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Effect of the Density of High-rise buildings on the Wind Environment

Xuchong Yi[1,a], Shuangxi Zhang[1,b]

[1]School of Geodesy and Geomatics, Wuhan University, Wuhan 430079, China.

[a]xuchongyi@whu.edu.cn, [b]shxzhang@sgg.whu.edu.cn

Abstract

An increasing number of tall buildings have been recently built in urban centers. However, quantitative research on the influence of the density of high-rise buildings on the multi-aspect wind environment remains limited. Through the control variate method, this study numerically simulates urban wind fields around tall building groups with different densities(street width) in a super-tall area model. The wind environment is evaluated according to three aspects: the high-rise wind noise, wall effect, and street ventilation. The results show that, for the super-tall model, the wider the street canyon, the lower is the high-rise wind noise and the better is the street ventilation. The wall effect is weak when the AR (building height/street width) is between 0.67 and 2.

Keywords

High-rise Building; Ventilation; Wind Noise; Wall Effect; Numerical Simulation.

1. Introduction

The rapid increase in the height and density of urban buildings[1] has caused a series of negative effects. Wind environmental problems, including poor ventilation, the wall effect, and wind noise, have attracted public attention[2-4]. Conventional methods for studying the wind environment include full-scale measurements, reduced-scale wind tunnel experiments, and numerical simulations with computational fluid dynamics[5] (CFD). Numerical simulations are widely used at present[6]. The key parameters for the wind environment are the building height[7], building density[8], and street aspect ratio[9] (AR). Although many studies on the wind environment have focused on the building structure and distribution, quantitative numerical research on the influence of the density variations of high-rise buildings on the multi-aspect wind environment remains limited. We numerically simulate the wind field around 2D high-rise building groups corresponding to different densities in a super-tall area model. The simulated wind field is used to comprehensively assess the high-rise wind noise, wall effect and ventilation to explore an appropriate parameter for a good wind environment.

2. Methods

2.1 Model Descriptions

We designed a 2D model to simulate the wind field corresponding to the densities of stepped tall building groups in a super-tall area. As showed in Model 1 (see Figure 1), the area included five stepped buildings with different height. The heights of the buildings are h-100, h-50, h, h-50, h-100, respectively, b is the building width, and w is the street width. Here, w is variable, while h and b are constants. The left boundary is the inlet boundary, the vertical velocity profile U_Z is given by the power law as follows:

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$$U_Z = U_S \left(\frac{z}{z_S}\right)^{\alpha} \tag{1}$$

where U_S is the velocity at the reference height, U_Z is the wind velocity, Z is the height, Z_S is the reference height, and α is the power-law exponent determined by the terrain category. A zero-pressure outlet boundary is adopted at the downstream outflow, and a symmetric boundary condition is used at the top boundary. The no-slip wall boundary condition is applied to all walls, roofs, and the ground of the street canyons. We set the background temperature to 293.15 K and the background pressure to a standard atmospheric pressure. The airflow conditions are normal temperature, low speed, and incompressibility, which conform with the Boussinesq turbulence hypothesis. In this study, the standard k–ε model is used to solve the governing equations

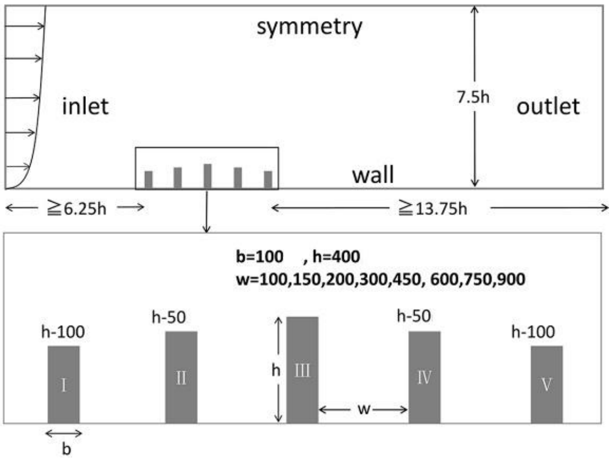

Figure 1. Model 1 with variable density

2.2 Model Validation

To verify the validity of our numerical simulation, we compared the results of the wind tunnel test performed at AIJ[10] with those of our numerical simulation. The building parameters we used in our simulation were the same as the wind tunnel data. Figure 2 presents a comparison of CFD predictions using standard k-e model with wind tunnel measurements. Although a small difference was observed between the wind tunnel test and simulation results in the near-surface area, the results exhibited strong agreement for other areas. The trend of wind speed in the numerical simulation was consistent with that in the wind tunnel test, which indicated that our numerical model can satisfactorily predict conditions of the wind environment.

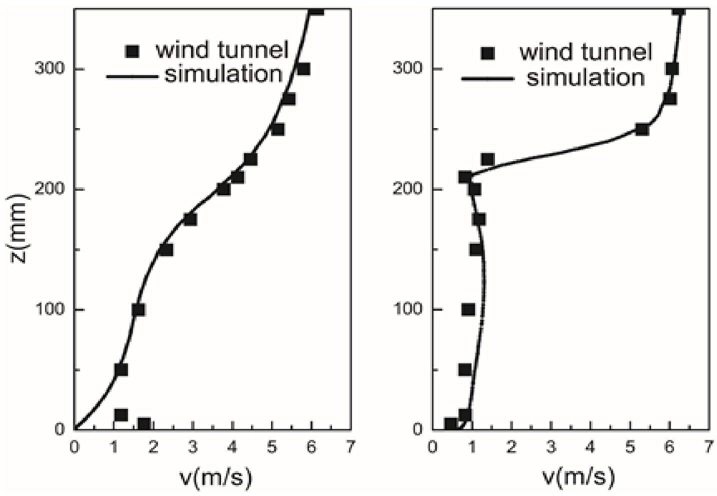

Figure 2. Velocity comparison between the numerical simulation and wind tunnel test model for upstream(left) and downstream(right)

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3. Results and Discussion

A formula describing the relationship between the wind speed and noise is developed. The wind speed change rate *Rv* is adopted to evaluate the wall effect. According to the measured data on wind noise and the wind speed[11], we fit the statistical relationship between the wind noise and wind speed in the form of Eq. (2),

$$L_{Aeq}(v) = 7.95408 \times v^{0.66221} + 15 \quad (2)$$

where L_{Aeq} is the A-weighted equivalent sound pressure level [unit: dB(A)] and *v* is the wind speed (unit: m/s).

The wind velocity change rate *Rv* is a ventilation index denoting the dimensionless velocity magnitude and is calculated as follows,

$$R_v = \frac{v - U_s}{U_s} \quad (3)$$

where *v* is the wind velocity and *Us* is the reference wind speed. Here, *Rv* denotes the difference between the wind speed in the street canyon and the reference wind speed. A bigger |*Rv*| value corresponds to stronger wall effect.

Figure 3. (a)–(h) display the simulation results of the wind field distribution around buildings with different densities (street widths). The distribution between the high-speed zones (deep red regions) and low-speed zones (deep blue regions) is similar in all the eight cases. The high-speed zone is distributed in the upper-right area of buildings, whereas the low-speed zone is distributed in the wake area, upwind corner, and street canyon. As the building density decreases and the street canyon width increases, the wind speed in the street canyon begins to slowly increase to 3 m/s and the wind speed of the wake area of the city also tends to increase. No obvious change occurs in the high-speed zones. A detailed analysis is given in the following text.

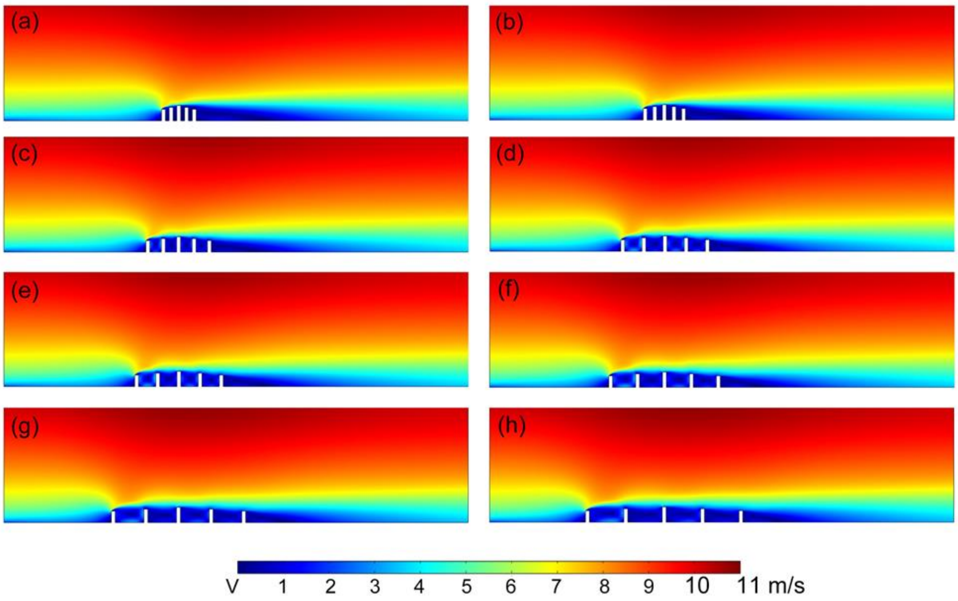

Figure 3. Simulation results of wind velocity fields around buildings with different street widths: (a) w = 100, (b) w = 150, (c) w = 200, (d) w = 300, (e) w = 450, (f) w = 600, (g) w = 750, and (h) w = 900

Figure 4(a)–(d) depict the flow regimes in street canyons when *w* = 100, 200, 450, and 600, respectively. When *w* is 100, there are two vortices in the first and second streets, and three vortices in the third and fourth streets. These vortices are unfavorable for the exchange of air at the bottom of the street canyon with the air above the building, thus the street ventilation is poor in this case. When

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w are 200, 400 and 600, respectively, in general, there is only a clockwise vortex in each street canyon. The air in the third and fourth canyons can partially exchange with the outside air because of the shorter downstream buildings, while the air in the first and second canyons is difficult to exchange with outside air because of the higher downstream buildings. Therefore, the ventilation of the third and fourth street canyons are relatively better than that of the first and second canyons. The bacteria and pollutants in the canyon are generally concentrated at the bottom. When the airflow carrying bacteria and pollutants in the street canyon moves to the upper right, the harmful polluted air will diffuse. As the width of the street increases, the polluted air in the canyon will diffuse and exchange with the outside air for a longer time, thus, the wider is the street, the better is the street ventilation.

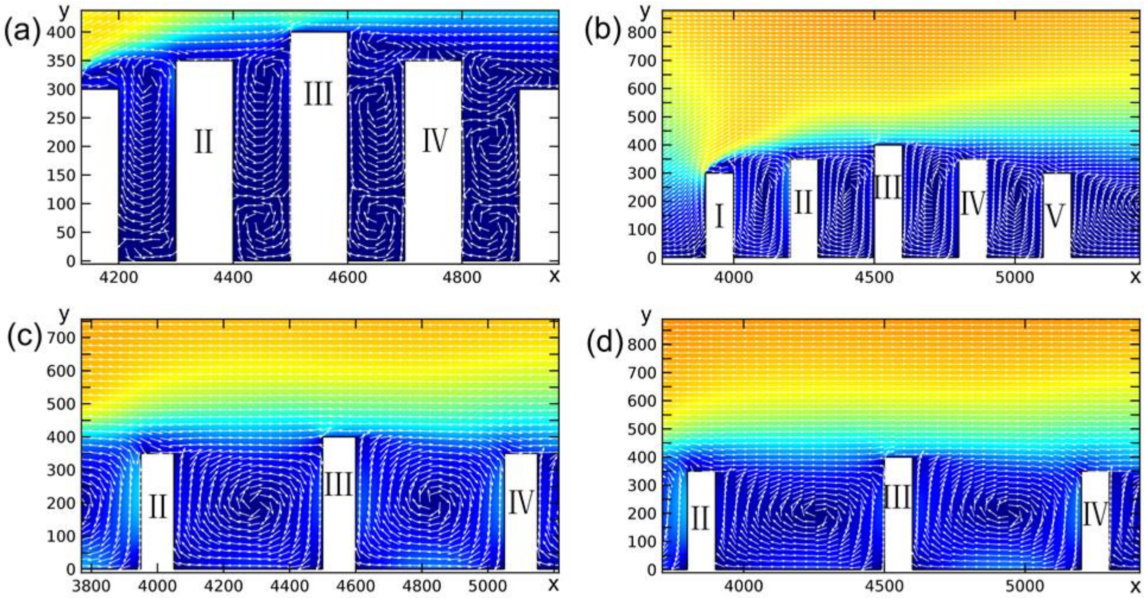

Figure 4. Flow regime in the street canyons at (a) w = 100 , (b) w = 200 , (c) w = 450 , and (d) w = 600

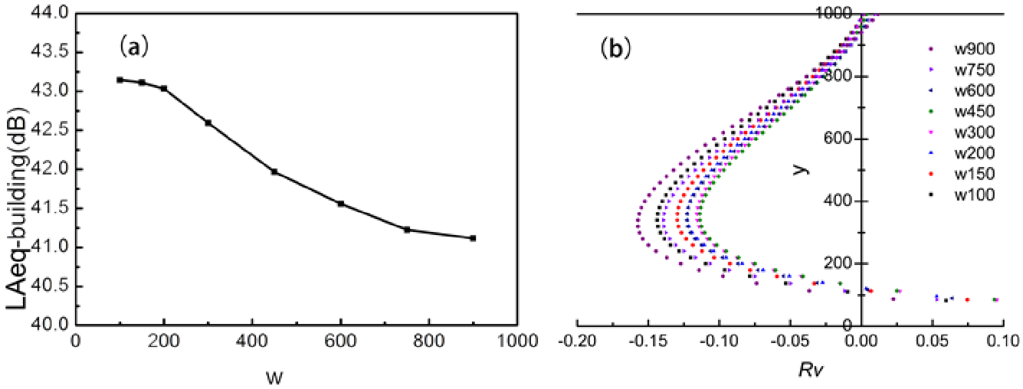

Figure 5. (a)Wind noise corresponding to different street widths, (b)The wind speed change rate corresponding to different street widths

Figure 5(a) displays the calculated wind noise corresponding to different street widths. We can find that, the wider the street width, the lower is the wind noise. When the street width is less than 200, the noise level does not change obviously with the street width. However, when the street width is larger than 200, the noise begins to sharply decrease with increasing street width. Therefore, to alleviate wind noise, street width should be larger than 200 and street aspect ratio should less than 2. Figure 5(b) depicts the wind speed change rate of the outlet boundary corresponding to different widths. The results shows that, for most y values, when the street width changes from 100 to 200, the

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absolute value of the wind speed change rate decreases. Moreover, when the street width changes from 600 to 900, the absolute value of the wind speed change rate increases. When w is between 200 and 600, the absolute value of the wind speed change rate is comparative smaller, thus, when AR is between 0.67 to 2, the wall effect is comparative weak.

4. Conclusion

This study proposes the evaluation of the wind noise parallel to the direction of the wall effect and the street ventilation in an urban wind environment. Through analysis, we obtained the following conclusions:

For the super-tall area model:

(1) The wider the street, the lower is the wind noise.

(2) When the AR is between 0.67 and 2, the wall effect is weak.

(3) The wider the street, the better is the street ventilation.

City planning and design must account for many factors. All types of city planning and design have advantages and disadvantages. No type of urban planning can achieve all goals. We can only improve certain aspects as much as possible. Tall buildings and a high building density are beneficial to city economies, however, these factors conflict with the environment. Thus, we offer the following advice: for cities with many skyscrapers, the wind environment can be improved by adjusting the street width between skyscrapers to a suitable value.

Acknowledgments

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