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Experiment Study on Incipient Floating Condition and Directional Stability of Car during Flood

Takaaki Okamoto[1], Takahiro Onishi[1], Keiichi Toda[1], Taisuke Ishigaki[2], and Ryuta Suzuki[1]
1. Dept. of civil engineering, Kyoto University
2. Faculty of Environmental and Urban Engineering, Kansai University
Kyoto, Japan

ABSTRACT

Flood flow causes heavy damage to people and property. In Nagasaki flood in 1982, flooded cars damage to the structures. Therefore, it is very important to study car behaviors on flooded roads. In this study, flume experiments were conducted using two types of model cars. The experimental data obtained for the small-scale model cars were used to determine the incipient velocity for flooded cars. We also measured the drag force exerted on the cars in flood roads. The results revealed the relationship between depth and velocity and produced a limit of stability for flooded vehicles. These results can be used as preliminary assessment to define the hazards to cars on flooded roads. We applied the flume experimental results to the numerical simulation results of a flood in underground parking in Osaka. The results revealed that the cars near the access road in underground parking were floated by a flood flow.

KEY WORDS: Directional stability; drag force; flooded car; incipient velocity.

INTRODUCTION

Flood flow causes heavy damage to people and property. In Nagasaki flood in 1982, flooded cars damage to the structures. Some previous research conducted the flume study and investigated the floating condition under which vehicles were swept away during a flood.

Shu et al. (2011) investigated incipient velocity for partially submerged vehicles by using three 1:18 scale models. They found that incipient velocity decreases with water depth. However, the location of the center of gravity is not considered in their research. The weight of the engine is the heaviest part of the real vehicle and rests almost on the front wheels. Humphries (2012) improved this (giving a weight distribution of 60:40 (front: rear)) and evaluated the incipient velocity for flooded cars accurately. Oshikawa & Komatsu (2014) measured the drag force on the model cars (compact car and SUV) by a 3-component force gage and calculated the drag coefficients. The drag coefficients raged between 0.7 and 5.2 in their research.

Still more works are needed because the drifting condition of cars and their behaviors on flooded roads are not understood. So, in the present study, incipient velocity for flooded cars was estimated using two different approaches. 1. Estimation of the velocity using small-scale model cars (Flooded car experiment), 2. Computation of the velocity based on the force analysis of a stationary vehicle in flood by using drag force coefficient.

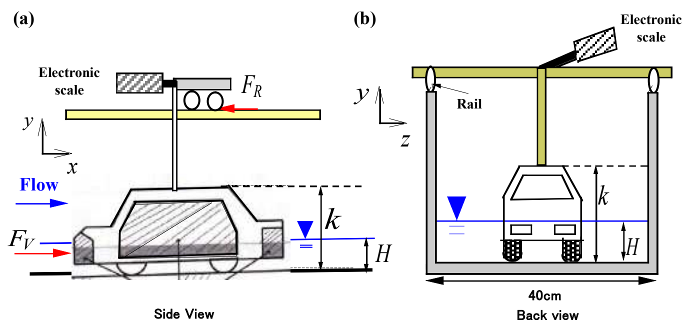

Fig. 1 Experimental setup (Drag force measurement)

EXPERIMENTAL METHOD

Drag Force Measurement

Two kinds of experiments were carried out in a 10.0m long and 40.0cm wide tilting flume, as shown in Fig.1. One is the measurement of drag force on the model car. The other is the measurement of the critical incipient floating condition using model cars. x, y and z are the streamwise, vertical and spanwise coordinates, respectively. The vertical origin, $y=0$, was chosen on the channel bed. H is the water depth and k is the model car height.

Fig.2 shows the drag force measurement set-up. Hydrodynamic force on the model car in x-direction was measured by the electronic scale. For measuring the drag force, a gap (1-2mm) is required between the model car and the channel bed to remove the effect of the bed-friction resistance (see Takemura & Tanaka (2007)). Two model cars were used in this study including SUV-type car (TOYOTA ESTIMA 1:18scale: L=25.5cm length, k=9.0cm height, b=9.6cm width) and sedan-type car (TOYOTA CROWN 1:18scale: L=26cm length, k=8.0cm height, b=9.6cm width).

Table 1 shows the hydraulic condition (drag force measurement). Bulk mean velocity U_m and relative water depth H/k were changed (H/k=0.25, 0.5, 1.0). The angle ϕ between the unidirectional flow and the model cars was also changed (ϕ=0, 90 and 180 degree). $Re \equiv U_m H / \nu$ is the Reynolds number, and $Fr \equiv U_m / \sqrt{gH}$ is the Froude number.

Table 1 Hydraulic condition

Depth H(cm)	Height k(cm)	Depth ratio H/k	Seden Um(cm/s)	Re	Fr	Direction(?	With or without Brake
2.0	8.0	0.25	22.5	4500	0.51	0, 90, 180	Without brake, emrgency brake and Parking brake
			31.25	6250	0.71	0, 90, 180	Without brake, emrgency brake and Parking brake
			45	9000	1.02	0, 90, 180	Without brake, emrgency brake and Parking brake
			60	12000	1.36	0, 90, 180	Without brake, emrgency brake and Parking brake
			75	15000	1.69	0, 90, 180	Without brake, emrgency brake and Parking brake
4.0		0.50	10	4000	0.16	0, 90, 180	Without brake, emrgency brake and Parking brake
			20	8000	0.32	0, 90, 180	Without brake, emrgency brake and Parking brake
			30	12000	0.48	0, 90, 180	Without brake, emrgency brake and Parking brake
			40	16000	0.64	0, 90, 180	Without brake, emrgency brake and Parking brake

Depth H(cm)	Height k(cm)	Depth ratio H/k	SUV型 Um(cm/s)	Re	Fr	Direction(?	With or without Brake
2.0	9.0	0.22	22.5	4500	0.51	0, 90, 180	Without brake, emrgency brake and Parking brake
			31.25	6250	0.71	0, 90, 180	Without brake, emrgency brake and Parking brake
			45	9000	1.02	0, 90, 180	Without brake, emrgency brake and Parking brake
			60	12000	1.36	0, 90, 180	Without brake, emrgency brake and Parking brake
			75	15000	1.69	0, 90, 180	Without brake, emrgency brake and Parking brake
4.0		0.44	10	4000	0.16	0, 90, 180	Without brake, emrgency brake and Parking brake
			20	8000	0.32	0, 90, 180	Without brake, emrgency brake and Parking brake
			30	12000	0.48	0, 90, 180	Without brake, emrgency brake and Parking brake
			40	16000	0.64	0, 90, 180	Without brake, emrgency brake and Parking brake

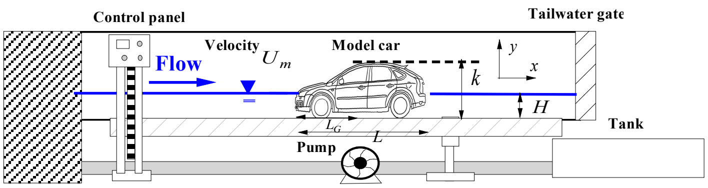

Fig. 2 Experimental setup (Flooded car experiment)

Flooded Car Experiment

The measurement of the critical incipient velocity which the vehicle starts to float was carried out by using 1:18 scale wooden model cars, as shown in Fig.1. The model car was positioned half way between the upstream and downstream gate. The weight of both model cars (SUV and sedan types) was adjusted to match the position of the center of gravity between the models and the prototypes. The apparent density of the model car was also adjusted. To determine the incipient velocity under three vehicle orientation angles (ϕ=0, 90 and 180 degree), the discharge in the flume was adjusted gradually.

Table 2 shows the hydraulic condition (critical incipient velocity measurement). Bulk mean velocity U_m and relative water depth H/k were changed. In this experiment, the car brake conditions were changed, i.e. 1.Without brake (Wheels are unlocked), 2. Emergency brake (The rear wheels are locked) and 3. Parking brake (All four wheels are locked). If wheels are unlocked, they are able to freely rotate and need little force to imitate movement.

RESULTS

Drag Force Coefficient of Flooded Car

Fig.3 shows the relation between bulk mean velocity U_m and drag force F_D for sedan-type and SUV-type cars ($\phi = 0°$). Drag force exerted on the model car is calculated as follow:

$$F_D = 0.5\rho C_D U_m{}^2 A_x \tag{1}$$

C_D is drag force coefficient. A_x is projected area normal to the incoming flow. It is observed that the drag force values increase as relative water depth becomes larger. The increase in F_D with relative depth is because when the flow is deeper, the frontal area A_x also increases.

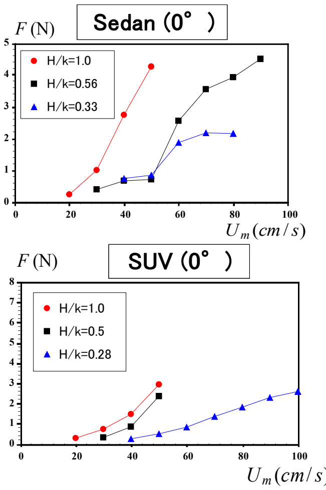

Fig. 3 Drag force exerted on car

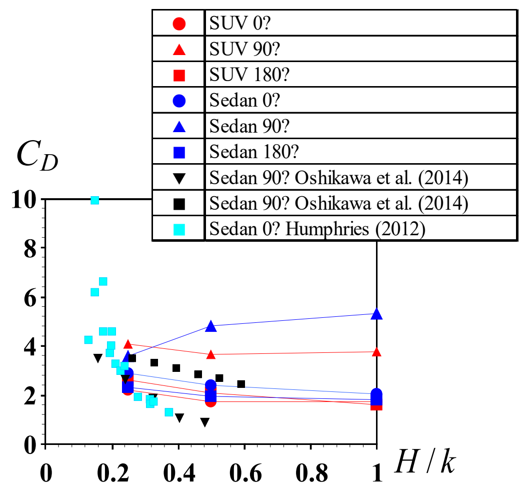

Fig. 4 Drag force coefficient

Fig.4 shows the relation between relative depth H/k and drag coefficient C_D. The drag force coefficient values range from 2.0 to 4.0. These values are in the same order of magnitude with the measured data of Oshikawa & Komatsu (2014). It is also observed that the values of C_D decrease as relative depth decreases. This tendency is in good agreement with Oshikawa & Komatsu (2014) and Humphries (2012). The values of the drag force coefficient for vehicle orientation angle $\phi = 90°$ are larger than those for $\phi = 0°$ and $180°$.

Incipient Velocity for Flooded Car

Fig.5 shows the relation between relative depth H/k and incipient velocity U_c. The results revealed that the incipient velocity increase with decreasing water depth for each model car and any orientation angle.

The incipient velocity for 90° case is smaller than that for 0° and 180° cases. This indicates that the increased projected area A_x creates more drag force for 90° case. Similar relationships between H/k and U_c are observed for 0° and 180° cases.

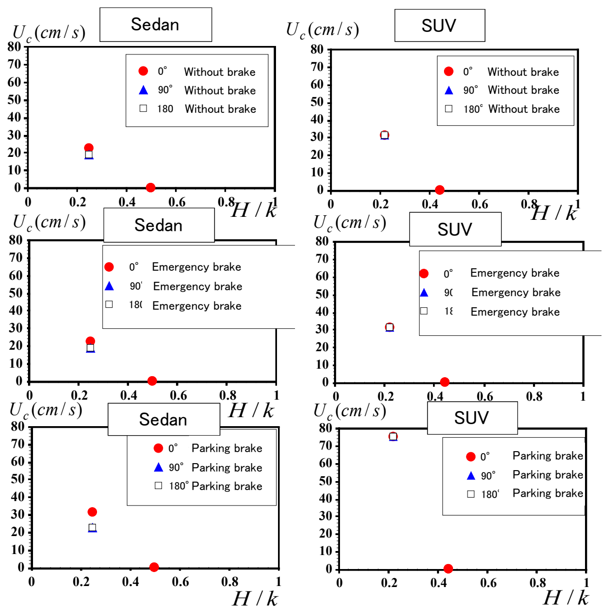

Fig. 5 Incipient velocity for flooded car

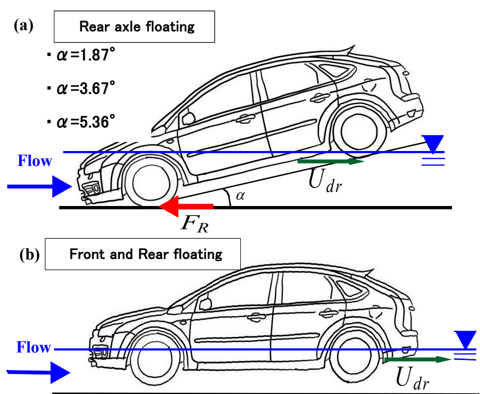

Fig. 6 Floating motion of flooded car

Fig.6 shows the floating motion of the flooded car. When the flow is deeper, buoyancy force is more influential. The rear of the model car is detached and the buoyancy force becomes smaller. This is because the gravity-center position of the present model cars is biased to the front wheel (SUV-type car: L_G=0.45L, sedan type car: L_G=0.44L).

Fig.7 shows the directional stability of floating car in flood. We observed the tendency of the model car to return to the upstream direction (the angle 0°) for 90° and 180° cases. The increased projected area A_x creates more drag force for 90° and 180° cases and tends to force the model car return to the angle 0°. For 0° case, the rotation motion was not observed. This is because the gravity-center position is biased to the front wheel.

Table 2 shows the floating motions of sedan-type car. For shallow flow and low-velocity case (H/k=0.25, U_m=22.5 cm/s), rear axel of the model car is detached.

In contrast, for deep flow case (H/k=0.5), front and rear axels are floating and the bed-friction force becomes smaller.

Table 2 Floating condition of flooded car(Sedan)

Depth	Depth ratio	Sedan			
H (cm)	*H/k*	Um(cm/s)	Direction(?	Floating motion	Angle(?
2.0	0.25	22.5	0	Rear axle floating	1.87
		31.25	0	Rear axle floating	5.36
		45	0	Rear axle floating	5.36
		60	0	Front and Rear axles floating	-
		75	0	Front and Rear axles floating	-
4.0	0.50	10	0	Front and Rear axles floating	-
		20	0	Front and Rear axles floating	-
		30	0	Front and Rear axles floating	-
		40	0	Front and Rear axles floating	-

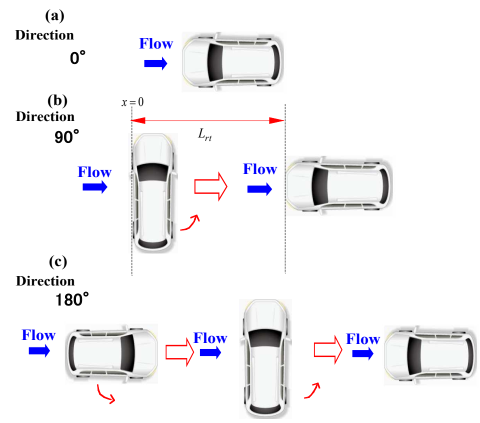

Fig. 7 Directional stability of floating car

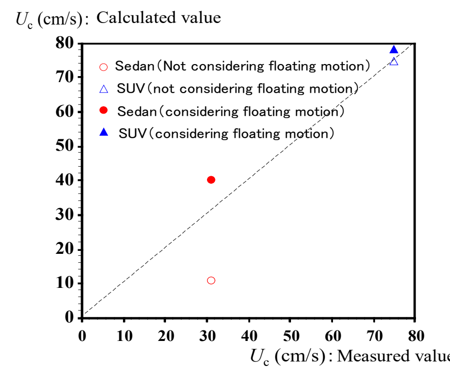

Fig. 8 Comparison between measured incipient velocity and calculated incipient velocity

Incipient Velocity Formula

At the critical incipient floating condition which the vehicle starts to float, drag force exerted on the model car is equal to the frictional resistance S as follows:

$$F_D = 0.5\rho C_D U_c^2 A_x = S = \mu(Mg - F_b) \quad (2)$$

μ is the dimensionless coefficient of friction. M is the weight of the vehicle and F_b is the buoyancy force. F_b is calculated as follows:

$$F_b = \rho g Vo(1-p) \quad (3)$$

Vo is the vehicle volume in water. p is the car porosity. In the present study, p=0. By using Eqs. (2) and (3), we can calculate the incipient velocity U_c.

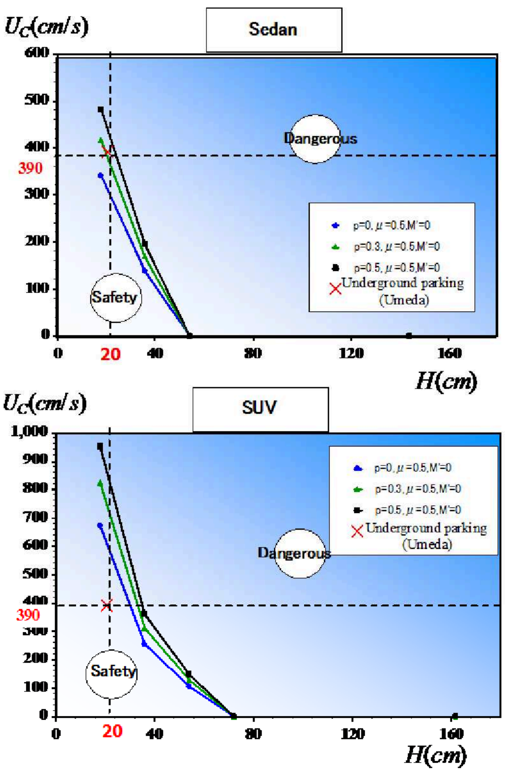

Fig. 9 Incipient velocity for flooded car (Real scale)

Fig.8 compares the calculated incipient velocity U_c with the measured incipient velocity U_c (see Fig.5). The calculated incipient velocity U_c is in good agreement with the measured data. So, it is judged that the present incipient velocity formula (Eqs. (2) and (3)) can calculate the incipient velocity U_c accurately.

Fig.9 shows the incipient velocity U_c for prototype cars calculated from the small-scale model cars using scale ratios. The car porosity p was changed (p=0, 0.3 0.5). For the same water depth, the incipient velocity which the SUV-type car starts to float is larger than that for the sedan-type car. Both model cars are swept away when the water reaches roughly to 50cm with the flow velocity of 2.0m/s (p=0).

When the car porosity p (ingress of water into flooded car) increases, the buoyancy force F_b decreases. Consequently, the incipient velocity U_c increases (see Eqs.(2) and (3)).

We compared the flume experimental results with the numerical simulation results of a flood in underground parking (A-F) in Umeda station (Osaka). Figs.10 and 11 shows the time series of the flow discharge entering the underground parking in Umeda station with a consideration of the heavy rain (the same level as the rain in Okazaki in 2008). It is observed that a flood flow ingresses into the underground parking A-F.

By using Manning formula, we calculated the flood flow depth and the flow velocity. The water depth is 20cm and the flow velocity is 3.9m/s when the flow discharge entering the underground parking F takes a maximum value (assuming that the slope of the access road is 5% and Manning coefficient of the road is 0.02). The numerical simulation result of a flood in Umeda station is also indicated in Fig. 9.

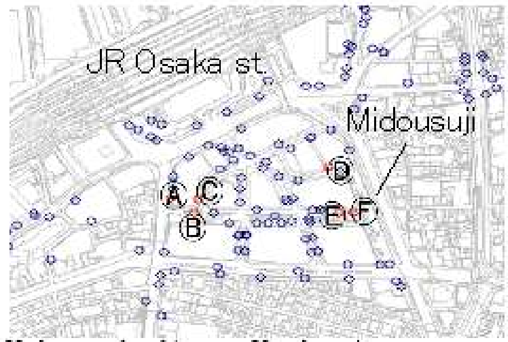

Fig. 10 Underground parking near Umeda station

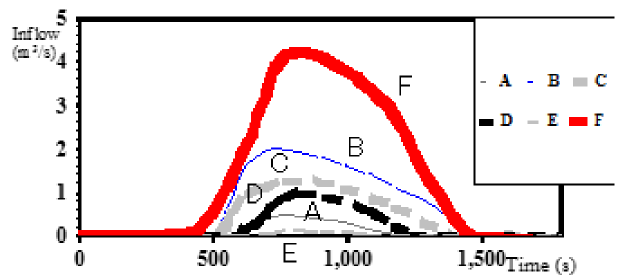

Fig. 11 Time series of the flow discharge entering the underground parking in Umeda station

The results revealed that the Sedan-type cars near the access road in underground parking F were floated by a flood flow.

CONCLUSION

In the present study, incipient velocity for flooded cars was estimated using two different approaches. 1. Estimation of the velocity using small-scale model cars (Flooded car experiment), 2. Computation of the velocity based on the force analysis of a stationary vehicle in flood by using drag force coefficient.

The calculated incipient velocity U_c is in good agreement with the measured data. So, it is concluded that the present incipient velocity formula can calculate the incipient velocity U_c accurately.

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