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Study on vertical wind speeds and gust factor near the ground with roughness blocks

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SUMMARY
Japanese codes and standards specify constant values for wind speeds near the ground. For relatively small buildings or structures, the provided wind speeds are typically conservative. However, as the altitude reduces, wind speeds decrease due to the ground's surface friction. To elucidate the characteristics of the wind speeds near the ground and to provide a reasonable design wind speed near the ground, the wind speeds were investigated using a CFD with large eddy simulation (LES). Numerous wind speeds were measured at many points by varying the distance of two types of blocks with uniform heights. Lastly, the gust factor was calculated and compared by combining the mean wind speed ratio with the roughness parameter from a previous study.

Keywords: Wind speed, Vertical profile, Gust factor, roughness parameter, CFD, LES

1. INTRODUCTION

In recent years, strong typhoons have damaged many low-rise buildings (e.g., Jebi, 2018 and Faxai, 2019). Typhoon Faxai caused severe wind-related damage, according to the Ministry of Land, Infrastructure, Transport and Tourism investigations. Most wind-induced damages occurred in the cladding and its components (e.g., wooden roof components and exterior materials). In addition, the Ministry of Construction Notification No.109 of 1971 (Notification No.109) was amended in December 2020, and as of April 2022, all new buildings' roof tiles are required to be fastened with nails or screws for adequate wind resistance (Kikitsu et al., 2022). There are significant concerns about wind-related disasters on small buildings; however, the Building Standard Law of Japan does not require detailed structural calculations on wind loads for such small buildings or structures.

The wind-resistant design for relatively small buildings in Japan is based on Notification No. 1454 from the Ministry of Construction or AIJ Recommendations for Loads on Buildings (2015). In accordance with these codes and specifications, the design wind loads below a height lower than Z_b are specified as a constant value, even though the wind speed near the ground decreases due to the surface roughness-induced friction. Notification No. 1454 specifies a Z_b height of 10 m for suburban areas, whereas most Japanese houses are lower than 10 m. Therefore, design wind speeds for relatively small structures are typically conservative. However, wind speeds may not be suitable for such small structures. Some industrial organizations recommend the old Japanese standard (q = $60\sqrt{h}$ [kgf/m^2] (h < 16 m), where q denotes the velocity pressure and h denotes the reference height) for the structural calculation of certain products for which the current wind loads are deemed too conservative. Based on CFD simulations with LES, the present study investigates the wind speeds near the ground with blocks for four types of roughness arrangements. Moreover, the gust factor is estimated using the theoretical equation with a roughness parameter to determine the scope of applications for the equation with roughness blocks.

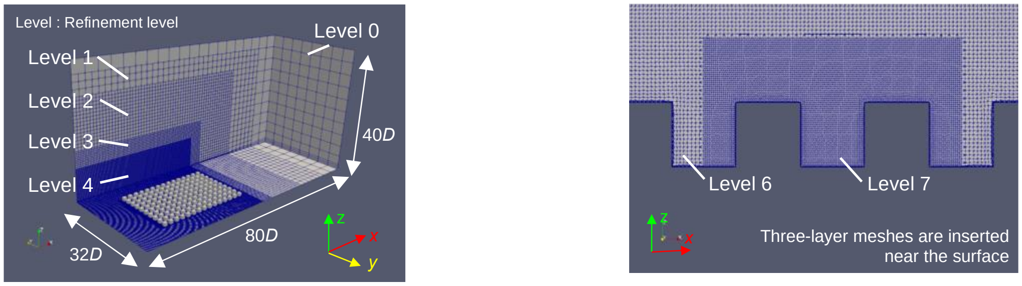
2. CFD SIMULATION

The CFD simulation is performed using a commercial CFD code, OpenFOAM (v2112). The governing equations are continuity equations and Navier-Stokes equations in the x, y, and z directions. The symbols u, v, and w represent the wind speeds in the x, y, and z directions, respectively. The turbulence model is the WALE model with a parameter value of 0.325. The computational domain and mesh resolution of the CFD simulation are depicted in Fig. 1. There are approximately 600 million mesh cells. The first-order implicit scheme was utilized for the temporal scheme, whereas the *filteredLinear2V* scheme implemented in OpenFOAM (Okaze et al., 2021) was utilized for the spatial scheme. The time step and sampling frequency are 1.0×10^{-4} s and 1000 Hz, respectively, in the model scale. Fig. 2 depicts the arrangement of roughness blocks and wind speed measurement points for the x-y plane. Wind velocity is measured at 25 points along the height direction. The distance between the roughness blocks is x, while their width and height are D = 50 mm and H = 50 mm and 100 mm, respectively. Fig. 3a depicts the vertical profiles of mean wind speeds and turbulence intensity at the center of the measurement point with no model. The inflow turbulence was generated by a preliminary calculation. The plots in the figure are the results of an experiment conducted in a wind tunnel (Takadate et al., 2022). Notably, the wind speeds are measured using an I-shaped hot-wire anemometer. The statistic values are evaluated using the ensemble average of five consecutive runs. Fig. 3b depicts the fluctuating wind speed power spectrum at z/D = 1. The turbulence length scale is approximately 0.25 m. Due to the filtering effect of LES, the power spectrum decreased in the high-frequency range, while the low-frequency spectral shapes are in good agreement.

3. WIND SPEEDS AND GUST FACTOR WITH ROUGHNESS BLOCKS

3.1. Validation of CFD simulation

The comparison of the mean wind speeds normalized by the wind speeds at z = 20D, U/U_{1000}, and the turbulence intensity, I_u, for the wind tunnel experiment and the CFD simulation is depicted in Fig. 4. Since the wind speeds were measured using an I-shaped hot-wire probe, the results are compared at two measurement points (Points A and B), except the wake region at Point C. The wind speeds obtained from the CFD simulation consist of three components; consequently, U/U_{1000} and I_u are calculated using the time-histories of the u component, and the root mean square of the three components ($\sqrt{u^2+v^2+w^2}$). Compared to the results between u and $\sqrt{u^2+v^2+w^2}$, the differences are observed in U/U_{1000} < 0.4 and I_u > 0.1. Almost all results are within the error of ±20% for each measurement point when the wind speeds are evaluated using $\sqrt{u^2+v^2+w^2}$. Further experiments are required to confirm the accuracy of the wind speeds



(a) Computational domain (b) Mesh division around model center

Fig. 1 Computational domain and mesh division

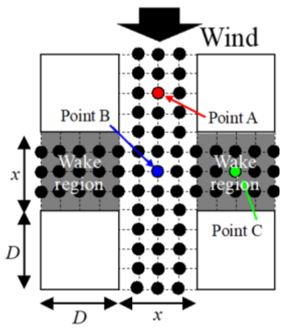
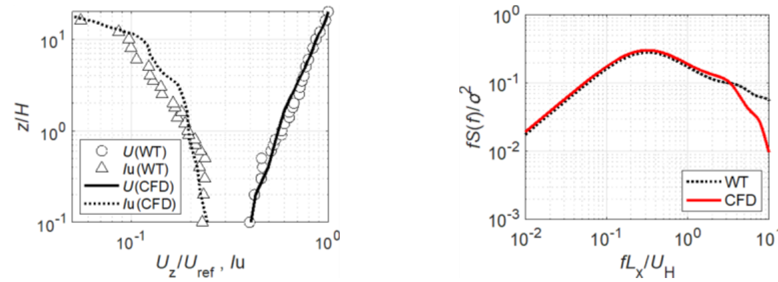
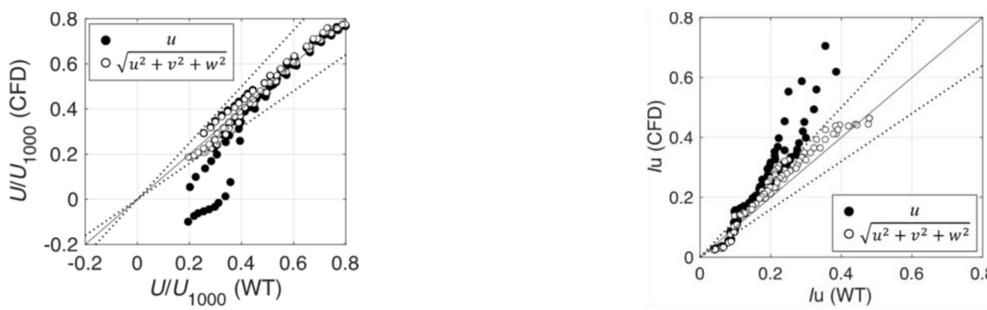


Fig. 2 Measurement points for *x*-*y* plane



(a) Profiles of the mean wind speeds and turbulence intensity (b) Power spectrum of fluctuating wind speeds

Fig. 3 Inflow turbulence of the wind tunnel experiment and the CFD simulation



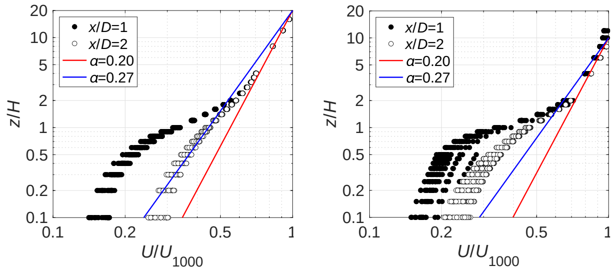
(a) Mean wind speeds (b) Turbulence intensity

Fig. 4 Comparison of the results between the wind tunnel experiment and the CFD simulation

in the wake region, but the relationship between the mean wind speed and gust factor was analyzed based on the simulation result.

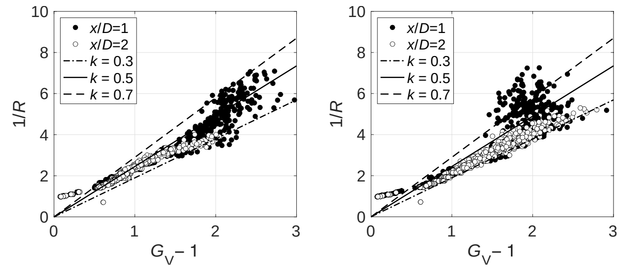
3.2. Mean wind speeds and gust factor

Fig. 5 depicts the vertical distributions of U/U_{1000} for H/D = 1 and 2. The solid lines represent the wind speeds for the exponents 0.20 and 0.27 of the power law. As the wind speeds are significantly influenced by the roughness blocks close to the measurement points, the mean speeds are plotted without the results around Points C, which corresponds to the wake region in Fig. 2. It should be noted that the wind speeds close to an obstacle are typically low and not as significant for the design wind loads on the structural calculation. Near the ground, the distributions of U/U_{1000} are typically smaller when x/D and z/H are smaller, and H/D is larger. The gust factor G_V, which is defined as the ratio of the maximum wind speeds to the mean wind speeds, can be theoretically derived as follows (Hino, 1964):



(a) H/D = 1 (b) H/D = 2

Fig. 5 Mean speed profiles measured without wake region



(a) H/D = 1 (b) H/D = 2

Fig. 6 Relationship between G_V-1 and 1/R

$$G_V - 1 = \gamma\,(1/R) \quad (1)$$

$$\gamma = 2\sqrt{3k} \ \ (0 \leqq k \leqq 1) \quad (2)$$

where k denotes the roughness parameter (k = 0 denotes a smooth wall, and k = 1 denotes a rough wall), and R is the ratio of the wind speed U/U_{1000}. Fig. 6 illustrates the relationship between G_V and 1/R, excluding the wake region depicted in Fig. 2. The gust factor is greater for x/D = 1 than for x/D = 2. Even though the gust factor may also be affected by the measurement period and the averaging time, the plots for x/D = 2 are nearly within the range k = 0.3–0.5. In contrast, the roughness parameter is greater than 0.5 for x/D = 1 when G_V is greater because the roughness density affects the roughness parameter.

4. CONCLUDING REMARKS

Based on the CFD simulation, the characteristics of the mean wind speeds and the gust factor near the ground with roughness blocks were investigated. The subsequent conclusions were reached.

- When H/D = 1, the distance of the roughness blocks x/D significantly impacted U/U_{1000}, and the mean wind speeds decreased as the measurement height approached the ground.
- The gust factor, excluding the wake region, can be estimated by the equation provided in a previous study. However, the roughness parameter differs depending on the arrangement of the roughness blocks. To propose reasonable design wind speeds near the ground, additional research is required on the measurement period, averaging time, and roughness parameters.

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