An Experimental Study of Fundamental Characteristics of Inflow Velocity from Damaged Opening

Toru KATAYAMA and Yoshiho IKEDA
Department of Marine System Engineering, Graduate School of Engineering Osaka Prefecture University

Abstract

In this study, a simple measurement of the inflow velocity from damaged opening is carried out and its fundamental characteristic is investigated. The results show that the discharge from the opening is changed according to the model size if the model is not large. Moreover, the discharge is also changed due to condition of flooding when the inside flooded water level is over the lower edge of the opening. In order to take the characteristics of discharge, estimation formulas are also discussed.

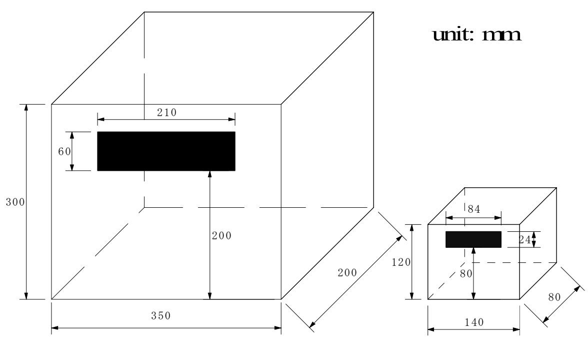
INTRODUCTION

In our previous study[1)], two different scale models (1/125, 1/50) of a Large Passenger Ship (110,000 gross tonnage), which has three decks in water tight compartments, were developed, and the damaged ship's behaviors in intermediate stages of flooding were investigated experimentally. In some conditions, large heel angle was observed for both of the models. However, the nondimensionalized time to reach the maximum heel angle of these different scale models was different. On the other hand, in previous numerical study[2)], the comparisons between the simulated and the measured results showed small difference in roll motion after reaching the maximum heel angle. As one of the causes of the differences, it was guessed that the inflow velocity from a damaged opening is affected by size of the opening and condition of inflow. In this study, the simple measurement of the inflow velocity from damaged opening is carried out and its fundamental characteristic is investigated and the estimation formulas are also discussed.

EXPERIMENTAL PROCEDURE

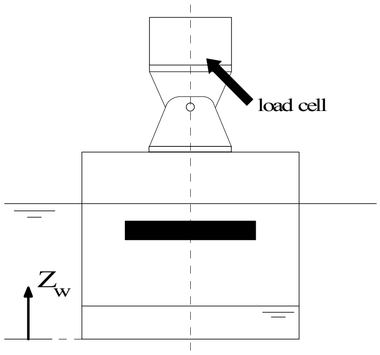
In order to investigate fundamental characteristics of inflow velocity from damaged opening, a simple experiment is carried out. Two geometric similar models, shown in Fig.1, were made with transparent acrylic boards whose thicknesses are 10 and 1.0mm and they are the boxes of rectangular parallelepiped. The measurements in the figure are inner size of the model. The black squares in the figure indicate the openings and it is located on the 1.0mm thickness acrylic board. The size of the openings is almost same size of them in the previous experimental study[1)].

Fig.2 shows a schematic view of the experiment. The model is fully captured by a load cell. In calm water, the opening of the model is released, and the vertical force acting on the model is measured until the end of flooding.



(*a*) large (*b*) small

Fig. 1 Models used in experiments.



$Z_w(t)$; water surface level inside model

Fig. 2 Schematic view of experiment.

The two relative water surface positions are selected in the experiments shown in Fig.3. For condition (a), the water surface position (;draft) is adjusted with the center height of the opening, and for condition (b), it is over the opening. Moreover, for condition (b), conditions (b-1) to (b-3), that have extra air duct except for the opening, are set up to investigate the effects of air compression on the inflow velocity from the opening.

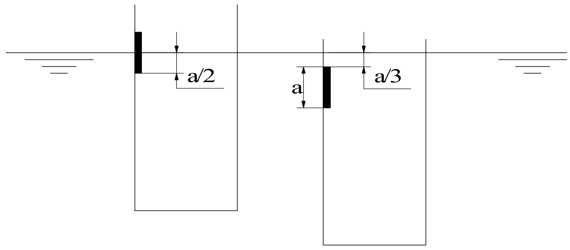
(b-1) the area of an air duct is same as the area of the opening
(b-2) the area of an air duct is same as 1/25 of the area of the opening
(b-3) no air duct

The water surface level inside the model $Z_w(t)$ (m) are obtained from the measured vertical force acting on the model $F(t)$ (kgf), by following equation.

$$F = \rho g Z_w(t) S + \frac{\rho S Z_w(t)}{t}\sqrt{2g(Z_{w0} - Z_w(t))} \quad (1)$$

where, Z_{w0} is the height of the under edge of the opening from the bottom inside the model, S is the area of the bottom inside the model. Moreover, the first term of Eq.(1) is the weight of flooded water in the model and its second term is the counter-force when water doing free fall and conflicting with the water surface inside the model. Furthermore, $Z_w(t)$ is figured with the discharge, $Q(t)$(m^3/sec), from the opening by following equation.

$$Z_w(t) = \frac{\int_0^t Q(\tau)\,d\tau}{S} \quad (2)$$



(a) (b)
a; height of opening

Fig. 3 Experimental conditions.

RESULT OF EXPERIMENT

Condition (a) in Fig.3

Figs.4 and 5 show the results for two different size models. Both results indicate that the inside water surface level increases with constant velocity until the inside water surface reaches to the lower edge of the opening, and after that, its velocity is decreased. This phenomenon could be understood from Eq.(2), the discharge from the opening is constant until inside water surface reaches to the lower edge of the opening, and after that, it is decreased.

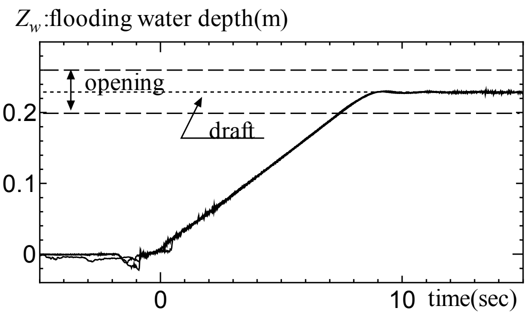


Fig.4 Time history of flooding water depth inside the large model under condition (a).

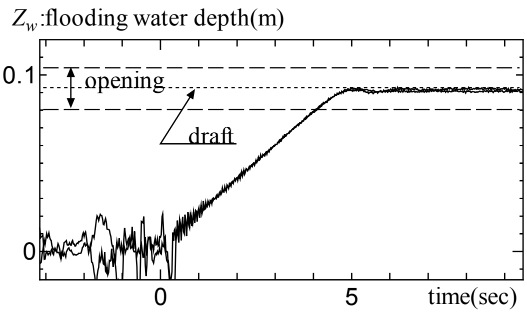


Fig.5 Time history of flooding water depth inside the small model under condition (a).

Condition (b) in Fig.3 with Air Duct (b-1)

Figs.6 and 7 show the results for condition (*b-1*). For this condition, there are no effects of air compression on the discharge from the opening. As condition (*a*), even if the size of the opening is different, both results indicate that the inside water surface level increases with constant velocity until the inside water surface reaches to the lower edge of the opening, after that, its velocity is decreased. From Eq.(2), the discharge from the opening is constant until the inside water surface reaches to the lower edge of the opening, and after that, it is decreased.

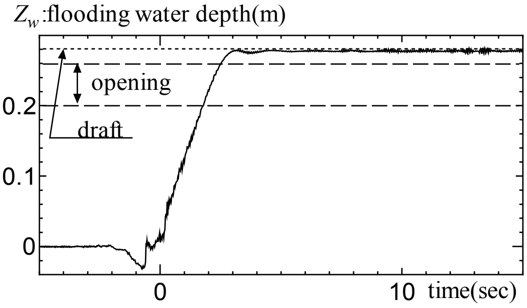


Fig.6 Time history of flooding water depth inside the large model under condition (*b-1*).

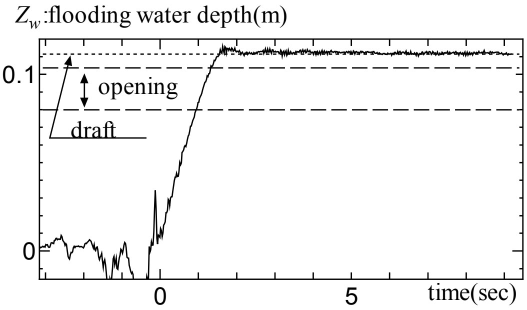


Fig.7 Time history of flooding water depth inside the small model under condition (*b-1*).

Effects of Size of Opening on Discharge

The measured results for different size of the models are compared in Figs.8 and 9. The results for the large model are transferred to small size according to Froude's law of similarity. Fig.8 shows the results for condition (*a*), and Fig.9 shows the results for condition (*b-1*). Both figures indicate some discrepancy on the velocity of increasing of inside water surface if the scale of model is different, and the discharge from the opening for the large model is smaller than one for the small model. These results are agree with the discrepancy of behavior for different size of the models observed in our previous experimental study[1]. The nondimensionalized time to reach maximum heel angle for the large model is longer than one for the small model. The discharge from the opening has the effects of model size, and the discharge from the opening for different size models is not necessarily similar.

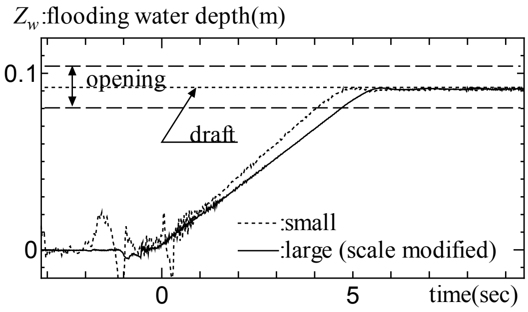


Fig.8 Comparison between small and large models as time history of flooding water depth under condition (*a*).

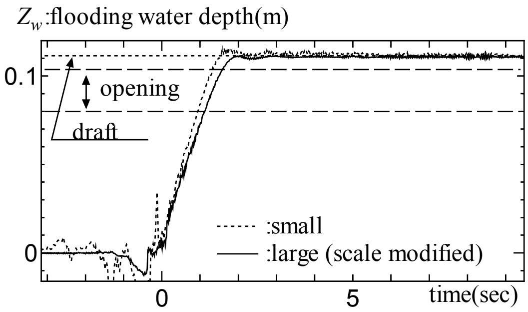


Fig.9 Comparison between small and large models as time history of flooding water depth under condition (*b-1*).

Effects of Area of Air Duct on Discharge from Opening

For condition (*b*) in Fig.3, if there is no air duct except for the opening, the trapped air in the model is compressed by ingress of flooding. The increasing of air pressure in the model may affect on the discharge from the opening. Fig.10 shows the results for conditions (*b-1*), (*b-2*) and (*b-3*) for the small model. The results indicate that the discharge from the opening is decreased according to decreasing of the area of air duct.

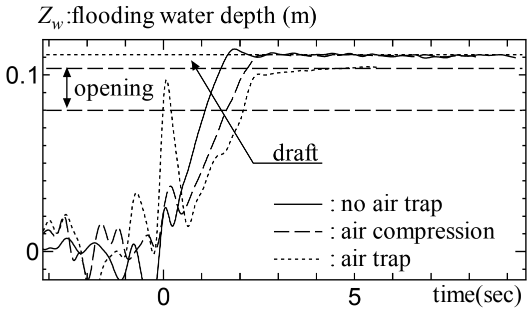


Fig.10 Comparison among three air ventilation conditions in the small model.

ESTIMATION OF DISCHARGE FROM OPENING

Estimating Models

As an example of simple estimating formula, the following model (:one coefficient model) is used in some simulation program of ship motion at intermediate stage of flooding[2].

$$Q(t) = C_0 \cdot A\sqrt{2gH} \tag{3}$$

A : area of damaged opening

where, H is smaller value which is the distance between the water surface and the center of the opening or the distance between the water surface and inside water level. C is the coefficient of discharge. In the simulation programs, C is usually assumed to constant. However, it is known that C is not necessary constant for relative positions between the water surface, the lower edge of the opening and the inside water level[3]. For example, in conditions (a) and (b), if inside water level is over the lower edge of the opening, C decreases from one for lower inside water level than the lower edge of the opening.

On the other hand, the equations (4) to (8) are modeled to consider the change in discharge. In the model (two coefficients model), the equations are formulated for five conditions according to the relative positions between the water surface, the lower edge of the opening and the inside water level, and these five conditions are shown in Fig.11.

(a) Center height of opening is in agreement with water surface

(1) $0 \le Z_w \le H - h$

$$Q_1 = C_1 \cdot \frac{2}{3}\sqrt{2g}bh^{\frac{3}{2}} \tag{4}$$

(2) $H - h \le Z_w \le H$

$$Q_2 = C_{21} \cdot \frac{2}{3}\sqrt{2g}b(H - Z_w)^{\frac{3}{2}} + C_{22} \cdot b(h - (H - Zw))\sqrt{2g(H - Z_w)} \tag{5}$$

(b) Water surface is over opening.

(1) $0 \le Z_w \le H - h$

$$Q_1 = C_1 \cdot \frac{2}{3}\sqrt{2g}b(h^{\frac{3}{2}} - h'^{\frac{3}{2}}) \tag{6}$$

(2) $H - h \le Z_w \le H - h'$

$$Q_2 = C_{21} \cdot \frac{2}{3}\sqrt{2g}b\{(H - Z_w)^{\frac{3}{2}} - h'^{\frac{3}{2}}\} + C_{22} \cdot b(h - (H - Z_w))\sqrt{2g(H - Z_w)} \tag{7}$$

(3) $H - h' \le Z_w \le H$

$$Q_3 = C_3 \cdot b(h - h')\sqrt{2g(H - Z_w)} \tag{8}$$

For the coefficients of discharges in equations (4) to (8), the relations of $C_1 = C_{21}$ and $C_{22} = C_3$ are realized. Moreover, if the vertical position of the opening is deep enough in comparison with the height of the opening, $C_0 = C_1$, and if the opening is also large enough, C_0, C_1 and C_{21} are approaching 0.62, and C_{22} and C_3 are approaching 0.53[3].

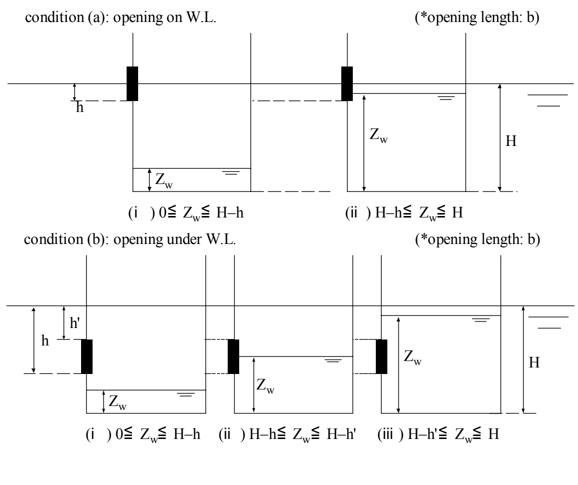


Fig.11 Location of opening and flooding water depth.

Coefficient of Discharge from Opening

In Table 3, the coefficients of discharges, which are obtained from the measured data, are shown. In calculations, C_0 is obtained from the measured data for conditions (*a*)(1) and (*b*)(1), C_1, C_{21}, C_{22} and C_3 are obtained from the measured data for conditions (*a*)(1), (*a*)(2), (*b*)(1) and (*b*)(3).

From Table 3, it is found that the coefficients for two different size models are not same, and it for the small model is lager than the other. On the other hand, for different conditions (*a*) and (*b-1*), although model size is same, C_0 is different. Moreover, in the table, C_{22} and C_3 are smaller than C_1 and C_{21}. These results are in agreement with the description on reference 3) as a common literature of hydraulics. And the coefficients for the large model are not necessarily in agreement with the result on the reference 3) for enough large opening. It demonstrate that the large opening size in this study may not be enough large.

Finally, Figs.12 to 15 show the calculated results by the above-mentioned estimation models. In the calculations, the coefficients written in Table 3 are used. Until the inside water surface reaches to the lower edge of the opening, both calculated results are in agreement with the measured results, because the coefficients of Table 3 are obtained by using the measured data under the conditions. And in these figures, the calculated results after the inside water surface reaching to the lower edge of the opening are closed. It is identified that two coefficients model is good agreement with the measured results. On the other hand, one coefficient model has small discrepancy for the measured results, and it has the tendency of over estimation.

Table 3 Coefficients of discharge.

Experimental condition	C_0	$C_1=C_{21}$	$C_{22}=C_3$
small & *a*	0.64	0.630	0.60
small & *b-1*	0.74	0.698	0.60
large & *a*	0.55	0.541	0.53
large & *b-1*	0.62	0.584	0.53

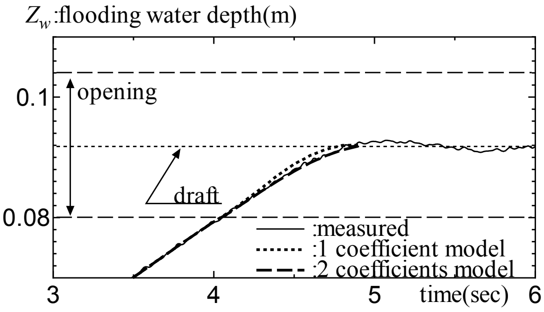


Fig.12 Time histories of calculated and measured flooding water depth inside the small model under condition (*a*).

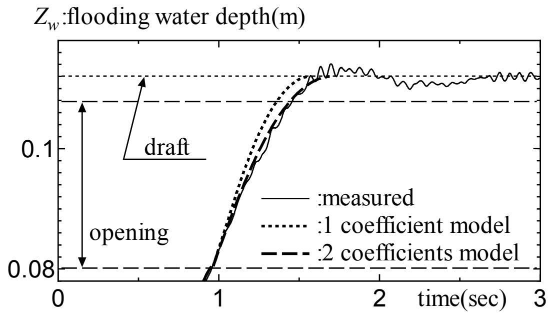


Fig.13 Time histories of calculated and measured flooding water depth inside the small model under condition (*b-1*).

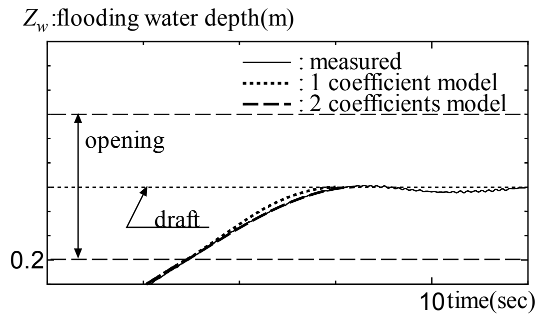


Fig.14 Time histories of calculated and measured flooding water depth inside the large model under condition (*a*).

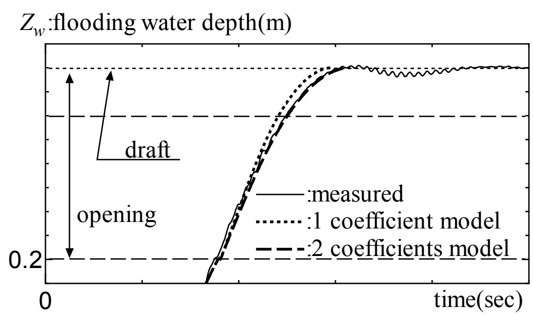


Fig.15 Time histories of calculated and measured flooding water depth inside the large model under condition (*b-1*).

CONCLUDING REMARKS

Following conclusions are obtained.

1. The discharge from an opening is constant, if the inside water surface is lower than the lower edge of the opening. The coefficient of the discharge is changed according to the size of opening. The opening of the large size model used in this study may not be large enough, because the coefficient of discharge is not agreement with the value in a common literature.
2. For the condition that the inside water surface is over the lower edge of opening, the coefficient of discharge is smaller constant value than one before the inside water surface reaching to the lower edge of the opening.
3. The coefficient of discharge is affected by air compression in the water tight compartment.
4. The most simple coefficient model could be over estimate to the discharge from opening, which is after the inside water surface reaching to the lower edge of the opening.

REFERENCE

1) Toru Katayama, Yuji Takeuchi and Yoshiho Ikeda, "A Study on Model Test Method to Assess Safety of Damaged Ship with Flooding from Damaged Opening", Journal of the Japan Society of Naval Architects and Ocean Engineers, No.1, 2005.
2) Yoshiho Ikeda, Shigesuke Ishida, Toru Katayama and Yuji Takeuchi, "Experimental and Numerical Studies on Roll Motion of a Damaged Large Passenger Ship in Intermediate Stages of Flooding", Proc. of 7th International Ship Stability Workshop, Shanghai, China, pp.42-46, November 1-3, 2004.
3) Shoushichiro Nagai, "Hydraulics", Corona Publishing Co. Ltd., Japan, 1957, pp.118-124 (in Japanese).