WIND FORCES ACTING ON INFLATABLE AMUSEMENT PRODUCTS AND CRITICAL WIND SPEEDS CAUSING ACCIDENTS

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ABSTRACT

Inflatable amusement products are a kind of play equipment used at amusement parks and event sites, and children play inside them. Recently, there have been many reports of accidents with these products caused by strong wind. They are very light (mass about 200 - 300kg when empty) and can be easily blown over by wind. In this study, wind tunnel tests were conducted to investigate the characteristics of wind forces acting on scale models of inflatable amusement products of various shapes. Mean wind force coefficients obtained from wind tunnel tests were used to estimate wind speeds causing accidents and to determine safe operating wind speeds.

KEYWORDS: INFLATABLE AMUSEMENT PRODUCTS, WIND FORCES, WIND SPEED ESTIMATION

Introduction

Inflatable amusement products are a kind of play equipment used at amusement parks and event sites, and children play inside them. Recently, there have been many reports of accidents with these products caused by strong wind. They are very light (mass about 200 - 300kg when empty) and can be easily blown over by wind. In addition, at event sites they are mainly used as temporary play equipment, and the anchorage systems are often insufficient to resist the wind load.

ASTM (American Society for Testing and Materials) has published “Standard Practice for Design, Manufacture, Operation, and Maintenance of Inflatable Amusement Devices”¹) and the maximum safe wind speed for operation was decided as follows: “Inflatable amusement devices should not be used when the wind is in excess of the maximum wind speed specified by the manufacturer. In the event that the manufacturer of the inflatable amusement device has not specified a maximum allowable wind speed for operation, the maximum wind speed for operations of inflatable amusement devices shall be 25 mph (11.1m/s).” This standard specifies not only the maximum wind speed for operation of inflatable amusement products, but also the number and strength of anchorage points to resist wind loading acting on them. However, there is no operation regulation for these kinds of products in Japan, so event organizers have used their own judgment.

In this study, wind tunnel tests were conducted to investigate the characteristics of wind forces acting on scale models of inflatable amusement products of various shapes. Mean wind force coefficients obtained from wind tunnel tests were used to estimate wind speeds causing accidents and to determine safe operating speeds.
Wind Tunnel Experiment

Wind force experiments were conducted to measure the mean wind force and to investigate the characteristics of wind forces acting on inflatable amusement products of various shapes. Picture 1 shows an example of an inflatable amusement product. There are many types, such as slide type, mat type, dome type with/without opening, etc. In this study, the three models shown in Figure 1 were used for the wind tunnel test. The model scale was 1/40 and a wind speed profile with a power law index of 0.2 was adopted for the approaching flow.
Figure 1 Wind force models of inflatable amusement

Wind Force Coefficient

The wind force coefficients were defined as:

\[ C_{F_i} = \frac{F_i}{q_H A}, \quad C_{M_i} = \frac{M_i}{q_H AH}, \quad C_{M_z} = \frac{M_z}{q_H AB} \]  

where \( F_i \): wind force for \( i \) component, \( M_i \): overturning moment about \( i \) axis, \( M_z \): torsional moment, \( q_H \): velocity pressure at top of model, \( A \): projected area at wind azimuth equal to 0 degrees

The definition of wind forces and moments are shown in Figure 1. A dynamic wind force balance that can be measure 6 components was used in these experiments.

Estimation of Critical Wind Speed Causing Accidents

The critical wind speeds causing accidents were estimated using the following equations:

\[ V_{\text{uplift}} = \sqrt{\frac{1.6W}{AC_{F_z}}} \]  
\[ V_{\text{slip}} = \sqrt{\frac{1.6\mu W_1}{A(C_{F_z}^2 + C_{F_y}^2)}} \]  
\[ V_{\text{rollover}} = \sqrt{\frac{1.6M_1}{A(C_{M_i} H + C_{F_z} L)}} \]

where \( V_{\text{uplift}} \): critical wind speed for uplift, \( V_{\text{slip}} \): critical wind speed for slip, \( V_{\text{rollover}} \): critical wind speed for rollover, \( W \): weight of inflatable amusement product, \( \mu \): static friction coefficient, \( W_1 \): weight of inflatable amusement product considering vertical wind force, \( L \): distance between edge of leeward side and centroid, and \( M_1 \): moment calculated from distance \( L \) and weight \( W \). The first equation estimates the critical wind speed causing the product to be blown over under uplift force. In this equation, the balance between uplift force \( (F_z) \) and product weight was considered. The critical wind speed for slip of the inflatable amusement product was estimated from the second equation. In this equation, the balance between wind force translational component and weight of inflatable amusement product that cancels the vertical wind force was considered. The critical wind speed for rollover of the inflatable amusement product was estimated from the third equation. For the estimation of critical wind speed for slip of inflatable products, the critical wind speed in case of reducing the weight of additional sandbags to half of normal situation was also estimated as \( V_{\text{slip}, \text{half}} \). This is because, depending on the wind direction, the half of the additional weight does not work to resist wind load.

Characteristics of Wind Force acting on Inflatable Amusement Products

Figures 2, 3 and 4 show the characteristics of wind forces acting on various shaped models of inflatable amusement products with wind azimuth. For the slider type model shown in Figure 2(a), the lift force coefficients \( C_{F_z} \) show negative values (i.e. downward forces were measured) when the wind azimuth was in the range of 0 to 30 degrees. This was because of
the slope of the slider. For the other model, the lift force coefficient showed positive values for all wind directions.

![Graph](image)

(a) Wind force coefficient
(b) Moment coefficient
Figure 2 Characteristics of wind forces acting on slide-type model with wind azimuth

![Graph](image)

(a) Wind force coefficient
(b) Moment coefficient
Figure 3 Characteristics of wind forces acting on mat-type model with wind azimuth

![Graph](image)

(a) Wind force coefficient
(b) Moment coefficient
Figure 4 Characteristics of wind forces acting on house-type model with wind azimuth

**Characteristics of Wind Force acting on Inflatable Amusement Products**

The critical wind speeds were estimated from Equations 2 to 4 and are shown in Figure 5. Table 1 shows the information of weights of inflatable products to be used in estimation. Critical wind speeds were calculated for each wind azimuth to investigate the effect of wind azimuth. In all cases, the critical wind speeds for uplift were higher than those for the others cases. In the range from 0 to 30 degrees for the results of slider type (Figure 5(a)), the critical wind speed for uplift was higher than 40m/s. This is because the wind force coefficients for the vertical direction were negative for these wind directions.
From these results, it can be said that the critical wind speed for inflatable amusement products is around 10m/s.

![Graph showing critical wind speed and wind azimuth for different types of inflatable products.](image)

(a) Slider type  
(b) Mat type

(c) House type (with opening)

Figure 5 Critical wind speed causing accident based on wind tunnel test

**Estimation of Wind Speed Caused Accident to “Shark Slider” in Amusement Park**

In February 2008, there was an accident to an inflatable amusement product named a “Shark Slider”, shown in Picture 2. This product was 5m high, 6m wide and 12m long, and had a very light mass of about 350kg. Additional weights (12 sandbags of 250N each) were tied around it. Children climb to the top of this slider through the mouth and go down its slider toward the tail. When the accident occurred, a girl was still inside the slider and it was blown almost 25m in the SW direction, as shown in Figure 6.

![Picture 2](image)

(a) Front view (b) Side view

Picture 2 photographs of "Shark Slider" which underwent an accident in an amusement park

| Table 1 Information of weight of inflatable products |
|---|---|---|
| type     | Weight | Additional weight |
| Slider type | 3000N | 4000N (200N*20) |
| Mat type  | 1000N | 1600N (200N*8)   |
| House type| 1500N | 1600N (200N*8)   |

_ : the numbers of sandbag
Characteristics of wind force acting on “Shark Slider” and wind speed estimation based on wind tunnel experiment

Wind tunnel setups

The wind force experiments were conducted to measure the mean wind force and to investigate the characteristics of wind forces acting on the “Shark Slider”. Figure 7 shows a schematic view and the dimensions of the wind force model of this slider. The model scale was 1/25 and a wind speed profile with a power law index of 0.2 was adopted for the approaching flow. The wind direction was varied at 10° intervals in the range from 0° to 180° and 45° and 135°. A dynamic wind force balance that could measure 6 components was used to measure the wind force (3 components of $F_x$, $F_y$, $F_z$) and the moments (3 components of $M_x$, $M_y$, $M_z$), as shown in Figure 7.
Characteristics of wind forces acting on “Shark Slider”

Figure 8 shows the characteristics of the mean wind forces acting on the “Shark Slider”. The vertical wind force $C_{Fz}$ in Figure 8(a) was positive for all wind direction. This means that the “Shark Slider” was pulled upward regardless of wind direction. From the investigative report of the accident to the “Shark Slider”, the wind direction when the accident occurred was estimated to be NE. In these experiments, NE corresponded to 135 degrees. The wind forces and moment coefficients show comparatively high values for this wind direction.

Estimation of wind speed causing accident to “Shark Slider”

The critical wind speeds for the “Shark Slider” were estimated from Equations 2 to 4 and are shown in Figure 9. They were calculated for each wind azimuth to investigate the effect of wind azimuth. In all cases, the critical wind speeds for uplift were higher than those for the others cases. This was the same results as for the other inflatable model as shown in previous chapters. For slip of the “Shark Slider”, the estimated wind speed was 5-6 m/s in the range from 30° to 150°. However, in the real situation, ropes were used to fix it to the ground, and the static friction coefficient might have been larger than that of this estimation. For the wind direction at which the accident occurred, i.e. 135 degrees, the critical wind speeds were estimated as 14m/s and 16m/s for rollover and uplift, respectively.
this operation manual, the upper limit wind speed in operation was decided as a 10-minute mean value of 10 m/s. However, the results of the wind tunnel experiments conducted in this study show that this wind speed is too low and that it is better to express it as an instantaneous wind speed and not a mean wind speed.

**Conclusion**

Wind tunnel experiments were conducted on inflatable amusement products, which had often suffered accidents due to strong wind, to investigate the characteristics of the wind forces. The mean wind force coefficients obtained from these experiments were used to estimate the critical wind speeds causing accidents. As a result, the critical wind speed for most cases of inflatable amusement products were found to be less than 15 m/s.

In addition, the critical wind speed causing accident to the “Shark Slider” was estimated from wind tunnel test results. It was thus found that an accident can happen if the instantaneous wind speed is higher than 15 m/s, even if the critical wind speed for slip (5-6 m/s) is ignored. The upper limit wind speed for inflatable products in the operation manual made by the investigative committee was a mean of 10 m/s, which is much lower than that of this study.

**References**


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