larger with submerged depth obviously, with a increasing rate larger than that for the formula in our existing design guidelines, but smaller than that by Westergaard.

1. Introduction

The hydrodynamic pressure on bridge pier in water during earthquake is studied in many papers, while the variation of the pressure with submerged depth has not been paid enough attention [1]. From the understanding of the authors of this paper, this variation is one of the original causes of the difference between the formulas of hydrodynamic pressure in Guidelines for seismic design of highway bridges of China [2] and those by Westergaard [3]. Also known as the distribution of hydrodynamic pressure on pier, it could not be revealed theoretically. A feasible way is to get information from test, even model test.

In this paper, design of a shaking table model test is introduced, the test is reported, and some preliminary results from the test are presented. The curves of the pressure distribution with submerged depth, are compared with those from the assumptions of the two classical references, respectively.

2. Why the Variation of Hydrodynamic Pressure with Submerged Depth is very Important

The first classical formula of hydrodynamic pressure during earthquake was presented by Westergaard in 1933 [3], for the case of a straight dam with a vertical upstream face, and then was modified by Goto and Toki for pier in 1965 [4] as shown in equation (1).

$$P = \frac{7}{4} k_0 \gamma_w a \sqrt{hy} \quad (1)$$



where k_0 is seismic coefficient for intensity of earthquake ground motion, γ_w is the density of water, a is the radius of horizontal section of the cylindrical pier, h is the total water depth, y is depth from the water surface, and P is maximum hydrodynamic pressures per unit depth at y .

This formula was simplified from Fourier series solution of the motion equation with a quadratic parabola for the general shape of the the pressure distribution diagram with vertical axis. In the simplification, the curve for the pressure is satisfied the condition of a horizontal tangent at the water surface, but not satisfied the other one of a vertical tangent at the dam bottom, since the parabola has a sloping tangent at the bottom.

Goto and Toki pointed out that equation (2) was not always applicable to bridge piers, since the hydrodynamic pressure on rigid piers would be less than that calculated by equation (1) and the decreasing should be remarkable for slender piers. They presented a formula for the pressure on a cylindrical submerged bridge piers during earthquake in 1965 [4], as shown in equation (2).

$$P = (1 - \frac{a}{2h})k_0\gamma_w\pi a^2\sqrt[3]{\frac{y}{h}} \quad (2)$$

where all parameters are the same as in equation (1).

The formula was simplified from series solution of three dimensional dynamic analysis with a cubic expression for shape of the pressure distribution instead of the parabola by Westergaard for dams. The cubic expression was chosen by means of shaking table model experiments with three cylinders and one column with simple harmonic motion inputs. It was mentioned [4] that the studies on the cross-sectional shape of piers different from circle should be carried out experimentally as well as theoretically.

This formula was adopted by Japanese Design Specifications for Highway Bridges [5, 6], and then by Specifications of earthquake resistant design for Highway Engineering of China (1989) and Chinese Guidelines for Seismic Design of Highway Bridges (2008) [7, 2].

Therefore, the distribution of hydrodynamic pressure with submerged depth governs the formula in our design code, is very important especially for bridge piers in deep water.

3. A shaking Table Model Test

A shaking table model test is designed for seismic response of a cable-stayed bridge in southwestern region of China with two level inputs of bi-directional horizontal motions.

The model is 1/50 scaled with total height of 4.54 m, is made of perspex, consists of the pylon limb and hollow rectangular piers with thickness 0.03 m and outer section 700 mm×310 mm, as shown in figure 1.

For the target of this paper, one pier of the model is fixed in a rectangular tank with a dimension of 2 m×3 m×2 m, and submerged in water with depth of 1.5 meter. The hydrodynamic pressure sensors are fixed at seven heights along the vertical central line of upstream face of the pier as shown in figure 1.

The hydrodynamic pressures are measured from all sensors from E1 and E2 inputs with peak acceleration 0.265g and 0.51g respectively in longitudinal and vertical directions, and transverse and vertical directions.

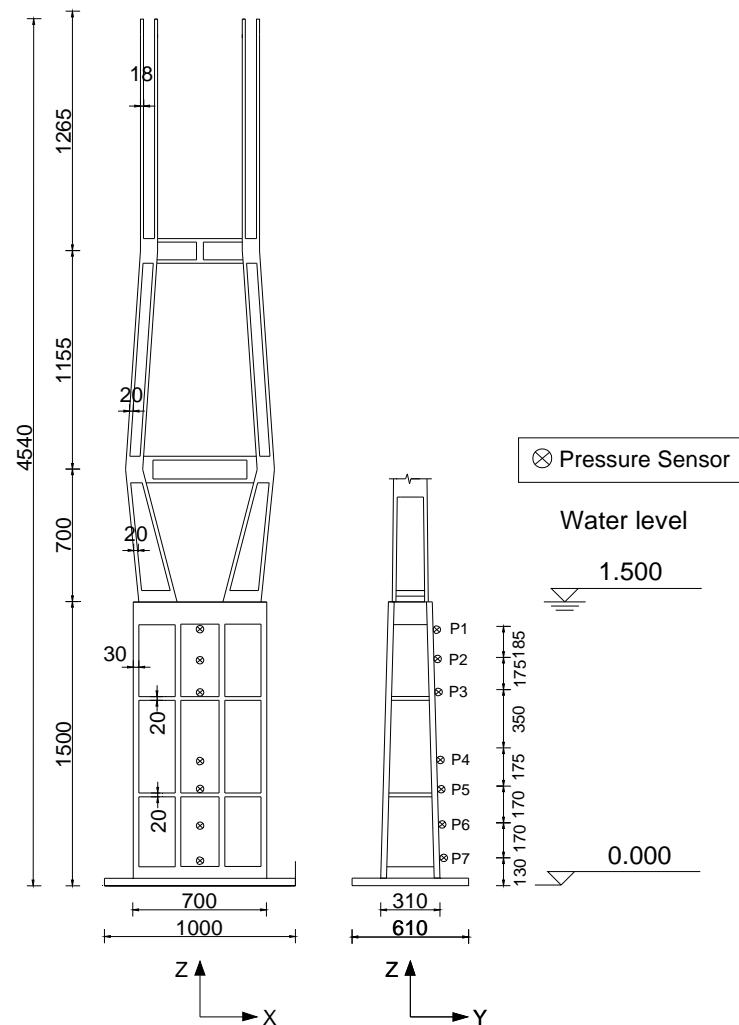


Figure 1. Details of the model pier; all dimensions are in millimeters.

Figure 2 shows the tank on shaking table and details of the table. Some wave absorbing stuff are put on the four lateral walls to reduce reflected wave.



Figures 2. The tank on shaking table (left) and the details of shaking table (right).

4. The Preliminary Results from the Test

The recording at each point during each input is a time history, since the input motion is acceleration time history. As an example, figure 3 shows a set of recordings in kpa at the 7 points in total water depth

1.5 m from inputs E1 and E2 in transverse and vertical directions. In the figure, the recordings in the left column are from E1 input while those in the right are from E2 input, those in each row are recorded at a point of P1 to P7 from top to bottom at the different submerged depths. One can see from the figure that the hydrodynamic pressures from the both inputs are getting larger with depth obviously.

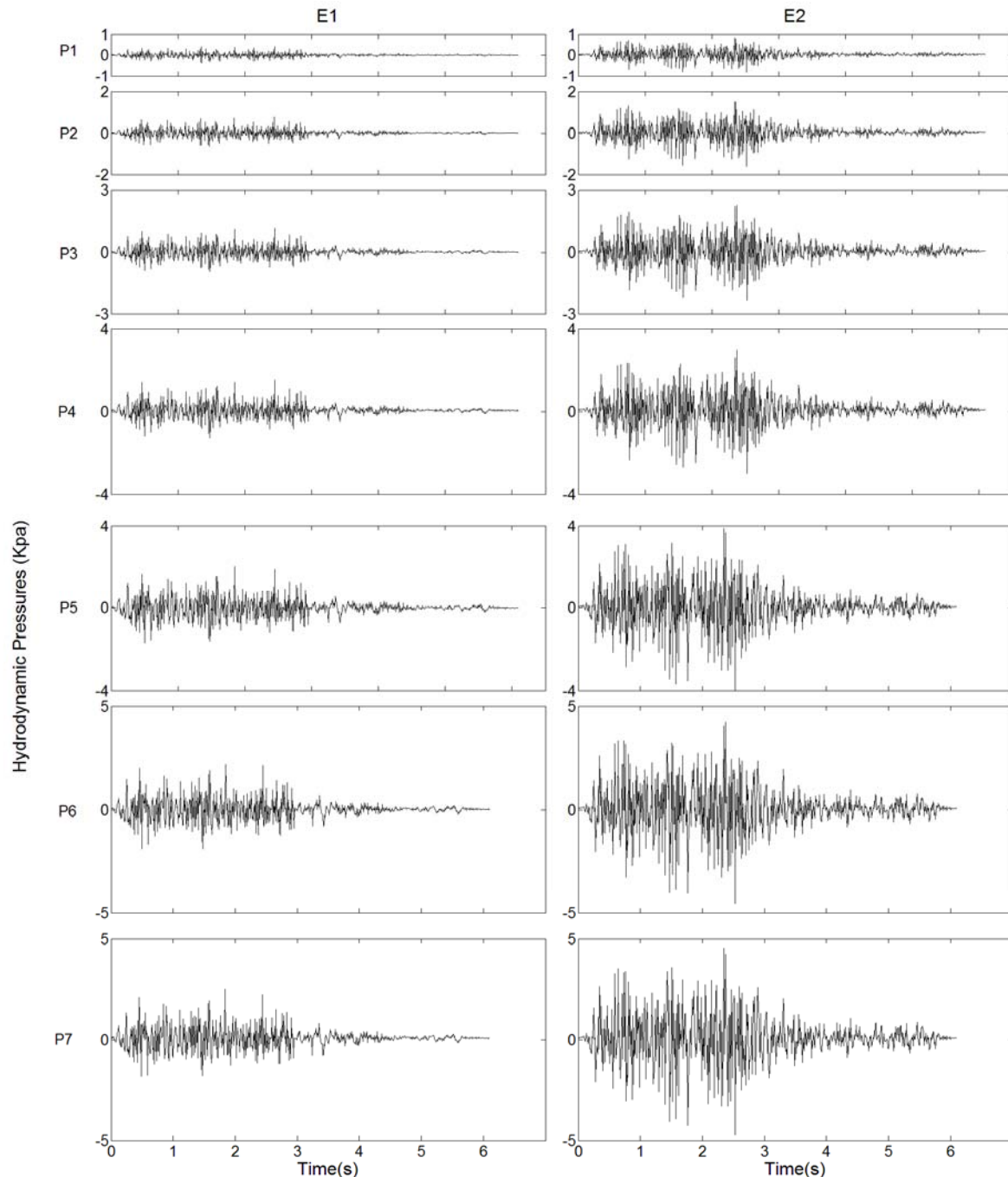
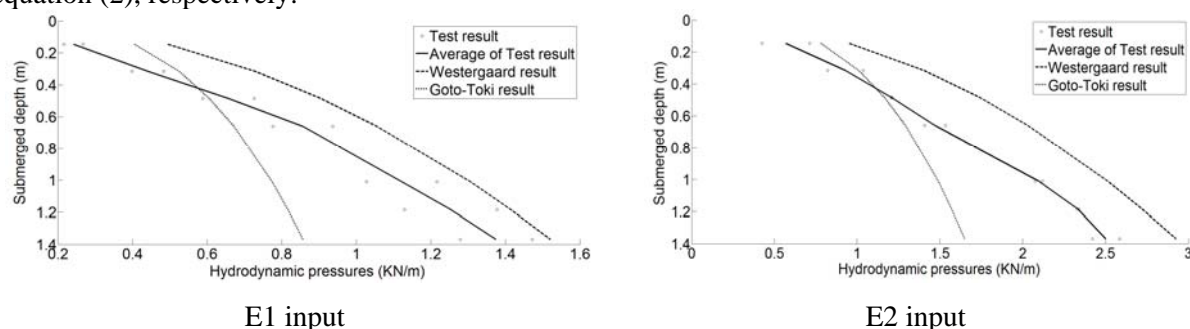


Figure 3. Time histories recorded at 7 depths from inputs in transverse and vertical directions. Totally 28 time histories are recorded at the 7 points respectively from the two level inputs in two bi-direction combinations. From a preliminary analysis, the absolute maximum amplitudes of the recordings are listed in table 1. One can see from the table that the hydrodynamic pressures from the both inputs and in the two bi-direction combinations are all getting larger with submerged depth obviously.

Table 1. The maximum amplitudes in kpa of the recordings at the 7 depths from the four inputs.

Input	P1	P2	P3	P4	P5	P6	P7
E1 X+Z	0.422	0.780	1.153	1.522	2.011	2.212	2.503
E1 Y+Z	0.523	0.948	1.421	1.834	2.382	2.697	2.882
E2 X+Z	0.831	1.611	2.370	3.002	4.150	4.557	4.740
E2 Y+Z	1.397	2.030	2.360	2.757	4.061	4.579	5.061

The hydrodynamic pressures at the 7 depths, the values in table 1 is multiplied by 0.7 m, the width of upstream face of the model pier, to get the pressure on the unit depth as the same as those by equation (1) and equation (2). Then the they are further divided by 1.37, the value of peak factor from random vibration theory, since the maximum values in table 1 are read from the non-stationary time histories as shown in figure 3, but those by the equations are the peak values are from simple harmonic excitation. The the results are shown in figure 4, for the two inputs E1 and E2, respectively. In the figure, the small gray circles are for the pressures from the test of this paper, the black solid lines connect the mean values of each depth and the black broken lines are for the corresponding pressures from equation (1) and equation (2), respectively.

**Figure 4.** The hydrodynamic pressures with submerged depth.

The results show that the increasing rate of hydrodynamic pressure with submerged depth is larger than that for the formula in our existing design guidelines, but smaller than that by Westergaard.

5. Conclusion

In order to improve the formula of hydrodynamic pressure in our design guidelines for highway bridges, the distribution of hydrodynamic pressure with submerged depth in water is studied by means of a shaking table model test in this paper. The model is designed and built for a pier of cable-stayed bridge submerged in 1.5 m water with a scale of 1/50. Two sets of motions, for E1 and E2 levels are input in two bi-directions, transverse and vertical, and longitudinal and vertical. The preliminary results of the test show that the hydrodynamic pressure is getting larger with submerged depth obviously, and the increasing rate is larger than that for the formula in our existing design guidelines, but smaller than that by Westergaard.

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