J11.4 LES ANALYSIS OF TURBULENT BOUNDARY-LAYER FLOW OVER URBAN-LIKE BUILDING ARRAYS WITH VARIOUS SPATIAL ARRANGEMENT AND HEIGHT DISTRIBUTION

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1. INTRODUCTION

So far, many researchers have studied the turbulent flow over urban-like roughness models. For example, Macdonald (1998) proposed an improved model for the estimation of surface roughness of obstacle arrays. Cheng et al.(2002) conducted a wind tunnel experiment and investigated the characteristics of the turbulent flows over a number of urban-type surfaces. Kanda (2006) performed large-eddy simulation (LES) on the turbulent flows of various surface geometries of building arrays and investigated the sensitivity of the drag coefficient to the surface geometry. However, the geometries of obstacles employed in these studies are too simplified to directly apply their results to real urban settings. On the other hand, the shape of city surfaces is complex and the building heights are highly variable. Ratti (2002) reported that the ratio of the standard deviation of building heights to the mean building height show 1.0 for some urban areas. Therefore, turbulent flow structures in realistic urban canopy should be further investigated.

In this study, we first examine the building morphological characteristics such as roughness density, the mean and standard deviation of building heights in actual urban area. From this analysis, we propose a model that represents realistic urban surface geometries. Next, we perform LES on the spatially-developing boundary layer flows over the above-mentioned building arrays and investigate the relationship between the turbulent flows and the building morphological characteristics.

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2.GEOMETRIC CHARACTERISTICS OF ACTUAL URBAN AREA

We investigate the building height characteristics in the 36-km^2 (6km×6km) area of Tokyo using a Geographic Information Systems (GIS) dataset (Kokusai Kogyo Co., Ltd). Roughness parameters in Tokyo are evaluated for the 1-km2 domain by calculating moving average. Figs.1, 2, 3, 4 and 5 show the frequency distributions of the average building height, the standard deviation of building height, the building height variability, the building plan area fraction and the building frontal area index, respectively. h_{av}, h_{sd}, h_{sd}/h_{av}, λ_p and λ_f represent the average building height, the standard deviation of building height, the building height variability and the building plan area fraction and the building frontal area index, respectively. The building height variability is defined as the ratio of the standard deviation of building height to the average building height. The building plan area fraction and the building frontal area index are defined as the ratio of the plan area of buildings to the total surface area and the ratio of the total frontal area of buildings to the total surface area, respectively.

The frequency of h_{av} is largest in the range of 10-20m and rapidly decreases with increasing of the average building height. The frequency of h_{sd} is also largest in the range of 10-20m and decreases rapidly with increasing of the standard deviation of building height. Focusing on the frequency of h_{av}/h_{sd}, it is easily found that building heights of central Tokyo is so much variable that the building height variability values exceed 0.5 in 97.8% of regions of central Tokyo. Furthermore, its frequency distribution shows a peak in the range of λ_p=0.8-0.9. The frequency distribution of λ_p ranges from λ_p=0.2 to 0.7 in central Tokyo and shows a peak in the range of λ_p=0.5-0.6. The frequency distribution of λ_f ranges from λ_p=0.1 to 0.7 in central Tokyo and shows a peak in the range of λ_p=0.3-0.4.

3. NUMERICAL MODEL

3.1 COMPUTATIONAL MODEL FOR TURBULENT FLOWS THROUGH AND OVER URBAN MODELS

Fig.6 shows a computational model for the spatially-developing boundary layer flows through and over a building-array model. The size of computational domain is 3.5H, 0.36H, H (H: the height of the computational domain) in x-, y- and z-directions, respectively. Here, x, y, and z represent the streamwise, spanwise and vertical directions, respectively. The numbers of

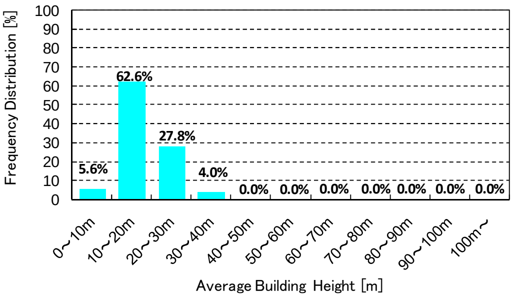

Fig.1.Frequency distribution of the average building height.

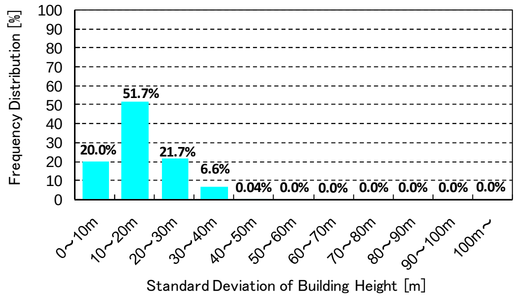

Fig.2. Frequency distribution of the standard deviation of building height.

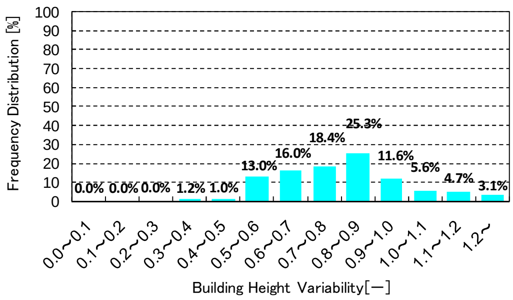

Fig.3. Frequency distribution of the building height variability.

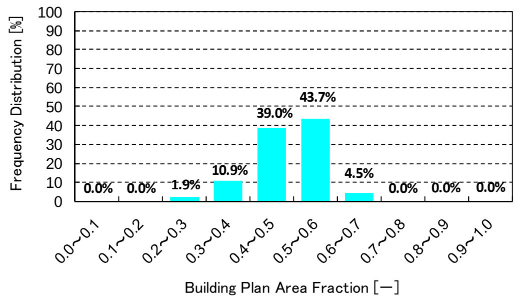

Fig.4. Frequency distribution of the building plan area fraction.

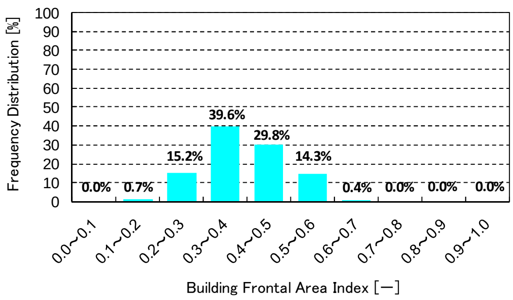

Fig.5. Frequency distribution of the building frontal area

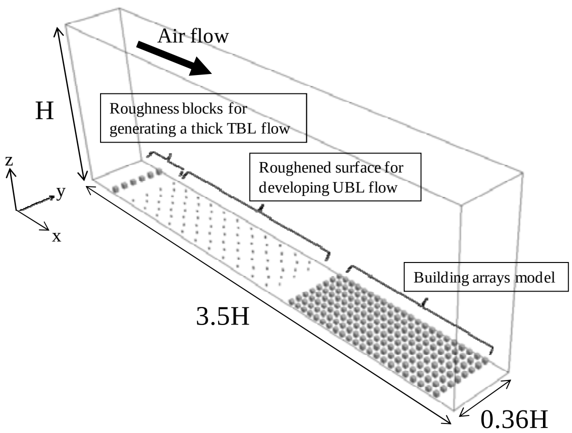

Fig.6. Computational model for building arrays model in the spatially-developing boundary layer

grid points are 400, 64 and 70, respectively. 6 roughness blocks (0.05H×0.05H×0.05H) for generating a thick turbulent boundary layer (TBL) flow are placed near the inlet. Furthermore, in order to generate urban boundary layer (UBL) turbulent flow, the ground surface is roughened by staggered arrays of roughness blocks (0.02H×0.02H×0.02H). Building arrays model are placed in a downstream area.

3.2 NUMERICAL CONDITIONS

In the present study, LES is conducted using the standard Smagorinsky model (Smagorinsky, 1963). The coupling algorithm of the velocity and pressure fields is based on MAC method with the Adams-Bashforth scheme for time integration. The Poisson equation is solved by SOR method. For the spatial discretization in the governing equation of flow field, a second-order accurate central difference is used.

At the streamwise inflow and outflow boundaries, a uniform flow is imposed at the inlet of the computational domain and a convective boundary condition is applied at the exit. At the top, free-slip conditions for streamwise and spanwise components are imposed and vertical velocity component is 0. At the spanwise lateral boundaries, periodic condition is imposed. At the ground surface, non-slip condition component is imposed for each velocity component. At the body surface, feedback forcing is applied(Goldstein, 1993).

3.3 MODELING OF URABN SURFACE GEOMETRY

Based on the urban morphological analysis of central Tokyo described in Section 2, we propose building arrays model that represents characteristics of realistic urban surface geometries. Table 1 shows the computational settings for the present LESs. The proposed building arrays models in the present study consist of square arrays (see Fig.6) of higher(h_{max}) and lower(h_{min}) building models with the building plan area fraction of λ_p=0.25, 0.44, 0.64 and the building height variability of h_{sd}/h_{av}=0.0, 0.33, 0.66, 1.1.

Building arrays models are consisting of 3 lower building models and 1 higher building model in the repeating unit. In all cases, the average building height is constant.

4. LES RESULTS OF VARIATION OF ROUGHNESS LENGTH WITH λ_p

Fig.8 shows the variation of the normalized roughness length, z_0/h_{av} with λ_p for cases with uniform heights and variable heights. Also plotted in this figure are various empirical relationships between z_0/h_{av} and λ_p (Macdonald, 1998;Raupach et al.,1980; Shao et al, 2005) for comparison. Roughness length, z_0 is estimated by fitting the calculated mean wind velocity profiles to log-law by the following expression.

$$u = \frac{u_\tau}{\kappa}\ln\left(\frac{z-d}{z_0}\right) \quad (3)$$

where κ and d are Karman constant, 0.41 and the zero-plane displacement, respectively. d is estimated by the following equation(Hanna, 2002).

$$\frac{d}{h_{av}} = 0.7 + 0.35(\lambda_f - 0.15) \quad 0.15 \le \lambda_f \le 1.0 \quad (4)$$

Case	λ_p	h_{sd}/h_{av}	h_{max}	h_{min}	Geometry of the repeated unit for building arrays
Case1	0.25	0.0	1.0h	1.0h	Square array consisting of 4 cubic building models with a height of 1.0h
Case2	0.25	0.33	1.56h	0.81h	Square array consisting of 3 building models with a height of 0.81h and 1 building model with a height of 1.56h
Case3	0.25	0.66	2.13h	0.63h	Square array consisting of 3 building models with a height of 0.63h and 1 building model with a height of 2.13h
Case4	0.25	1.1	2.88h	0.38h	Square array consisting of 3 building models with a height of 0.38h and 1 building model with a height of 2.88h
Case5	0.44	0.0	1.0h	1.0h	Square array consisting of 4 cubic building models with a height of 1.0h
Case6	0.44	0.33	1.56h	0.81h	Square array consisting of 3 building models with a height of 0.81h and 1 building model with a height of 1.56h
Case7	0.44	0.66	2.13h	0.63h	Square array consisting of 3 building models with a height of 0.63h and 1 building model with a height of 2.13h
Case8	0.44	1.1	2.88h	0.38h	Square array consisting of 3 building models with a height of 0.38h and 1 building model with a height of 2.88h
Case9	0.64	0.0	1.0h	1.0h	Square array consisting of 4 cubic building models with a height of 1.0h
Case10	0.64	0.33	1.56h	0.81h	Square array consisting of 3 building models with a height of 0.81h and 1 building model with a height of 1.56h
Case11	0.64	0.66	2.13h	0.63h	Square array consisting of 3 building models with a height of 0.63h and 1 building model with a height of 2.13h
Case12	0.64	1.1	2.88h	0.38h	Square array consisting of 3 building models with a height of 0.38h and 1 building model with a height of 2.88h

Table1 Computational settings.

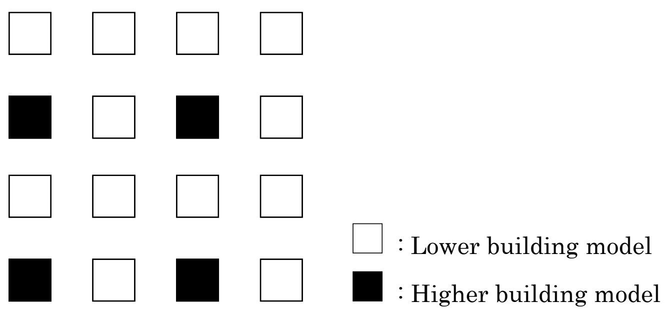

Fig.7. Layout of a repeating unit area for building arrays

Although the log-law profile is commonly used for boundary-layer flows over various surface, Cheng et al.(2002) pointed out that the log-law region may not exist in the extremely rough surfaces such as actual urban area. Also in the present study, it is predicted that the log-law region does not exist especially in the case of building arrays model with highly variable building heights. However, in order to qualitatively investigate the effects of the variability of building heights on z_0, we try to evaluate z_0 by fitting method.

The distribution of z_0/h_{av} for the empirical models (Macdonald,1998; Raupach et al.,1980; Shao et al., 2005) shows a peak in the range of λ_p=0.15-0.2 and then gradually decreases for λ_p > 0.2. z_0/h_{av} of LES data of building arrays models with uniform heights also decrease with

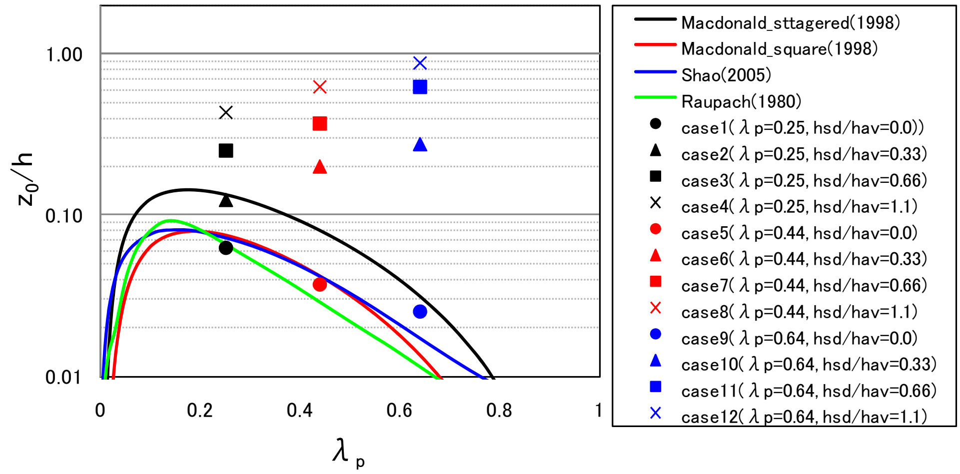

Fig.8. Variation of the roughness length with λ_p

the increase of λ_p, which is consistent with the empirical models. z_0/h_{av} of building arrays model with the low variability of building heights and λ_p (such as case2) is also consistent with that of building arrays model with uniform heights.

On the other hand, z_0/h_{av} of LES data of building arrays models with variable heights are much larger than those of building arrays models with uniform heights for $\lambda_p > 0.25$ except for case2 and increase with the increase of λ_p. For the variable height cases, the empirical model is not applicable to the LES results. Furthermore, z_0/h_{av} increases with the variability of building heights for λ_p=0.25, 0.44 and 0.64, respectively. These tendencies, such as increment of z_0/h_{av} with λ_p for $\lambda_p > 0.25$ are very different from those in the case of building arrays models with uniform heights. It is also found that for highly variable building heights and λ_p, the evaluated z_0 becomes a nearly same magnitude as the average building height. For highly variable building heights, the ratio of the higher building height to the TBL thickness is comparatively large and the existence of the higher building affects the upper layer of the TBL. Therefore, building arrays model with highly variable building heights are no longer recognized as a rough ground surface, which overestimates larger values of z_0/h_{av}.

As Kanda(2006) pointed out, it is thought to be difficult to apply the previous empirical models based on the assumption of uniform heights to actual urban area.

5.CONCLUSION

In this study, we examine the building morphological characteristics and perform LES on the TBL flows over the building arrays that represent realistic urban surface geometries.

From the LES results, it is found that z_0/h_{av} of building arrays model with the low variability of building heights and λ_p ($h_{sd}/h_{av} < 0.33$, $\lambda_p < 0.25$) is consistent with that of building arrays model with uniform heights. On the other hand, the values of z_0/h_{av} from the LES of building arrays models with variable heights are much larger than those of building arrays models with uniform heights for $\lambda_p > 0.25$ and increase with the increase of λ_p. These tendencies, such as increment of z_0/h_{av} with λ_p for $\lambda_p > 0.25$ are very different from those in the case of building arrays models with uniform heights.

Furthermore, for highly variable building heights and λ_p, z_0 becomes a nearly same magnitude as the average building height because the existence of the higher building affects the upper layer of the TBL. Therefore, building arrays model with highly variable building heights are no longer recognized as a rough ground surface, which overestimates larger values of $z_0/h_{av.}$ This implies that it is difficult to apply the previous empirical models based on the assumption of uniform heights to actual urban area.

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