Seismic Hydrodynamic Pressure on Concrete Bridge Pier with Submerged Depth from a Set of Shaking Table Model Tests

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Abstract. To study the variation of hydrodynamic pressure on concrete bridge pier with submerged depth in water, a series of shaking table model tests are completed recently. The result shows that the pressures increase with submerged depth obviously with a similar rate for all pier models, input direction combinations and total water depths. The hydrodynamic pressures and the rates increase with the total water depth and input intensity. The pressures on the three models with cross section, rectangular, elliptic and variable rectangular, are varied and different from the provision on the shape coefficient of pier in seismic design codes of highway bridges. The effect of the absorbing stuff adopted in the tests to reduce the potential reflection wave is not obvious. The result suggests to fix more sensors not only at central but also along the edge lines, to examine the potential horizontal variation of pressures on upstream faces of the piers with different section shapes and the reflected wave must be eliminated with some new way in future test to close to the reality.

Keywords: Seismic Hydrodynamic Pressure; Concrete bridge pier; Submerged depth; Shaking table test.

1. Introduction

Many results of numerical studies on hydrodynamic pressure on bridge pier have been published recently, while just few tests were carried out, especially on some important basic rules, such as the distribution of the hydrodynamic pressure with submerged depth [1, 2, 3, 4, 5]. The distribution governs the formula in our design code, is very important especially for bridge piers in deep water, and could not be revealed theoretically. A feasible way is to get information from test, actually model test. The authors of this paper reported preliminary result of a shaking table model test last year [6]. The model was the pylon limb and hollow rectangular piers made of Perspex. The result shows that the hydrodynamic pressure is getting larger with submerged depth obviously, and the increasing rate is larger than that by Goto [7] which is the basis of the formula in existing seismic design codes of highway bridges of Japan and China [8, 9]. After that test, a set of tests is completed for concrete piers with three kinds of cross sections recently, in order to find if the variation of the hydrodynamic pressure with submerged depth increases similarly, and the influence of section shape of pier, effect of absorbing stuff for potential
reflection wave on the pressure distribution as well. The results of the tests are presented in this paper, and they provide a valuable basis of further numerical analysis.

2. The Models on Shaking Table

Three concrete models for bridge piers with cross-sections of rectangular, elliptic and variable rectangular (in brief variable, below), are designed for the tests respectively. They are all made of C50 concrete and HRB 400 rebar. The size of rectangular pier model is 0.500 m × 0.300 m × 2.890 m in length, width and height; that of elliptic cross-section model is 0.484 m × 0.310 m × 2.870 m in major axis, minor axis and height; the width and height of the variable section pier model are 0.302 m and 3.190 m respectively, and the length is from 0.310 m at the top to 0.615 m at the bottom. Each pier model is fixed at the bottom of a steel tank on shaking table with a dimension of 2.000 m × 3.000 m × 2.000 m in the tests with water depth of 1.1 and 1.6 meter respectively. Some wave absorbing stuff are set on the four lateral walls of the tank to reduce potential reflected wave with counterparts without the stuff. Fig. 1 shows three concrete piers and the wave absorbing stuff on the tank walls.

Figure 1. Three concrete pier models (left) and wave absorbing stuff on walls of the tank (right).

The hydrodynamic pressure sensors are fixed at eight heights along the vertical central line of upstream face of the pier, as shown in Fig. 2. The DEV1 data acquisition system is adopted to record water pressures in each test, the measurement range reach 100 kPa with precision ±0.03%.
Figure 2. Positions of the fixed pressure sensors.

The hydrodynamic pressures at 4 sensors emerged in 1.1m water are recorded from E1 and E2 inputs of ground motion time histories as the same in [6] with peak acceleration 0.265g and 0.51g in longitudinal and vertical directions (X+Z, in brief), and in transverse and vertical directions (Y+Z) respectively, and at the all 8 sensors in 1.6m water are recorded only from E1 input.

3. The Observed Data from the Tests
The observation records of each test is a set of time histories of hydrodynamic pressures at all sensors in water from each of the two inputs. Totally 192 time histories are recorded at the 4 or 8 points on the three pier models in tests with or without absorbing stuff respectively, from the two level inputs in two bi-direction combinations. The absolute maximum amplitude of each time history are acquired, and the static water pressure at the corresponding depth are taken away to get the hydrodynamic pressure value. The results are listed in the Table 1 and Table 2 for the tests in water 1.1 m and 1.6 m. In Table 1, the hydrodynamic pressures at 4 submerged depths on the three pier models are listed for 4 tests with absorbing stuff and 4 counterparts without that, respectively from inputs E1 and E2 in bi-directions X+Z and Y+Z. In Table 2, the pressure at 8 submerged depths on the piers are listed for 2 tests with absorbing stuff and 2 without that, respectively from inputs E1 in the two bi-directions.
### Table 1. The hydrodynamic pressures on the three pier models in 1.1 m water (kPa).

| Pier model       | Submerged depth (m) | Without absorbing stuff | With absorbing stuff |
|------------------|---------------------|-------------------------|----------------------|
|                  | E1 X+Z  | E1 Y+Z  | E2 X+Z  | E2 Y+Z  | E1 X+Z  | E1 Y+Z  | E2 X+Z  | E2 Y+Z  |
| Rectangular      | 0.180   | 0.253   | 0.335   | 0.402   | 0.520   | 0.265   | 0.256   | 0.412   | 0.566   |
| section          | 0.310   | 0.419   | 0.389   | 0.717   | 0.801   | 0.457   | 0.336   | 0.723   | 0.775   |
|                  | 0.500   | 0.632   | 0.451   | 1.199   | 1.184   | 0.671   | 0.483   | 1.171   | 1.125   |
|                  | 0.620   | 0.796   | 0.616   | 1.509   | 1.395   | 0.825   | 0.648   | 1.517   | 1.389   |
| Elliptic         | 0.190   | 0.254   | 0.370   | 0.394   | 0.644   | 0.226   | 0.314   | 0.395   | 0.686   |
| section          | 0.320   | 0.444   | 0.518   | 0.694   | 0.965   | 0.378   | 0.460   | 0.696   | 1.025   |
|                  | 0.510   | 0.711   | 0.744   | 1.093   | 1.415   | 0.658   | 0.663   | 1.113   | 1.405   |
|                  | 0.620   | 0.852   | 0.784   | 1.423   | 1.702   | 0.767   | 0.823   | 1.398   | 1.661   |
| Variable         | 0.165   | 0.255   | 0.410   | 0.409   | 0.676   | 0.170   | 0.291   | 0.412   | 0.672   |
| section          | 0.335   | 0.598   | 0.681   | 0.823   | 0.973   | 0.385   | 0.405   | 0.841   | 0.959   |
|                  | 0.490   | 0.821   | 0.831   | 1.236   | 1.315   | 0.588   | 0.539   | 1.252   | 1.358   |
|                  | 0.610   | 0.978   | 0.895   | 1.555   | 1.525   | 0.738   | 0.640   | 1.562   | 1.616   |

### Table 2. The hydrodynamic pressures on the three pier models in 1.6 m water (kPa).

| Pier model       | Submerged depth (m) | Without absorbing stuff | With absorbing stuff |
|------------------|---------------------|-------------------------|----------------------|
|                  | E1 X+Z  | E1 Y+Z  | E2 X+Z  | E2 Y+Z  | E1 X+Z  | E1 Y+Z  | E2 X+Z  | E2 Y+Z  |
| Rectangular      | 0.075   | 0.274   | 0.303   | 0.195   | 0.335   |
| cross-section    | 0.195   | 0.695   | 0.639   | 0.572   | 0.725   |
|                  | 0.365   | 1.235   | 1.017   | 1.061   | 1.128   |
|                  | 0.505   | 1.625   | 1.300   | 1.446   | 1.402   |
|                  | 0.680   | 2.064   | 1.504   | 1.794   | 1.825   |
|                  | 0.810   | 2.341   | 1.794   | 1.995   | 2.073   |
|                  | 1.000   | 2.693   | 1.990   | 2.380   | 2.495   |
|                  | 1.120   | 2.873   | 2.110   | 2.549   | 2.682   |
|                  | 0.065   | 0.143   | 0.301   | 0.137   | 0.272   |
|                  | 0.205   | 0.476   | 0.769   | 0.476   | 0.759   |
|                  | 0.360   | 0.863   | 1.219   | 0.904   | 1.283   |
| Elliptic         | 0.505   | 1.082   | 1.551   | 1.156   | 1.567   |
| cross-section    | 0.690   | 1.395   | 1.915   | 1.536   | 1.977   |
|                  | 0.820   | 1.624   | 2.170   | 1.816   | 2.232   |
|                  | 1.010   | 1.982   | 2.408   | 1.990   | 2.355   |
|                  | 1.120   | 1.986   | 2.556   | 2.326   | 2.650   |
|                  | 0.075   | 0.217   | 0.392   | 0.223   | 0.435   |
|                  | 0.200   | 0.536   | 0.824   | 0.550   | 0.888   |
|                  | 0.350   | 0.950   | 1.175   | 0.972   | 1.366   |
| Variable         | 0.515   | 1.285   | 1.543   | 1.445   | 1.691   |
| cross-section    | 0.665   | 1.578   | 1.755   | 1.832   | 1.982   |
|                  | 0.835   | 1.802   | 2.061   | 2.226   | 2.391   |
|                  | 0.990   | 2.022   | 2.377   | 2.480   | 2.692   |
|                  | 1.110   | 2.120   | 2.507   | 2.619   | 2.860   |
4. Analysis of the Pressure Variation with Submerged Depth

The pressure variation with submerged depth are analyzed from the result data in the above two tables, and the effects of the total water depth, of the shape of pier model and of the absorbing stuff on the variation are studied as well.

4.1. The Distributions of Pressure on Piers with Submerged Depth in Tests of 1.1 m and 1.6 m Water

The hydrodynamic pressures on piers in 1.1 m and 1.6 m water are plotted in Fig. 3, with solid and dash lines respectively. In the figures, the small square, circle and triangle are for the pressures on the piers with rectangular, elliptic and variable cross-section respectively, and all results are of the tests with input E1 and without absorbing stuff.

One can see from the Fig. 3 that the pressures increase with the submerged depth obviously with a similar rate for the all pier models, the input direction combinations and the total water depths. The hydrodynamic pressures and the increasing rates in 1.6 m water are larger than that in 1.1 m water at the same submerged depth. There are some difference among the results of the three pier models. The order among the three is not stable, so should be studied further.

4.2. Influence of Section Shape of the Pier Model on the Pressure Distribution

The comparison of pressures on piers with the three kinds of sections in 1.1 m and 1.6 m water are shown in Fig. 4 (a) and Fig. 4 (b) respectively. In the figures, all the symbols are the same as in the Fig. 3, but solid and dash lines are for the results from inputs E1 and E2.

One can see from the figures that the pressures from E2 are always larger than those from E1, and the pressure increasing rates with submerged depth of tests with E2 input are larger than those from E1. The order of the pressures on the three models is varied from variable>rectangular>elliptic in most cases to rectangular>variable>elliptic in Fig. 4 (a) right for E1 and Fig. 4 (b) left, and variable>elliptic>rectangular just in one case, Fig. 4 (a) left for E1. This is quite different from the provision on the shape coefficient of pier in Chinese, Japanese and Euro codes for seismic design of highway bridges [8, 9, 10], it may come from the difference between pressures on the vertical central line and on the edge line. The result arouses the authors to fix more sensors on every depth level at central and edge lines, to examine if the pressures at edges of upstream faces of the piers with different section shapes are really different and if the difference is in accordance with the shape coefficients in the codes.

Figure 3. The pressures with submerged depth from inputs E1 in X+Z (left) and Y+Z (right).

Figure 4. (a). Hydrodynamic pressures on the 3 pier models in 1.1 m water from inputs E1 and E2 in X+Z (left) and Y+Z (right).
Figure 4. (b). Hydrodynamic pressures on the 3 pier models in 1.6 m water from inputs E1 in X+Z (left) and Y+Z (right).

4.3. Effect of the Absorbing Stuff for Potential Reflection Wave

As shown in Table 1 and Table 2, two sets of tests were carried out for each situations with and without absorbing stuff, since the tank size was limited and there must be reflected wave that disturbs the flow field badly. The results provide data to show the effect of the stuff to reduce the potential reflected wave. The comparisons between results with and without absorbing stuff are plotted for the three pier models respectively, in Fig. 5. In the figures, the ratios of pressures on the three pier models from tests with the absorbing stuff to the counterparts without the stuff are showed by the same symbols as in the Fig. 3, but the solid lines link the mean ratios at each of the submerged depths by E1 input and the dash lines link those by E2 input.

Figure 5. (a). Ratio of hydrodynamic pressures on piers in 1.1 m water with and without absorbing stuff from inputs E1 and E2 in X+Z (left) and Y+Z (right).

Figure 5. (b). Ratio of hydrodynamic pressures on piers in 1.6 m water with and without absorbing stuff from E1 inputs in X+Z (left) and Y+Z (right).

One can see from the figures that the effect of the absorbing stuff to reduce the potential reflection wave is not obvious. The ratios from E2 inputs are almost equal to 1.0, that means the absorbing stuff did nothing to reduce strong reflection wave generated by so strong input. The ratios from E1 are also around 1.0, and is larger than 1.0 in shallow water, and less than 1.0 in deeper water, the result seems to show the reflection wave may reduce the pressure in some cases with maximum discount 30%. These may be checked by further study, and eliminated by some effective measure in test to close to the reality.
5. Conclusion
A set of shaking table tests of hydrodynamic pressures on concrete pier models with three kinds of cross sections, rectangular, elliptic and variable, are reported. The result shows that the pressures increase with submerged depth obviously with a similar rate for all pier models, input direction combinations and total water depths. The hydrodynamic pressures and the increasing rates in 1.6 m water are larger than that in 1.1 m water at the same submerged depth. The pressures from stronger input are always larger, and the increasing rates too. The order of the pressures on the three models is different from the provision on the shape coefficient of pier in seismic design codes of highway bridges. The effect of the absorbing stuff adopted in the tests to reduce the potential reflected wave is not obvious.

The result arouses the authors to fix more sensors not only at central and but also the edge lines, to examine if the pressures at edges of upstream faces of the piers with different section shapes are really different from those on central lines and if the difference is in accordance with the shape coefficients in the codes. The reflected wave must be eliminated in future test in some effective way to close to the reality.

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