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Original Research Paper

Research on the Green Wind Environment Based on Numerical Simulation

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ABSTRACT

With the continuous innovations in computer technology, the computer numerical simulation method has been widely applied. This paper is based on the numerical simulation method, it is anchored to the architectural green wind environmental studies, explored the relationship between the environment and the building and the role of the environment on the building development, and the impact of the wind environment on the architectural design and the structural design, in order to restore the positive interactions between the environment and the building, and lay the foundation for the road to the sustainable development of the building.

INTRODUCTION

With urban high-rise buildings and high-density areas, the structure of the urban space has become very complex, resulting in various wind environment problems. As this issue has become more predominant, the awareness of the problem has increased as well, and therefore, research on building wind environment is necessary. Because the gas flow phenomenon and the complexity of object geometry, many problems of aerodynamic research, not only depends on the method of calculation, but must pass through the wind tunnel experiment. Calculation can be used to find the limits of the formula rules, or provide data and theory analysis to combine with research, to solve the rational problems. The model-based wind tunnel experiments can provide a reliable assessment for the environment of pedestrians at a specific height, and also investigate the comfort factors from wind effects on various aspects such as temperature, solar radiation, humidity, pollutant and diffusion. Before the numerical simulation method is used, the wind tunnel experiment is the main method in assessment of the building wind environment. There are continuous developments in computer technology, allowing computer numerical simulation to be widely applied. This paper is based on the numerical simulation method. It is anchored to the architectural wind environment studies, the relationship between the environment and the building, and the role of the environment on future development. This paper also explores the impact of the wind environment on the architectural and structural design in order to restore the positive interactions between the natural and built environment, as well as, lay the foundation for the road to the sustainable development of the building.

OVERVIEW OF WIND FIELD

Characteristics of wind field: This analysis will focus on the speed as one of wind's most important characteristic. The surface of the earth can resist the horizontal movement of air through ground friction to slow the velocity of the airflow. The effect of the earth's resistance on the airflow lessens with an increase in height. When the height exceeds a certain value, the influence of the surface friction can be ignored. Air will flow with a velocity gradient along isobars, which refers to the height of the atmospheric boundary layer height or thickness (Plate 1999). To express the free atmosphere above the atmosphere boundary layer δ will be used. ZG will represent the gradient wind height, or the starting point of the gradient wind velocity, and VzG to represent gradient wind speed (Fig. 1).

The mean velocity profile has two main types, the logarithmic rate, and the index rate. Since the difference between the two is not obvious, the index rate is generally used when doing calculation. The formula is as follows:

$$Vavg(z') = v^{*}avg^{*}In(z'/z0)/k$$

where the Kaman constant is k at 0.40; effective height is z'; average wind speed in the lower atmosphere at the height of z'; v* as the average friction velocity is Vavg (z'); surface roughness length is z0.

The general wind speed is, naturally and irrationally produced, but in engineering design the wind pressure must be rationally calculated, therefore the conversion equation

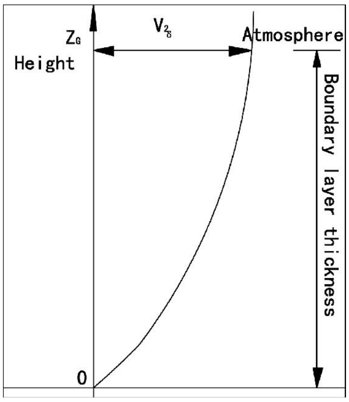


Fig. 1: Atmospheric boundary layer.

should be taken into consideration.

According to the specific standards in China, the basic wind pressure can be summarized as follows: The basic wind pressure utilizes the wind speed (m/s), which is the average of the data from the statistics over the last 50 years, at a maximum of 10 min and at the height of 10 m in the local, open, flat ground. The standard value of the mean wind load that is perpendicular to the surface of the building should abide by the following formula.

$$w_{cz} = \mu_s \mu_z w_0$$

In the average wind load standard value formula; w_{cz} is the wind load shape coefficient; μ_s is the coefficient of the change of wind pressure; μ_z is the wind pressure height coefficient; w_0 is the basic wind pressure. It can be checked directly for a period of 100 years. As for the wind pressure height coefficient, it utilizes a logarithmic rate to consider this change. As for the wind load shape coefficient, it can be determined through the numerical table, according to the wind tunnel test or through numerical simulation. For some particularly important wind load calculations with relatively complex shapes, it is better to use wind tunnel test or numerical simulation to determine the coefficient.

Effect of wind field: Wind, generally, can be divided into static or fluctuating wind. The main distinction is found in the wind's frequency (f). The difference being that static wind generally will not produce resonance or a vibration phenomenon on a building structure. When considering static wind, it is mainly on account of the static wind as a uniform transverse load distribution. This has a lateral displacement on the structure, creating an overall lack of stability on the building structure and causes collapse or partial failure phenomenon (Zhang 2006). Alternatively, the frequency of fluctuating wind will cause the vibration of the structure (left and right). This movement is strong enough to where the users inside will be affected, which creates a problem of comfort to consider. This is applicable in large spanning structures, high-rises and super high-rises. At the lower levels, static wind and fluctuating wind can be considered as a whole, where vibration is not taken into consideration. In practice, lower levels are considered a rigid body and the fluctuating wind to coefficient is multiplied by the corresponding experience method. Therefore, it can be regarded as a static wind.

This is only the preliminary understanding of wind. Further research would require books on meteorological data and information to help better understand the wind's morphology and characteristics. Because the wind fields have an influence on buildings, the building structure may be changed. Through accumulated time and research, in general, it can be summed up as the following:

1. The structure or structural component receives heavy wind to create the overall instability phenomenon.
2. The structure or structural component may have deformation due to the excessive wind, which may cause the damage to the external walls, or interior wall decor.
3. Due to the repeated wind vibration, wearing damage can be caused in structure or structural component.
4. Using the aero-elastic instability, it can lead the structure to have more aerodynamic movement in the wind.
5. The movement from the aerodynamics is so large that building occupants or staff feels discomfort.

EVALUATION OF BUILDING WIND ENVIRONMENT

Evaluation of building wind environment, principally utilizes investigation of the influence of human comfort by temperature, solar radiation, humidity, pollutant diffusion and effects of wind on the building structure. This study will focus on the diffusion of contaminants and structural wind resistance of a typical wind field to discuss the method of evaluating building wind environment and other differences.

Pollutant diffusion: The different wind conditions have varying effects on the city street pollutant convection diffusion law. In the free stream, velocity is 5.37 m/s (400 mm). The conditions are obtained from the diffusion pattern, which is line source (traffic source) of the discharged pollution in the city, by a laser concentration field measurement system. Digital analysis on the resulting experimental picture can achieve the relative quantitative results. Then, by contrasting the results of the numerical simulation and wind tunnel test results, the qualitative consistent effect can be reached. This can provide a basis for predicting the air quality and on how to improve the quality of the air around a building near a heavy traffic area. For continuing improvement, the traffic environment can be studied to ensure that it does not become more heavily polluted.

Resist wind structures: During the determination of the structure of a building, the main considerations include safety aspects and the economy, so that the development can positively contribute to the city's economy, while also maintaining regulatory safety requirements.

For the safety and economy, the reliable calculation is based on the probability theory of the structure, utilizing the current innovations to become the theoretical basis of the present. It is also important to become a symbol of safety through the analysis of the structure, and using the index B to measure the beta structure reliability. In general, the limit state of the structure refers to the whole or a part of the structure that is damaged and cannot meet the design requirements.

In order to guarantee reliability, it is imperative to ensure the structure's safety and the positive economic contributions. To guarantee the project's detailed planning is suitable, the essential research is in the wind resistant design of a building.

The main component of the wind is the horizontal component. For the high-rise structure, the horizontal component is the main research object, and the vertical component can be neglected. Both the horizontal and vertical components should be considered when the structure contains a large projection plane.

The wind plays an influential role in the structure that is vertically high and soft, or long and thin. In general, these structures are based on adjustable layouts that are able to produce a better effect and device control methods that use vibration to achieve real-time responses, in relation to the wind environment. Under the impact of wind, not only does the vibration occur along with wind, the building also produces cross wind vibration, particularly the vortex shedding resonance that can create a magnitude that is same or more.

In addition, due to the improvement of living standards, not only the requirements about the strength, stiffness and stability have been created, but also the comfort levels within the buildings.

NUMERICAL SIMULATION STUDIES

This paper is the study of the wind environment simulation based on two buildings, named A block and B block, located in Shanghai, Tongji United Plaza. Through the CFD simulation, the standard k-ε turbulence model is selected for the outdoor wind environment around the entire building, in order to generalize a law to analyse the outdoor environment (Cenang et al. 1993).

Project overview: Tongji United Plaza is located in Shanghai City, Yanpu District, built for Tongji University's 100th anniversary. The plaza is made up of buildings A, B, C, and D. Five relatively independent structures that also can be seen as an organic combination. A and B are 5A high-grade commercial office buildings, building C is mixed use, apartment office building, D is a four star hotel, and building E is a commercial plaza. Among them, Tongji Plaza in the Southern District covers an area of 16736 square meters, a total construction area of about 8000 square meters, and contains financial office spaces, commercial use, and a hotel. This plaza used the concept of international office building design in accordance with the LEED certification standards, which is an American standard system for green building construction. The building facade adopts the LOW-E double hollow glass curtain wall and air conditioning, ventilation and other major building equipment with electric control, and automatic adjustment, for reduction in energy consumption. Many strategies were used in order to make the building energy consumption achieve the international ASHEAE energy saving standards. By using water-saving appliances and selecting water-saving plants, a 30% reduction of water use was also achieved. Through soil erosion control, storm water management, urban heat island effect management, and the use of environment friendly refrigerant, this site has become a green model of science and technology, as well as supports initiatives for environmental protection, increased indoor comfort, and energy efficiency (Tao 2003). The two buildings have 22 floors. Each level is about 4 meters, all with a square floor column design, reaching a total of 88 meters height.

In this paper, we will use CFD simulation to analyse the outdoor wind environment of the model composed of the road intersection and the A and B building block. This research with the application of computational fluid dynamics CFD, combined with Shanghai City geographic information, will utilize the average of the years of data for meteorological elements in Shanghai, as initial conditions for multi-scale atmospheric data simulation. Visual analysis tools will be used to analyse the result based on the numerical simulation evaluation, and the direct view display effect of the building on the atmospheric flow field, providing data on the building wind environment.

Fig. 2: Tongji union square area.

Fig. 3: The Plaza Tongji real map.

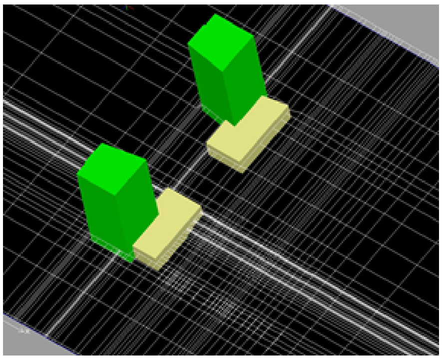


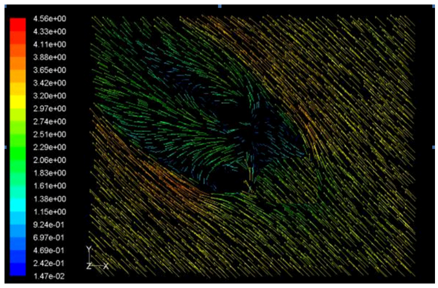
Fig. 4: Simplified CFD model.

Simulation Study

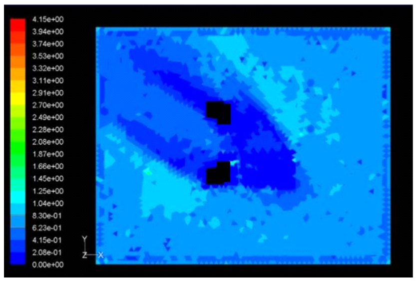
Establish the model: Tongji United Plaza model will be established with a cross section at the height of 1.5 m, to provide analysis on the wind environment for pedestrians. Fig. 4 is a simplified simulation model of Tongji United Plaza building with CFD. In the process of modelling, the main object is wind environment around Tongji United Plaza, therefore the surrounding environment is assumed to be open ground and its impact on the plaza will be ignored in the study (Yang et al. 2014).

As Fig. 3 shows, the model boundary size: 650 m × 450 m; model is 1:1, the highest point is 88 m (the top of A, B), and the building base is in 0 m.

***Relevant calculation equation*:** 1. Standard k-ε model calculation equation: The wind flow is in compressible and low speed turbulence in this model. The mathematical model often uses the standard k-ε equation. The calculation of the standard k-ε equation is low cost, and contains small fluctuation, and high precision in numerical calculation. Therefore, it is widely used in low speed turbulence numerical simulation. For these reasons, this paper uses the standard k-ε model. The coefficient of the standard k-ε model is listed in Table 1. All of the control differential equations including the continuity equation, momentum equation, and the K equation can be expressed as the ε equation, assuming the



(a) Vector graph of wind speed.



(b) Cloud graph of wind speed.

Fig. 5: 1.5m high simulation of summer wind velocity diagram.

fluid is incompressible, steady state after been simplified (shown in equation 5).

(1) The turbulent viscosity coefficient

$$\eta_t = C_\mu \rho k^2$$

(2) The continuity equation

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0$$

(3) The momentum equation

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = \frac{\partial}{\partial x_i}(\eta_{off}\frac{\partial u_i}{\partial x_i}) - \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}(\eta_{off}\frac{\partial u_i}{\partial x_j})$$

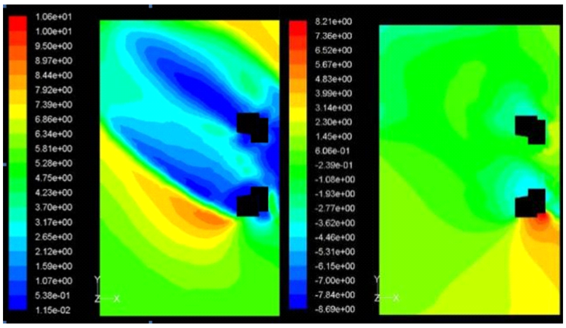
(4) The K equation

$$\frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\{(\eta + \frac{\eta_t}{\sigma_k})\frac{\partial k}{\partial x_i}\} - \rho\varepsilon + \eta_t(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_i}{\partial x_j})\frac{\partial u_j}{\partial x_i}$$

(5) The ε equation

$$\frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i}\{(\eta + \frac{\eta_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_i}\} - c_2\frac{\rho\varepsilon^2}{k} + \frac{c_1\varepsilon\eta_t}{k}(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j})\frac{\partial u_j}{\partial x_i}$$

2. Flexible structure under the condition of along wind static and dynamic wind load and displacement equation: As the wind record shows, in addition to the average wind speed, it includes the wind fluctuating wind speed component. When the structure is very rigid, wind vibration iner-



(a) Wind graph of stress(dynamic pressure) (b) Wind graph of stress (static pressure)

Fig. 6: 1.5 m high simulation of summer wind pressure diagram.

tial force caused by a fluctuating is not obvious, and can be omitted. When the structure is flexible in addition to the static wind load, the wind vibration inertial force, namely wind vibration load, should be considered.

The total wind load expression is:

W(z, t) = w(z) + wd(z, t)

In the formula W(z,t), with a total of wind load at a certain rate of guarantee, W(z) is the mean wind load at the height of Z, and wd(z, t) is the wind load with a guarantee rate of vibration. The flexible structure's wind sensitivity comes from the vertical, one dimensional cantilever structure. The quality of the structure, specifically the vertical height and stiffness distribution is not uniform; we abstract it into a one-dimensional cantilever with an infinite degree freedom system.

The equations of motion can be express as:

$$y_d(z,t) = \sum_{j=1}^{\infty} y_{dj}(z,t) = \sum_{j=1}^{\infty} \phi_j(z) q_j(t)$$

In the equation, $y_d(z,t)$ -the j mode of dynamic displacement; $\phi_j(z)$ -The coordinates j mode at Z height; $q_j(t)$ -The generalized coordinates in j mode.

Then the structure of Z at the Z height of the maximum peak displacement can be expressed as:

$$y(z) = g\sigma_y(z) = g\sum_{j=1}^{m} \sigma_{yj}(z)$$

In the formula:

$\sum_{j=1}^{m} \sigma_{yj}(z)$ -J model displacement response of root variance

g- Peak factor, the expression of (Ximiu & Scanlan 1992):

$$g = 2\ln vT + \frac{0.577}{2\ln vT}$$

Table1: Coefficient of standard k-ε model.

C_μ	C_1	C_2	σ_k	σ_ε
0.09	1.44	1.92	1.0	1.3

g- Commonly used in the range of 3-4

3. Wind vibration in crosswind structure situation: When wind effects on the structure, it will produce an alternate vortex behind both sides of the structure, and from one side to another in the alternate shedding vortex, then creating Carmen vortex. Carmen vortex makes the building pressure on the surface have a periodic variation, and the direction of the effect is vertical with wind. These effects cause the structure to produce a vortex vibration, whose direction is vertical with wind. The vibration is a forced vibration with the whirlpool's emergence. When the vibration is enhanced, the vortex will appear controlled by vibration, and reacts with reverberation characteristics. When the speed reaches within a given wind speed range, the vibration becomes more significant.

For a vertical cantilever structure, impact on the vortex exciting force load, the equation is:

$$m(z)y''(z,t) + c(z)y'(z,t) + \frac{2}{z^2}\left[EI(z)y''(z,t)\right] = \frac{1}{2}\rho v^2(z)D(z)\mu_L \sin w_s t$$

In the formula,

$y''(z,t)$ -Horizontal acceleration in different particle;

$y'(z,t)$ -Horizontal velocity in different particle;

ρ -The mass density of air;

v -The average speed of flow;

$D(z)$ -The feature size of object projection in the plane perpendicular with the mean flow velocity.

μ_L -Lift coefficient

***Boundary condition settings*:** The user defined functions in the CFD application, Fluent, are used to find the average wind speed that is consistent with the experimental wind and turbulence characteristics.

Due to the surface friction effect, the wind speed near the earth's surface, specifically a height just above ground, decreases. Only from 300 m to more than 500 m height the wind speed is not affected by the surface friction, and can flow freely under the effect of atmospheric gradient (Qian 1995).

Outlet boundary conditions: Fully developed flow boundary conditions, where the flow field of the physical quantities along the exit method to the gradient is zero; the fluid domain at the top and two sides; the free slip wall condition; the surface of the building and the ground; no slip wall condition.

SIMULATION RESULTS ANALYSIS AND DISCUSSION

According to the evaluation standard for green building, in the selection requirement, 1.5 meters height is selected as the object of study. Figs. 5 and 6 show the numerical simulation of the wind velocity and pressure, in summer conditions, on the building and at a height of 1.5 meters (Yang 2010).

The experiment shows that the building suffers a push wind effect in the southeast, but attracts wind pressure in the northwest and the top. It can be concluded that through the analysis for the bluff building, the centre and above on the building suffers the largest wind pressure, while the wind pressure is small when close to the sides and near the bottom. The downward flow has mobility on the surface, and also around the sides and the top. The vortex zone will appear when the air flow blows down because of a horizontal cylinder that forms in the windward side close to the ground buildings. The pressure distribution law indicates that if the airflow is separated at the angle on the sides of the building, pedestrians will feel wind pressure when walking behind the building. It will create discomfort, and potentially cause serious harm.

CONCLUSION

Wind environment is the effect of air flow on the interior and exterior of buildings. It is an important part of an environmental design. If the wind environment is not assessed, it may produce many problems, which directly affect people's lives. The wind environment conditions are not only related to the local climate, but to the building size, layout and other relevant factors. By the above analysed examples, along with the development of computer technology and the improvement of computational fluid dynamic theory, wind tunnel experiments can effectively and efficiently produce reliable test results. However, these experiments can be limited by many conditions and the utilizable range may be small. The numerical simulation can make up for the shortcomings of the experiments because it can obtain more accurate results by the use of computer software applications. Only in the numerical calculation, the simulation is completely the same. The comparison to one another can provide additional information and guide the construction layout design more precisely. Wind tunnel experiments, with computer numerical simulation, will be favourable in designing future buildings that are conducive to good wind environments. The wind environment should be analysed to allow the design to be optimized in the early stage of the design plan. It will effectively improve and stabilize the wind environment around the building, to create safe and comfortable spaces indoors and outdoors.

ACKNOWLEDGEMENTS

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