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EXPERIMENTAL STUDY ON HYDRODYNAMIC DRAG OF WALLS IN NATURAL RIVER FLOWS

HITOSHI KUWAMURA

Dept of Architecture, the University of Tokyo, Tokyo, Japan

Hydrodynamic drag of a free-standing wall partially submerged in inundation flow was experimentally investigated in a natural river. A wall plate and sensors for measuring drag force, fluid velocity, and water depth were installed in a testing frame made of stainless steel. Regulator plates were immersed on the river bed in the up and down streams of the frame to provide a uniform and steady flow in the testing area. The drag coefficient C_D was significantly influenced by Froude number F_r, but not by Reynolds number R_e. The C_D had a minimum value slightly over 1.0 at around $F_r = 1.0$, and increased up to 2.0 with the changes of F_r toward 0.5 and 2.0. The blockage ratio of the wall in the flume showed a large effect on the C_D for subcritical flow ($F_r < 1.0$), but little effect for supercritical flow ($F_r > 1.0$). The formula $C_D = 1.0 + F_r^2/4$, is suitable to the test data for $F_r > 1.0$, but underestimates $F_r < 1.0$.

Keywords: Hydrodynamic force, Tsunami, Flood, Inundation, Drag coefficient, Form drag, Wave drag, Free-standing wall, Natural river.

1 INTRODUCTION

Recent severe hydro-hazards represented by the great tsunamis of 2011 East Japan Earthquake and the high tidal waves of 2013 Philippines Typhoon caused a tremendous amount of loss of human lives and houses washed away by the water flows. Structural engineers may simply say the structural resistances were less than the hydrodynamic forces. However, the loading effect of such inundation flows on land structures, especially hydrodynamic drag, is scarcely known in the engineering for hydro-hazard mitigation. This paper deals with the hydrodynamic drag of a free-standing wall partially submerged in an inundation flow, on the basis of experimental investigations in a natural river. The drag in this case is the sum of form and wave resistances attributed to bottom and surface flows respectively. The drag coefficient is drawn from an experiment for the use of hydro-resistant design.

2 EXPERIMENTAL SCHEME

Inundation flows generate several types of loading effects on land-structures, such as hydrostatic forces, buoyant forces, hydrodynamic forces, surge impulsive forces, debris impact forces, debris damming forces, uplift forces, and gravity loads of retained water on elevated floors, as described in the design guidelines for tsunami evacuation structures by FEMA (2008). This paper treats only drag forces categorized as hydrodynamic forces. The hydrodynamic drag is the resistance of a structure fully surrounded by water flows in a steady condition lasting much longer than several minutes during a flood. Thus, natural rivers provide a good test field for experiments of hydrodynamic drags that require a huge volume of water supply, as long as the natural flow is conditioned to be uniform and steady in the testing space.

2.1 Experimental Setup

The experimental setup, which was settled horizontally in the straight part of a river, is shown in Figure 1. The set was composed of a testing frame with a floor panel, a front regulator, a rear regulator, and side boards. The first three were made of stainless steel and the last ones made of timber. The entire length of the set in the flow direction was three meters. The testing frame accommodated a structural model and necessary sensors, i.e., a load cell measuring drag force, level gauges measuring water depths, and a current meter measuring fluid velocity (Figure 1). The structural model connected to the load cell was suspended by a rack jack so that the model can be moved up and down. The gap between the structural model and the floor panel was adjusted 0.3 to 0.5 mm, so that the fluid velocity underneath the bottom face of the structure was zero. As long as the depth (h_o) and velocity (v_o) of the incoming flow were measured, the structural mode was raised fully into the air apart from the water surface. The front regulator plate immersed on the river bed in the upstream part of the structure smoothed the incoming flow by diminishing the surface waves. The rear regulator developed a normal wake associated with vortexes behind the structure. The side boards parallel to the stream clarified the flume width such that the inner width (B_o) of the flume was 90 cm.

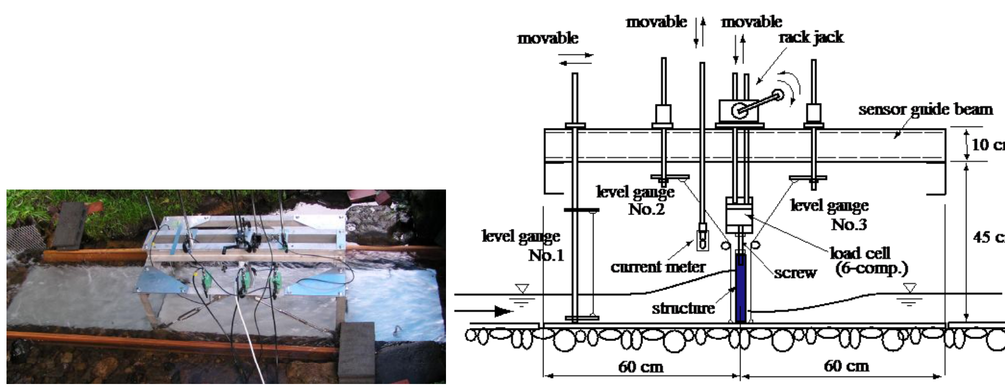

Figure 1. Experimental setup (left), and arrangement of structure and sensors (right).

2.2 Verification of Uniform and Steady Flows

The water flow conditions free from the structural obstacle were checked in advance so that the hydrodynamic drag would be measured in a uniform and steady flow in the area of the testing frame. The inundation depths and velocities at seven points with the same intervals along the flow (x-direction through the center of the testing frame) and across the flow (y-direction through the frame center) were measured in turn. The examples are shown in Figure 2, from which the flow in the testing area was found to be fairly uniform and steady.

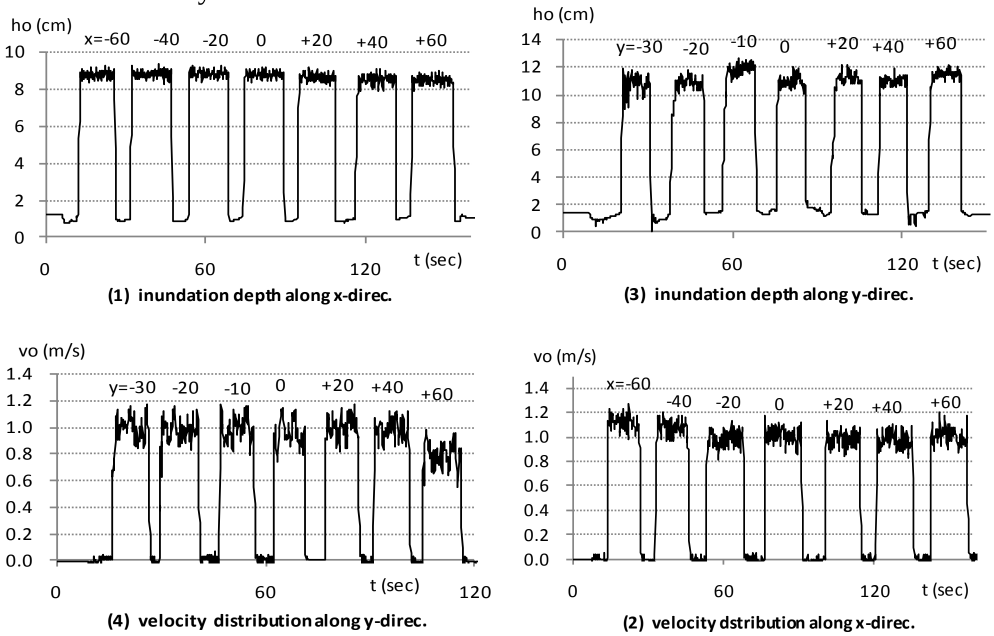

Figure 2. Distributions of inundation depth and velocity along and across the stream.

2.3 Structural Models

The structural model in this study was a flat rectangular plate representing an isolated wall standing in an inundation flow. The plate was made of 10-mm thick stainless steel plate with a sharp right angle at the edges. The inundation flow attacked perpendicular to the face of the plate. The plate height was 20 cm, enough to prevent overflow in this study, and the width (B) was selected from cases of 10, 20, and 30 cm, which are denoted by B10, B20, and B30 respectively in the graphs.

2.4 Dimensional Analysis and Similarity

The subject of this study is the hydrodynamic drag force (P_D) of a flat rectangular plate with a finite width (B) placed in an open channel with a finite width (B_o). It was subjected to a perpendicularly approaching uniform and steady water flow with depth (h_o), velocity (v_o), density (ρ, 1000kg/m^3), and kinematic viscosity (ν, 1.2×10^{-6} m^2/s at 12^{o}C); the water did not overflow beyond the top of the plate in the circumstance of acceleration of gravity (g, 9.8m/s^2). The fundamental dimensions involved in these eight variables were mass, length, and time. Thus, five dimensionless products govern this subject. Here, we adopt the following five products:

$$C_D\left(=\frac{P_D}{\frac{1}{2}\rho {v_o}^2 B h_o}\right),\qquad F_r\left(=\frac{v_o}{\sqrt{g h_o}}\right),\qquad R_e\left(=\frac{v_o B}{\nu}\right),\qquad \frac{h_o}{B},\qquad \text{and}\qquad \frac{B}{B_o}$$

where C_D is drag coefficient, F_r is Froude number, R_e is Reynolds number, h_o/B is aspect ratio, and B/B_o is blockage ratio. Therefore, the drag coefficient is given by a function of the other four dimensionless parameters, but the Reynolds number is known to be negligible for the C_D of bluff structures like box-shaped buildings with vertical walls. Then we can assume the following equation:

$$C_D = \Phi\left(F_r, R_e, \frac{h_o}{B}, \frac{B}{B_o}\right) \;\Rightarrow\; C_D = \Phi\left(F_r, \frac{h_o}{B}, \frac{B}{B_o}\right) \tag{1}$$

This means that the C_D obtained from a hydraulic experiment by using a small-scale model can be applied to a large-scale actual structure when F_r, h_o/B, and B/B_o are the same respectively between experiment and practice. The form of the function Φ is obtained from the experiment, because it is difficult even for today's supercomputers to solve this problem. Experimental studies for seeking the C_D values of a flat plate partially submerged in an inundation flow have not been done. Even tests of square or rectangular columns are very scarce at present and limited to very small Froude numbers (Fukuoka *et al*. 1997, Akiyama *et al*. 2002). The design guidelines of FEMA (2008) recommend 2.0 for C_D without any verification.

3 EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Test Ranges of Inundation Depth and Velocity

Since the experiment by natural river flow stretched intermittently over six months, the flow conditions changed from season to season as well as day by day. The inundation depth (h_o) and velocity (v_o) measured from the testing floor panel without the structural model ranged from 2 to 13 cm and 0.5 to 1.4 m/s respectively. Consequently, the Froude number ranges from 0.5 to 2.0, and the Reynolds number $4{\times}10^4$ to $4{\times}10^5$. The total samples was 98, i.e., 39 for B=10 cm, 28 for B=20 cm, and 31 for B=30 cm.

3.2 Drag Coefficient vs. Froude Number and Blockage Ratio

The experimental data on drag coefficient vs. Froude number are plotted in Figure 3.

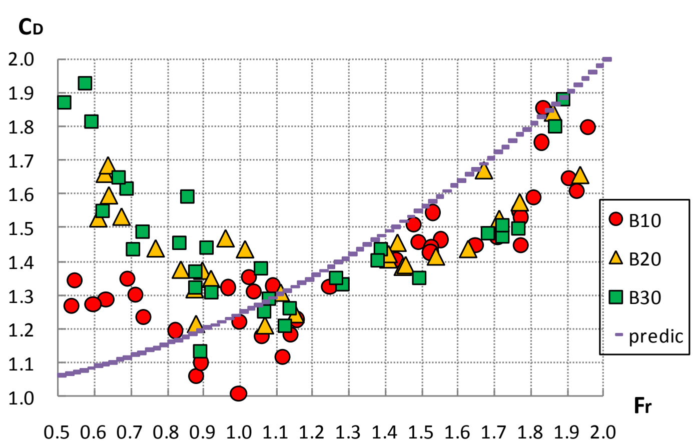

Figure 3. Drag coefficient of an isolated wall standing in non-overflow inundation.

The drag coefficient C_D is significantly influenced by Froude number F_r. C_D has a minimum value slightly over 1.0 at around F_r =1.0, and increases up to 2.0 with the changes of F_r toward 0.5 and 2.0. The FEMA recommendation (C_D=2.0) may be an excessive demand for a wide range of F_r. The blockage ratio B/B_o of the wall in the flume has a great influence on the C_D for subcritical flows represented by F_r<1.0, in the way that a larger B/B_o invites a larger C_D, while offering little influence for supercritical flows represented by F_r >1.0. This may suggest that the form drag attributed to the bottom flow is sensitive to neighborhood obstacles, while wave drag attributed to surface flow is not. The curve in the graph will be explained later.

3.3 Drag Coefficient vs. Reynolds Number and Aspect Ratio

The experimental data on drag coefficient vs. Reynolds number and aspect ratio are plotted in Figure 4. The Reynolds number shows no apparent influence on drag coefficient as expected. But the aspect ratio shows a moderate effect of a smaller h_o/B inviting a larger C_D. This suggests that the coefficient of wave drag is larger than that of form drag if separated, because wave drag is predominant in a shallow inundation.

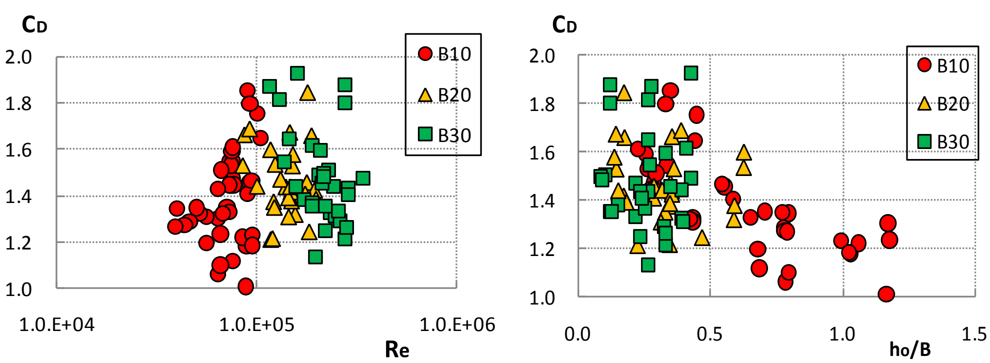

Figure 4. Effects of Reynolds number and aspect ratio on drag coefficient.

3.4 Semi-Empirical Formula for Drag Coefficient

Assuming a stream line A-B on the water surface in front of the wall through the center of the wall (Figure 5), and applying Bernoulli's theorem to remote point A and stagnation point B, we obtain the following equation for the front water depth:

$$h_f = \left(1 + \frac{1}{2}{F_r}^2\right) h_o \tag{2}$$

Assuming a stream line A*-B*-C* in the horizontal plane through the rear surface of the dead or still water, and applying Bernoulli's theorem to points A* and C* (noting that a pressure loss was induced by the resistance of the wall, assumed to be ${C_{Dp}}^* \rho\, {v_o}^2/2$) by introducing a virtual form drag coefficient C_{Dp}*, we obtain the following equation for the rear water depth:

$$h_r = \left[1 + \frac{1}{2}(1 - {C_{Dp}}^*){F_r}^2\right] h_o \tag{3}$$

Assuming that the drag force is fully attributed to the unbalance of the hydrostatic pressures acting on the front and rear faces of the wall, the drag force is given by

$$P_D = \frac{1}{2}\rho g B\left(h_f{}^2 - h_r{}^2\right) \tag{4}$$

Substituting Eq. (2) and Eq. (3) into Eq. (4), and assuming C_{Dp}*=1.0, we obtain the following equation for the drag coefficient:

$$P_D = \left(1 + \frac{1}{4}F_r{}^2\right)\frac{1}{2}\rho v_o{}^2 B h_o \xrightarrow{yields} C_D = 1 + \frac{1}{4}F_r{}^2 \tag{5}$$

This equation's curve was drawn in Figure 3. It conservatively suits the experimental data for supercritical flow (F_r >1), while it underestimates subcritical flow (F_r <1), due to the reason that the subcritical flow is affected sensitively by the blockage effect of the side boards of the open channel.

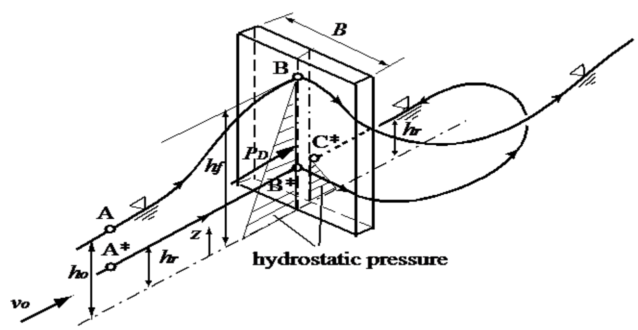

Figure 5. Assumed stream lines and hydrostatic pressures on the front and rear faces.

4 CONCLUSIONS

The hydrodynamic drag of a free-standing wall partially submerged in inundation flow was experimentally investigated in a natural river. Uniform and steady flows were obtained by immersing regulator plates on the river bed in the up and down streams of the testing area. The drag coefficient C_D was significantly influenced by Froude number F_r, but not by Reynolds number R_e in the ranges of 0.5<F_r <2.0 and $4\times10^4<R_e<4\times10^5$. The C_D had a minimum slightly over 1.0 at around F_r =1.0, and increased up to 2.0 with the changes of F_r toward 0.5 and 2.0. The blockage ratio of the wall in the flume showed a large effect on the C_D for subcritical flow (F_r<1.0), but little effect for supercritical flow (F_r>1.0). With the decrease of incoming fluid depth, wave drag became predominant over form drag. The formula C_D =1.0+$F_r{}^2$/4, is suitable to the test data for F_r>1.0, but underestimates F_r<1.0 due to the blockage effect.

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