AERODYNAMIC PARAMETERS OF URBAN BUILDING ARRAYS WITH RANDOM GEOMETRY

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Abstract

A series of wind tunnel experiments was performed using several types of urban building arrays to measure bulk drag coefficient (C_d) and mean wind profile. The aerodynamic parameter e.g. roughness length (z_o), and displacement height (d) were estimated from measured data. The geometry of the roughness arrays has two particular characteristics in terms of so-called 'randomness'. First of them is randomness of each element height (namely vertical randomness); another is randomness of rotation angle of each element (namely horizontal randomness). The result for the random arrays was compared with those for the regular arrays with no randomness of both 'vertical' and 'horizontal'. The following results were obtained:

(1) When comparing the result for arrays with the standard deviation of element height among 0, 0.58 and 1.12, it is predicted that the transition of wake flow to skimming flow over arrays with large height variation takes place under the higher packing densities compared with uniform arrays.
(2) Displacement height of the arrays with random height is larger than that of the uniform arrays and exceed the average height of roughness.
(3) C_d of cubical arrays with random angles is larger than that of the staggered arrays, and smaller than that of 45 degree rotated array.

Key words: urban building arrays, wind tunnel experiment, drag coefficient

1. INTRODUCTION

It is very important to understand the flow within and over the urban canopy from the view points of thermal comfort of the pedestrians and also for the dispersion of atmospheric pollutants. Over a decade, many wind tunnel experiments or computational simulations have been carried out to grasp the various aerodynamic effect of urban geometry using regular array, for example, Thorsten (2003), and Cheng and Castro (2002) (hereafter CC). The most previous works used the arrays of uniform blocks with the layout of staggered or square, and some works investigated the arrays with height variability. CC conducted an experimental study over the arrays of blocks with five different heights. The effect of height variation also has been investigated using large-eddy simulation (hereafter LES) by Kanda (2006) and Jiang et al. (2008). More recently, Xie etc. al (2008) has performed a LES on flow over random urban obstacles to extend the study of CC. Meanwhile, Maruyama (1993) had investigated the drag coefficient of cubical arrays of blocks, those are rotated. However, the layout, height variability and shape of buildings in real urban areas are more random and complex compared with these works, and there are a very few systematic studies involved the air flow around random arrays. Most of researchers only focus on a random height with limited conditions of area density.

The aim of this study is to investigate the aerodynamic effects of two types of randomness of geometry. First of them is random height and another is randomness of rotation angle. We estimate the bulk drag coefficient (C_d), roughness length (z_o), and displacement height (d) for the numerous arrays on a basis of wind tunnel experiment. The geometric condition of vertical randomness is designed by using statistical analysis based on GIS data of Tokyo and we also used a several conditions of area density. Hence the arrays we investigated have relatively representative geometry of high-density area of real urban. The results are compared with those of regular arrays.

3. EXPERIMENTAL SET-UP

3.1. Roughness surfaces

There were seven types of arrays involved in this study with different horizontal arrangement patterns, height variations, and element angles. The elements of roughness arrays were sharp-edged cubes and rectangular blocks, made from wood and glued onto thin plastic plates. Besides, all blocks have uniform baseboards with 25 mm x 25 mm, hereafter we mention the length 25 mm *L* as the standard length scale.

The schematic diagrams of the array with random height (hereafter R1.5) and that with random rotation angle (hereafter Dr1) are shown in Figure 1, and the overview of the roughness arrays is summarized in Table 1. The numbers 1 and 1.5 refer to the height of blocks, L and 1.5L. Both R1.5 and Dr1 are staggered arrays. R1.5 consists of nine types of blocks with average different height, the height and quantity of those are defined based on the probability density function (PDF) with a mean and standard deviation of 1.5L and 1.68L respectively. The

PDF is expressed by a Weibull distribution, which is derived from the GIS data of Tokyo City (Hagishima and Tanimoto, 2004). Besides, the rotation angle of each element of Dr1 varies with the range of -45° and +44°. The average of angle is almost 0°, whereas the standard deviation of angle is 23.74°. The arrangement of each element of R1.5 is manually defined by using so-called "artificial" random process, whereas that of Dr1 is based on random number by computational method. These two arrays are investigated under the different packing densities, defined by both plan area ratio λ_p and frontal area ratio λ_f. We used four conditions of λ_p (7.7%, 17.4%, 30.9% and 39.1%) for R1.5 array, whereas only three conditions of λ_p (7.7%, 17.4% and 30.9%) were used for Dr1 array. The configuration of each blocks of array R1.5 is defined somewhat 'artificially'. Thus we measured total drag of R1.5 under the two different wind directions (R1.5a and R1.5b) for all conditions of packing density, and drag force of both R1.5a and R1.5b show good agreement. It is the proof of the 'fair' randomness of array R1.5.

In addition, we compared the results of array R1.5 and Dr1 with those of three types of array of our previous experiment (Hagishima and Tanimoto 2007). First type is the uniform cubical arrays with staggered patterns (hereafter St1) and square patterns (hereafter Sq1). Besides, the staggered arrays with height average 1.5L (hereafter St1.5). Second type is the arrays consist of two types of blocks with different height. The last type is the staggered arrays with the rotation angle of 45 degrees (hereafter D1).

3.2. Instrumentation

The experiments were performed in a low speed single-return wind tunnel at the laboratory of the IGSES, Kyushu University. This equipment has a working section 1 m high x 1.5 m wide x 8 m long. The measurements of both drag force and wind speed are at a leeward point approximately 3 m apart from spires. The total surface drag force acting on the floating elements was measured by using a strain gauge. The length of the surrounding area for windward and leeward directions are about 3 m and 0.18 m respectively which are covered with roughness elements. Hence, the length of fetch is approximately 120 times of L. The free stream velocity was measured by a Pitot-static tube connected to a differential pressure gauge (Shibata, ISP-30-20DS) at a height of 20*L*. A split-film anemometer (TSI, 1288) was used to measure the vertical velocity profiles over the arrays. The measurements were carried out at 16 points within a horizontal plane at 28 different levels with data acquiring frequency of 1000 Hz. All the experiment was done under the condition of free stream velocity of 8 m/s.

4. RESULTS AND DISCUSSION

4.1 Drag coefficient C_d for arrays with random and regular heights

The C_d can be estimated using the measure drag force and wind speed at a height of 20L based on the relation:

$$\tau_o = \frac{F}{A} = C_d \cdot \frac{1}{2} \rho U_{20L}^2 \qquad (1)$$

where τ_o is the shear stress due to both form drag and friction drag [N/m^2], F is drag force of the flow [N], A is the plan area of the floating element [m^2], U_{20L} is the mean speed at a height of 20L [m/s], and ρ is the air density [kg/m^3]. Figure 2 indicates the comparisons of C_d for arrays with uniform and non-uniform height. All of them have the same averaged height (1.5L), but standard deviations of height of both St1.5-st and St1.5-sq are smaller than that of R1.5. It can be seen clearly that C_d of uniform array St1.5 shows a peak at λ_p = 7.7%, and those of ST1.5-st and ST1.5-sq show a peak at approximately λ_p = 32%. In contrast, C_d of R1.5 increases gradually with the increase of λ_p and there is no specific peak. We predict that the peak of R1.5 can be shifted to a higher λ_p due to the following reasons. It is well known that the peak of surface shear stress of uniform array for packing density is related to the transition of flow regime around the blocks. Meanwhile, Xie et al (2008) pointed out that the tall buildings generate significant effect on the total drag. Hence it can be predicted that the peak of C_d for non-uniform array will be dominantly defined by the layout of tall blocks, on which large drag force act. In our study, the standard deviation of R1.5 is largest among three and St1.5 is the smallest. In other words, the heights of tallest blocks for ST1.5-sq and ST1.5-st is 3.0L, in contrast 3.76H is that for R1.5. Thus, the monotone increase of C_d of R1.5 should be observed in our experimental condition. The estimated C_d values for arrays with rotation angle (Dr1) is smaller than those of rotation angle is 45° (D1) but larger than that of staggered array St1 as shown in Figure 3. Moreover, the C_ds of St1 and D1 have a peak at λ_f = 17.4% and λ_f = 24.5% respectively, but Dr1 has a peak at λ_p = 21.6%. Maruyama (1993) clarified that the C_d of staggered cubical arrays was largest when the rotation angle is 45° and smallest for 0° angle, meanwhile the arrays with random angles showed intermediate values between previous those. It is consistent with our result. In addition, the effect of large frontal area due to rotation is more effective under the condition of λ_p = 17.4%, and that is less effective for high λ_p condition because of the skimming flow regime.

4.2 Roughness length z_o and displacement height *d*

The aerodynamic parameters for R1.5 are shown in Figures 4. Roughly speaking, the estimated z_o for all arrays indicates the similar behavior of C_d. The values of z_o for R1.5 are much smaller than those of ST1.5-st and

ST1.5-sq at λ_f = 11.6% and λ_f = 26.0%, and the discrepancy is less remarkable for C_d. z_o is assumed to be the length scale indicates the magnitude of forces acting on the surface, hence both of z_o and C_d share the similar physical meaning. However z_o is defined by the physical quantities in inertial sublayer whereas C_d is determined by wind speed above boundary layer. Such a difference may cause the slightly different tendency. The estimated z_o for *Dr1* also shows the similar behavior with that of C_d and has a peak at approximately λ_f = 22%, whereas D1 and St1 have a peak about λ_f = 25% and 18% respectively as shown in Figure 5. The values of displacement height, *d* for R1.5 are larger than those of St1.5, ST1.5-st and ST1.5-sq. Besides, *d* has a positive correlation with the standard deviation of height (σ/H_{ave}) as shown in Figure 6. d increases drastically under the condition of σ/H_{ave} from 0 to 1.12. This condition is similar to the result of Jiang (2008) in which the d increases linearly with the standard deviation. In contrast, the d for rotation angle, Dr1 increases gradually with increasing of λ_f, whereas the St1 have a peak at λ_f = 30.9% and D1 shows the fluctuation in the value of *d*. We cannot explain the reason of this tendency due to insufficient materials, but we will make further investigation on this issue in the future.

5. CONCLUSION

We performed a series of wind tunnel experiment using various types of arrays, and reached the following concluding remarks. Firstly, the λ_p condition where transition of dominant flow regime from wake interference to skimming takes place will increase with the increase of height variations of the arrays. It is caused by the fact that the tallest blocks have main contribution of the total drag of arrays. In addition, the standard deviation of array increases the total drag. Secondly, the array with maximum rotation angles will increase the C_D because of increasing the frontal area on which drag force acting. Lastly, we point out that the effect of random geometry on aerodynamic parameters is significant to understand the air flow around the buildings in the real urban city.

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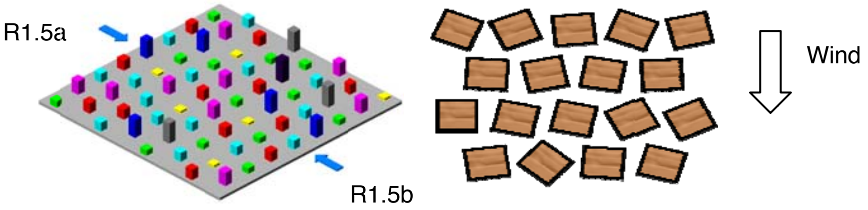
Table 1 : Overview of the roughness arrays. H_{ave} is the average height of blocks, L is the standard length scale of blocks (L = 25 mm), and σ is the standard deviation of the height of cubes.

Arrays	Arrangement	H_{ave}	σ/H_{ave}	Remarks
R1.5	Staggered	1.5L	1.12	Combination of cubes (0.36L, 0.84L, 1.32L, 1.5L, 2.0L, 2.64L, 3.0L, 3.32L, 3.76L)
Dr1	Staggered	L	0	Range of angle between -45 to 44° with mean and standard deviation are 0° and 23.74°
St1	Staggered	L	0	Cubical arrays (L x L x L)
Sq1	Square			
D1	Diamond			
St1.5	Staggered	1.5L	0	Uniform arrays with blocks (L x L x 1.5L)
ST1.5-sq	Staggered	1.5L	0.58	3:1 combination of cubes (L x L x L) and tall rectangular blocks (L x L x 3L) ('ST' and 'SQ' refer the arrangement pattern of all blocks but 'st' and 'sq' refer that of tall blocks)
ST1.5-st	Staggered			



(a) (b)

Figure 1 (a) Perspective view of one unit of the roughness elements for R1.5; (b) schematic plan view of the array Dr1

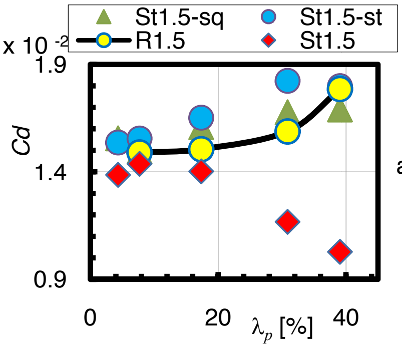


Figure 2 C_d of arrays with random height, uniform height and non-uniform height for various λ_p values.

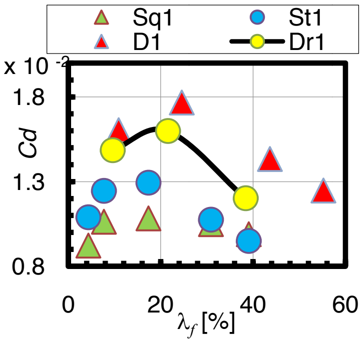
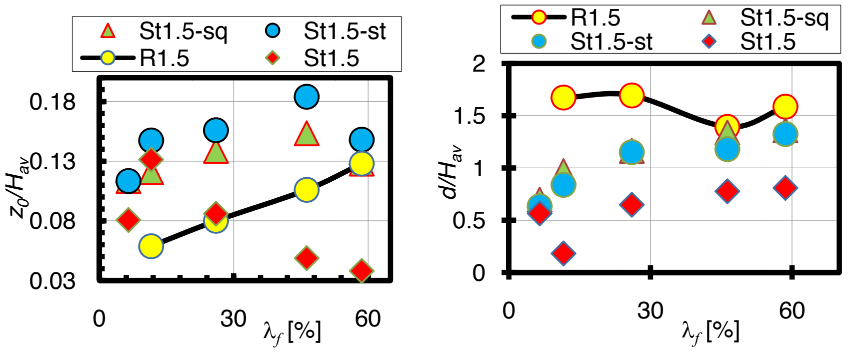
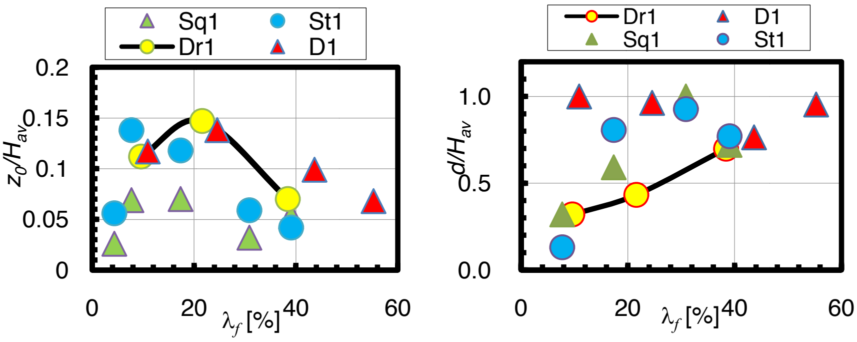


Figure 3 C_d of staggered cubical arrays with rotated and non-rotated conditions for various λ_p values.



(a) Roughness length, z_o (b) Displacement height, d

Figure 4 Estimated aerodynamic parameters for arrays with random height, uniform height and non-uniform height



(a) Roughness length, z_o (b) Displacement height, d

Figure 5 Estimated aerodynamic parameters of cubical arrays with rotation angle

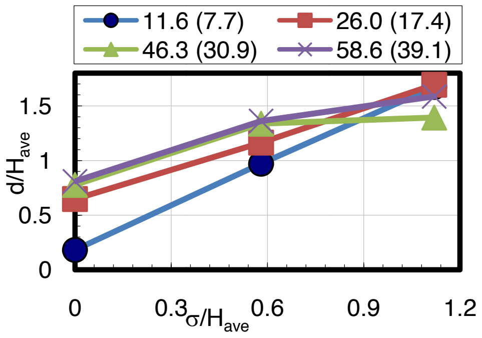


Figure 6 Correlation between displacement height and standard deviation of height of blocks. The plots are the results of array R1.5, St1.5, and St1.5-sq