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The Study on Flight Initiation Wind Speed of Wind-borne Debris by Wind Tunnel Test

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1. Introduction

During the 10 year period 2001-2010, an average of 2.5 typhoons per year affected the Korean peninsula. These typhoons are accompanied by the strong wind and the heavy rain. The strong winds can cause a fatal damage to structures and humans. Specially, the strong wind can cause wind-borne debris, and these the debris can cause the loss of offsite power (LOOP) in nuclear power plants (NPPs) Therefore, it is necessary to predict the starting wind speed of wind-borne debris, to ensure the safety of NPPs. The purpose of this study is to provide a method and data for estimating the flight initiation wind speed of wind-borne debris under various conditions. We measured the drag, lift, and pitching moment coefficient according to the aspect ratio of the debris through the wind tunnel test. In addition, an engineering formula for predicting the flight initiation wind speed based on the force equilibrium condition of the debris was presented and compared with the free flying tests.

2. Flight initiation speeds

We defined the flight initiation wind speed as if the debris moved a bit. Therefore, the flight initiation can be divided into lift, slip, and overturn depending on the direction in which the debris moves. Then, the flight initiation wind speed can be obtained by the equilibrium conditions of force including aerodynamic drag, lift and pitching moment acting on the debris (see Fig. 1). The equations are corresponding to initiation speed for lift, slip and over-turn, respectively.

$$V_{cr}^{lift} \geq \sqrt{\frac{Mg}{0.5\rho BLC_L}} \quad (1)$$

$$V_{cr}^{slip} \geq \sqrt{\frac{\mu Mg}{0.5\rho L(HC_D+\mu BC_L)}} \quad (2)$$

$$V_{cr}^{overturn} \geq \sqrt{\frac{BMg}{0.5\rho L(LH^2C_D+B^2LC_L+2BLHC_M)}} \quad (3)$$

where V_{cr} = flight initiation wind speed, V = free stream wind speed, M = mass of debris (kg), g is gravitational acceleration (m/s^2), ρ = air density (kg/m^3), μ = friction coefficient, B = debris width (m), L = debris length (m), H = debris thickness (m), C_L(=lift/(0.5ρV^{2}BL)) = lift coefficient, C_D(=drag/(0.5ρV^{2}LH)) = drag coefficient, and C_M(=moment/(0.5ρV^{2}BLH)) = pitching moment coefficient.

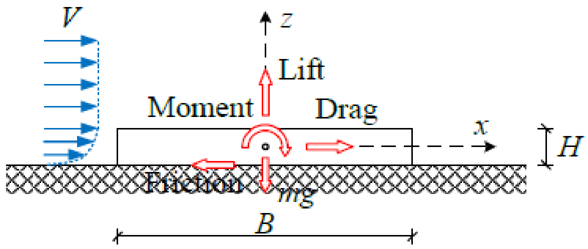

Figure 1. Forces acting on debris

3. Wind tunnel test and results

The aerodynamic forces required to calculate the flight initiation speed were measured in the wind tunnel test. The experiment was carried out in the open circuit type small wind tunnel at KOCED Wind Tunnel Center of Chonbuk National University, Korea. The size of the test section is 1m wide, 1.5m high and 5m long, maximum wind speed is 20m/s and turbulence intensity is 1% or less.

Figure 2 shows the aerodynamic measurement in the wind tunnel. The test specimens for wind-borne debris were made of rectangular plates. The specimen was attached to a load cell capable of measuring two forces and one moment placed below the horizontal separation plate. The aerodynamic forces were obtained by changing the aspect ratio and height of the specimen. The ratio of width to thickness varied from 1 to 50.

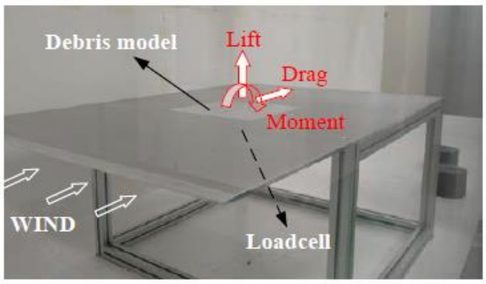

Figure 2. Test setup for the wind tunnel test

According to the wind tunnel test results, the drag coefficient increases sharply as B/H becomes decrease (thickness increase). However, as B/H increases (thickness decrease), the drag coefficient converges to near 0.65. The lift and pitching moment coefficients are opposite to each other at B/H=2. Most of the wind-borne debris is flat plate with aspect ratios greater than 2, the aerodynamic force coefficients gradually vary as the aspect ratio increases.

4. Predicted vs measured wind speeds

In order to compare the flight initiation speed estimated from Eqs. (1) to (3) and actual wind speed, the free flying tests were conducted using the same test specimens as used in the aerodynamic force measurements. By gradually increasing the wind speed, the flight initiation speeds were picked when the specimen moved a little from its original equilibrium state. Then, the type of flight was classified as lift, slip, and overturn according to the direction of movement.

Figure 3 compares the flight initiation wind speed computed from Eqs. (1) to (3) and the measured speed from the free flying wind tunnel tests. As shown in the figure, the predicted wind speeds were higher than those measured in the free flying test. Figure 4 shows the prediction error of the flight initiation wind speed. Depending on the aspect ratio, on average, the predicted speeds were 20 to 30% higher than the measured value.

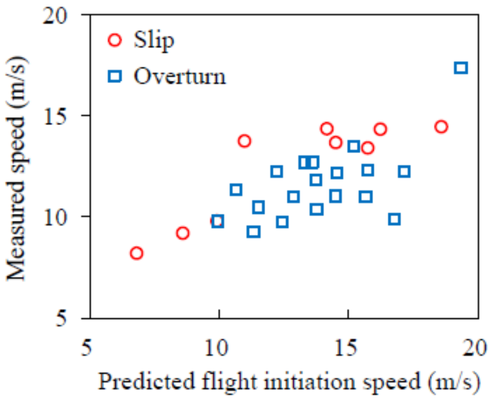

Figure 3. Measured and predicted flight initiation wind speed.

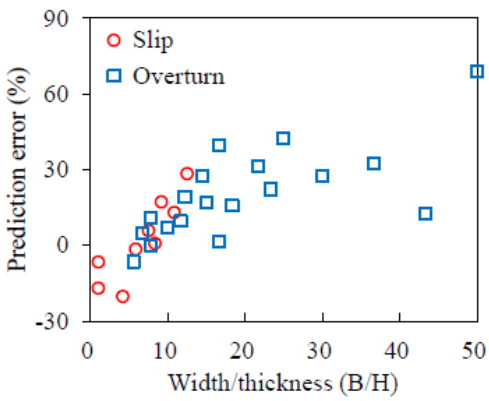

Figure 4. Prediction error of flight initiation wind speed according to the aspect ratio of debris

The reason why the difference between the predicted and the measured wind speeds can be explained from the boundary layer wind speed near surface in Fig 1. The free stream wind speed was used to compute the aerodynamic forces in prediction. However, the actual wind speed acting on the actual debris is lower than the free stream wind speed because of the boundary layer flow caused by surface friction. Moreover, the gap between the specimen and surface due to imperfection of specimen or surface roughness may affect the aerodynamic forces. Therefore, the aerodynamic force acting on the actual debris is lower than the computed one, and then the measured flight initiation speeds were lower than the predicted ones.

The flight initiated by direct lift did not occur in both the prediction and the measurement. As shown in Figure 4, most of the debris starts flying by slip or overturning. If the ratio of width to thickness (B/H) is less than 10, slip is dominant. However, overturning mainly occurs if the ratio exceeds 10. In other words, the flight was initiated by slip at compact debris, and by overturning at plate debris.

5. Conclusions

The aerodynamic forces acting on debris with various aspect ratios were measured and presented from the wind tunnel tests. Then, the regression equations are presented to estimate aerodynamic force coefficients according to aspect ratio. The flight initiation wind speed equations were derived from the force equilibrium, and were verified from the free flying test of debris. The actual flight initiation speeds were 20~30% lower than that of the predicted ones. It is considered that the wind velocity acting on the debris is lower compared with the free stream wind velocity because of the surface boundary layer flow and the gap between the debris and surface. The debris starts to fly by slip or overturning not lift. If the ratio of width to thickness is less than 10, slip occurs mainly. Others are overturning dominant.

According to the test results, it was concluded that the flight initiation speed is directly related to the kind of the plate shape. Therefore the shape of wind-borne debris should be considered to ensure the safety of NPPs from high wind.

6. ACKNOWLEDGEMENTS

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