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Estimation of low-occurrence strong wind speed in an actual urban area using statistical methods with RANS results

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SUMMARY:
Urban wind environment closely affects pedestrian safety and comfort. Apart from the mean wind speeds, the low-occurrence strong wind speed (LOSWS) is an appropriate indicator for evaluating the pedestrian-level wind environment. Several previous studies have analyzed LOSWSs in idealized cases based on large-eddy simulations. However, the method for calculating LOSWSs from time-series data obtained from unsteady simulations remains difficult to be applied for actual urban cases because the large data amount brings challenge for storage and analysis. Therefore, this study analyzed the performance of two statistical methods, the KB method assuming the Weibull distribution and RANS-beta model assuming the beta distribution, for estimating LOSWSs in an actual urban area (Niigata city, Japan) by using the low-cost Reynolds-averaged Navier–Stokes (RANS) simulation results. The RANS simulations with k-ε model and k-ω model were validated with the wind-tunnel experimental results in benchmark datasets provided by the Architectural Institute of Japan. Accordingly, the statistics from the RANS simulations were used in the statistical methods for estimating LOSWSs. The KB method showed comparable accuracy with RANS-beta model. Although further validations are still needed, our results showed that both statistical methods can provide a new prediction approach of LOSWSs for evaluating urban wind environment.

Keywords: Wind environment, Low-occurrence strong wind speed, Reynolds-averaged Navier–Stokes simulation

1. INTRODUCTION

Wind environment in urban area is an important aspect related to the pedestrian safety and comfort. Recently, several studies conducted large-eddy simulations (LESs) (Ikegaya et al., 2020) or experiments based on particle image velocimetry (Hirose et al., 2022) for studying the low-occurrence strong wind speed (LOSWS) in idealized cases by obtaining time-series data of velocity components at pedestrian levels around buildings. Although the LOSWSs analyzed in these studies have high accuracy since they were directly calculated from the time-series data, the huge data amount also brings difficulties in storage and analysis. In addition, these studies only focused on idealized building or array cases. It is still necessary to evaluate the wind environment in actual urban cases since the flow patterns in actual urban cases are more complicated than these idealized cases. Moreover, the costs of the transient numerical simulations and wind-tunnel experiments to obtain the time-series data are significantly high. More convenient and economical way to obtain LOSWS distribution in urban area is still expected. Therefore, this study aims to analyze the performances of two statistical methods (KB method based on the Weibull distribution from Wang and Okaze, 2022, and RANS-beta model based on the beta distribution from Efthimiou et al., 2017) for estimating the LOSWSs in an actual urban case from the low-cost Reynolds-averaged Navier–Stokes (RANS) simulation results.

2. METHOD

2.1. Numerical Descriptions

A downtown area in Niigata City, Japan was analyzed in the study. The geometric model is shown in Fig. 1 (a). The model covers a circular area with the diameter as 400 m, and the tallest building is 60 m. The scale ratio between the simulation scale and the full scale was set as 1:1. The length, width, and height of the computational domain were set as 1300 m, 1000 m, and 250 m, respectively. Totally, 80 probe points were distributed at the pedestrian level (2 m), as shown in Fig. 1 (b). The wind direction (easterly wind) was also labeled in Fig. 1. The numerical simulations were conducted with the RANS k-ε and k-ω models. The convection and diffusion terms were discretized using the second-order linear-interpolation scheme. The tolerance of the convergence criterion was 1.0×10^{-4}. The bottom and building surfaces were defined as the Spalding wall function. The top and sides of the domain were defined as the slip condition. The outlet condition was defined as zero-gradient velocity and zero static pressure. For the inlet condition, the streamwise velocity component u and turbulent kinetic energy k were prescribed based on the experimental data from the Architectural Institute of Japan (AIJ benchmark case-E), and the turbulent kinetic energy dissipation rate was determined by assuming local equilibrium as $\varepsilon = {C_\mu}^{0.5} k \frac{du}{dz}$, where $C_\mu = 0.09$ and z denotes the vertical direction. The hexahedral cells were applied to discretize the computational domain with a four-level refinement. Between the adjacent refinement levels, the edge of one cubic cell was uniformly split into two edges of smaller cells. For the lowest level (coarsest level), the length of the cubic cell was set as 5 m. The minimum cell size was set as 0.625 m above the ground. The total cell number was about 26.3 million.

2.2. Statistical Methods

The LOSWS was estimated using the KB method (Wang and Okaze, 2022) and RANS-beta model (Efthimiou et al., 2017) with the RANS simulation results. The flow charts of the KB method and RANS-beta model are shown in Figs. 2 (a, b). In the KB method, the shape parameter of the Weibull distribution β and effective mean wind speed $\langle s \rangle_{Eff} = (\langle u \rangle^2 + \langle v \rangle^2 + \langle w \rangle^2 + 2k)^{0.5}$ are determined by the statistical values of $\langle u \rangle$, $\langle v \rangle$, $\langle w \rangle$, k, $K = 0.5(\langle u \rangle^2 + \langle v \rangle^2 + \langle w \rangle^2)$, where $\langle u \rangle$, $\langle v \rangle$, $\langle w \rangle$ are the mean wind velocity components, and K is the mean kinetic energy. Accordingly, the gust factor G_q with exceedance probability q of the Weibull distribution is determined as a function of β. Finally, LOSWS s_q is determined from G_q and $\langle s \rangle_{Eff}$. In the RANS-beta model, the integral time scale of the wind speed, T_v is estimated from k and ε, and the mean wind speed is estimated as $\langle s \rangle = (\langle u \rangle^2 + \langle v \rangle^2 + \langle w \rangle^2)^{0.5}$. The wind speed fluctuation intensity I is determined by $\langle s \rangle$ and $\langle s'^2 \rangle = 2k/3$, where $s' = s - \langle s \rangle$ is the wind speed fluctuation. Accordingly, the beta distribution parameter η can be estimated from T_v, I, and time interval $\Delta\tau$ set as 0.0001 in this study. Consequently, based on the theoretical relationship of the beta distribution, the other beta distribution parameters α and ξ, and the maximum wind speed s_{max} can be determined. Finally, from the probability density distribution of the beta distribution, the LOSWS s_q can be obtained. For the further details of the statistical models, please refer to Wang and Okaze, 2022 and Efthimiou et al., 2017.

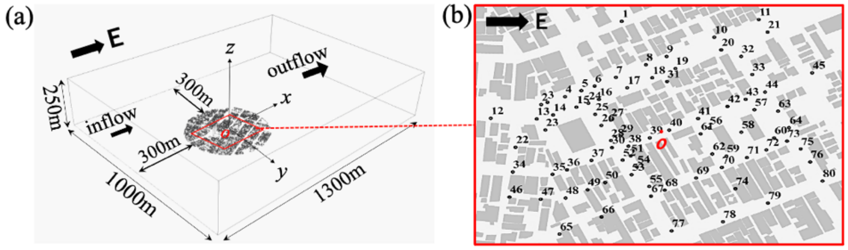

Figure 1. (a) Computational domain and building models. (b) Probe points. *o* denotes the coordinate origin.

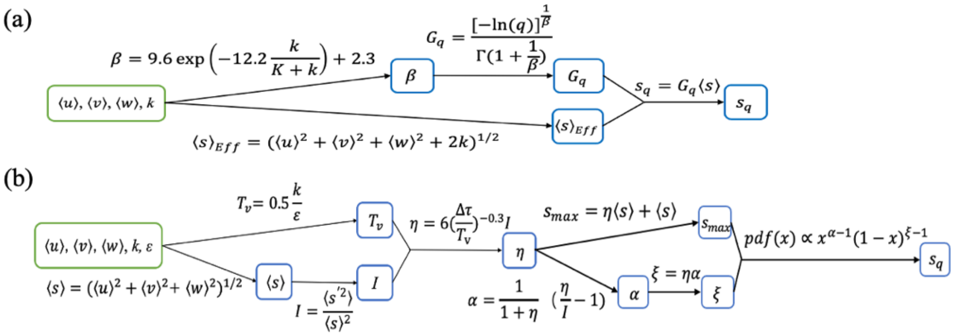

Figure 2. Flow charts of (a) KB method and (b) RANS-beta model. Γ in (a) represents the Gamma function.

3. RESULT

The wind speed ratio (defined as $\langle s\rangle_{Eff}/u_H$ and $\langle s\rangle/u_H$, where u_H = 3.8 m/s is the mean streamwise wind velocity at the reference height H = 2 m of the inlet boundary) of the numerical simulations were compared with the experimental results (AIJ benchmark case-E) in Fig. 3. It was found that the *k-ε* model results are significantly close to those of the *k-ω* model. In addition, *k-ε* model and *k-ω* model results acceptably agree with wind-tunnel experimental result at most points. The comparisons of s_q estimated by the KB method and RANS-beta model are shown in Fig. 4. It was found that the results of the KB method are close to the results of RANS-beta model. The estimated s_q based on *k-ω* model results showed slightly higher consistency between the methods. Since the RANS-beta model was already validated to have acceptable accuracy with the measurement results (Efthimiou et al., 2019), the result of KB method was expected to be applicable for the urban area cases with complex building layouts.

4. CONCLUSIONS

In this study, low-occurrence strong wind speeds (LOSWSs) in an actual urban area (Niigata city, Japan) were estimated by the KB method and RANS-beta model. The input parameters for the statistical methods are from the RANS simulations with *k-ε* model and *k-ω* model. It was found that RANS simulation results of *k-ε* and *k-ω* models agree well with the wind-tunnel experiment result at most points. The LOSWSs estimated by the KB method and RANS-beta model are close to each other. More detailed validation of the KB method needs to be conducted by comparing with the results from large-eddy simulations and full-scale measurements in future studies.

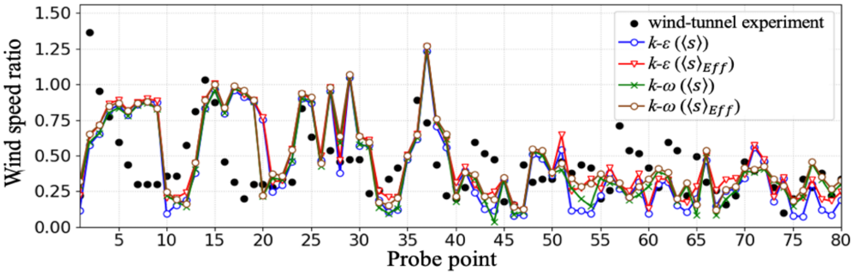

Figure 3. Comparison of wind speed ratios obtained by *k*-*ε* model and *k*-*ω* model. *x*-axis denotes the number of the probe points from 1 to 80 in Fig 1 (b).

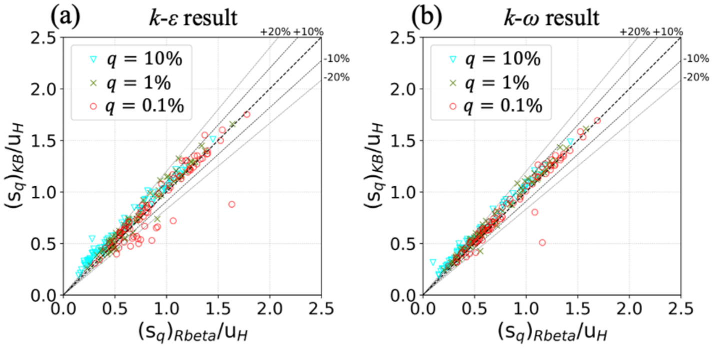

Figure 4. Comparison of s_q estimated by KB method and RANS-beta model. (a) *k*-*ε* model. (b) *k*-*ω* model.

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