Field Measurement and Numerical Simulation of the Relationship Between Vertical Wind Environment and Building Morphology in Residential Areas in Xi'an, China

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Field measurement and numerical simulation of the relationship between vertical wind environment and building morphology in residential areas in Xi'an, China

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Abstract: The inadequate consideration of the impact of building morphology on ventilation efficiency in many urban residential areas has resulted in a series of environmental problems that threaten human health. The purpose of this paper is to establish a prediction model between ventilation efficiency and building forms in residential areas. Firstly, the characteristics of vertical wind profile in residential areas are measured through unmanned aerial vehicle (UAV); secondly, the wind speed ratio (WSR) at different height levels under the impact of morphological index (floor area ratio, building density, average building height, enclosure degree, height fall and maximum building height) in the residential area is simulated by ENVI-met; finally, two kinds of prediction formulas are obtained: (1) the average ventilation efficiency at the pedestrian level and (2) the prediction formula of WSR at different heights. The results show that the wind speed (WS) in residential area below 35 m is about 0.6 m/s lower than that in park. The results of numerical simulation show that the mean WSR at the pedestrian level is negatively correlated with each index and the height fall morphological index has the greatest impact on the WSR at different heights. The research can provide a reference for the optimal planning and design of ventilation efficiency of residential buildings, especially those in static wind areas.

Key words: Vertical wind environment; unmanned aerial vehicle measurement; numerical simulation; static wind area

Nomenclature：

UAV——Unmanned Aerial Vehicle

FAR——Floor Area Ratio

BD——Building Density, %

ABH——Average Building Height, m

ED——Enclosure Degree

HF——Height Fall, m

MBH——Maximum Building Height

SVF——Sky View Factor

WS——Wind Speed, m/s

WSR——Wind Speed Ratio

1. Introduction

The urbanization of China has been a boost to a large number of urban residential areas, which give rise to many environmental problems while satisfying the housing needs of residents. Insufficient consideration of ventilation efficiency in residential areas will bring adverse impacts on air pollution reduction, high temperature weather mitigation and human thermal comfort, or even cause the spread of epidemics (Feng W, 2020; Hong B, 2015; Mochida A, 2008; Vazquez-Prokopec G M, 2010; N. E. Yuan C, Norford L K. , 2014). Urban residents generally spend more than 2/3 of their time in residential area (State bureau of technical supervision, 2018). It is therefore of great significance to enhance the ventilation efficiency in residential areas for residents' health and quality of life (State Bureau of Technical Supervision, 2018).

The previous studies on residential wind environment were carried out from two aspects: planning and layout, and building morphology. Some scholars discussed the correlation between building layout and ventilation efficiency of residential area. Asfour et al. simulated the wind field of different types of residential area layout by CFD. The results showed that the residential buildings arranged around a central space, forming a layout open to the prevailing wind, can make the residential area well-ventilated (S., 2010). Some scholars also paid attention to the relationship between building morphology index and ventilation efficiency of wind environment. Kubota et al., for example, found a striking correlation between BD and the WSR at mean pedestrian level from wind tunnel test results of 22 Japanese urban residential areas (M. M. Kubota T, Tominaga Y, et al. 1699-1708., 2008). Yang et al. measured the wind environment of 10 high-rise residential areas in central Shanghai. They found that the ventilation efficiency in the pedestrian area is significantly related to the ED of the buildings and the green space, and that a 10% increase in SVF can raise the WSR by 7%~8% (Yang F, 2013). Li et al. studied the correlation of the FAR with the ventilation efficiency of residential areas, and reported that when the FAR rises from 0.63 to 2.32, the mean WSR of residential area declines by 0.18 (Li L, 2018). This paper mainly discusses the influence of building morphology index on ventilation efficiency of residential areas, from pedestrian height and vertical direction.

The previous studies mostly focused on the impact of building morphology factors on ventilation efficiency at the pedestrian height (Du Y, 2017; Jones P J, 2004; Mittal H, 2019; To A P, 1995), few of them investigated the impact in the vertical direction. Some scholars have explored the wind profile on the urban scale. As early as 1981, Landsberg and Helmut proposed that the roughness of the city would affect the surface resistance, WS and the wind profile of the city (E., 1981). Edward et al., after taking the dense urban morphology and the impact on the wind field into consideration, made a high-resolution map of Hong Kong's urban surface roughness using the mapping method, which provided guidance for urban planning (Ng E, 2011). Liu et al. constructed a full-scale urban model with a length of 2-20 km, simulated the urban wind flow via RANS (Reynolds average Navier-Stockes) equation, and compared the differences of wind profiles in the vertical direction with and without building details (Liu S, 2017). In fact, most of the recent relevant research regarding wind environment is conducted on the urban scale, or from pedestrian level, and few research focuses on the vertical wind environment on the residential area scale.

The purpose of this paper is to investigate the relationship between the design index of residential buildings and the ventilation efficiency. The research mainly includes the following aspects: 1) to compare the difference of wind profile between open area and residential area in the city; 2) to explore the coupling mechanism between the ventilation efficiency and the building morphology of residential area at different heights; 3) to establish a prediction model in residential area at different heights. This paper can provide reference for improving the ventilation efficiency of residential areas, especially those in low WS cities and regions.

2. Methodology

2.1 Field measurements

Xi'an City (107.40-109.49° E, 33.42-34.4° N) is located in Guanzhong Basin in the middle of Weihe River Basin. Xi'an has a warm semi humid continental monsoon climate with distinct four seasons and relatively dry air (Jin LN, 2014). The annual dominant wind direction in Xi'an is 67.5° (0° is the north, 90° is the east), the frequency is 11%, the static wind (0-0.2m/s) frequency is 35%, the outdoor mean WS in summers is 1.9 m/s, and the outdoor mean WS in winters is 1.4 m/s (Ministry of housing and urban-rural development, 2012). Located in area with a typical low WS, Xi'an is facing great challenges in air pollution, heat island effect and other issues.

In this paper, an open park and a typical residential area in Xi'an are selected to compare the differences of near surface wind profiles of different land use types. The measurement time was on August 13, 2017, and the relevant information of the measurement points is given in Table 1.

Table 1 Location of field measurements

Climatic region	City	Measured location	Scene photos

Cold region (II B)	Xi’an	Zishui Park (109°0′39.06″E, 34°20′10.39″N)	
Cold region (II B)	Xi’an	Shijiaxingcheng community (109°0′39.06″E, 34°20′10.39″N)	

The vertical WS in the residential area was measured by a drone (model: Dajiang M600 UAV). The UAV is equipped with a two-dimensional ultrasonic anemometer namely Decagon DS-2 (accuracy: 0.30 m/s or < 3%; range: 0 to 30 m/s; resolution: 0.01 m/s) (Figure 1).

The wind data of the vertical wind environment were measured by the test equipment carried by the UAV at typical points in the selected area within a height range of 1.5-100 m, and the data were collected through a 5 min hovering every 10 meters. The vertical wind profiles of residential area and park were tested.

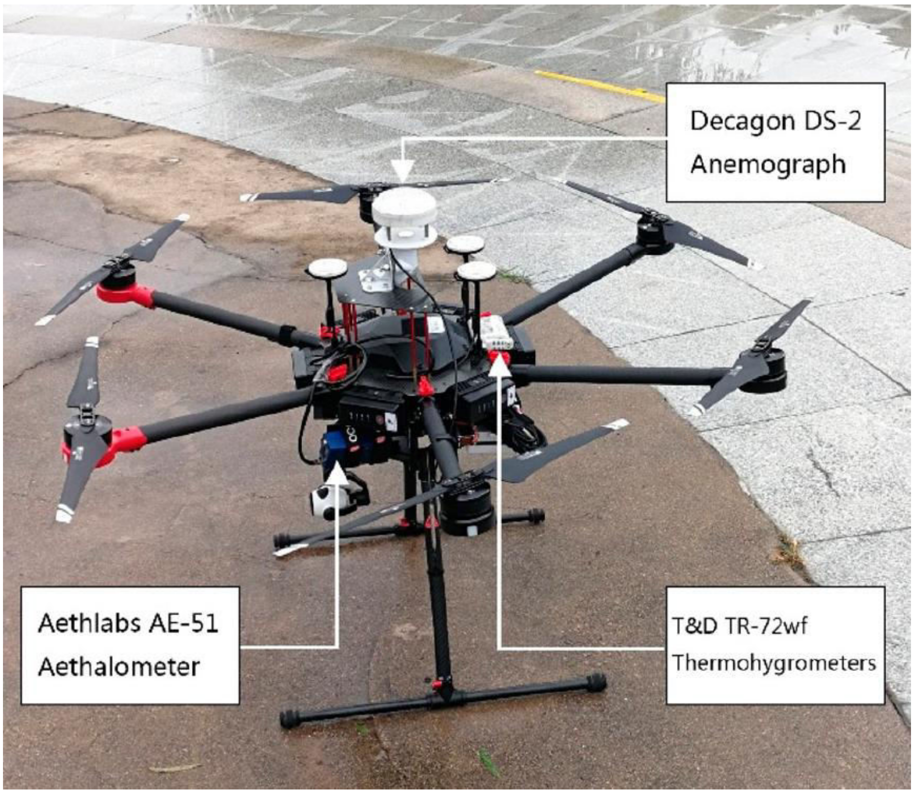

Figure 1 UAV and test equipment (Zhen M, 2019)

In order to evaluate and compare the wind environment in various scenes, the WSR index is used to evaluate the ventilation efficiency in residential areas at different heights (FL., 2005; Ren Chao, 2017).

$$\mathrm{VRw} = \frac{V_p}{V_\infty}$$

V_∞ is the wind speed at the top of the boundary layer (where the wind speed is not affected by the urban canopy) in m/s;

V_P is the wind speed at a certain height above the ground in m/s;

VRw is the ventilation efficiency at the current level affected by the built-up area.

2.2 ENVI-met simulation

The ENVI-met adopted in this paper is a simulation program of urban microclimate developed by Michael Bruce to simulate the wind and thermal environment on a block scale (Bruse, Fleer, & Software, 1998). In recent years, ENVI-met has been widely verified and applied in the field of urban wind environment (Á., 2013; Jung W S, 2006; Wang Y, 2019).

The simulation study is carried out on a typical determinant residential area with a length of 400 m and a width of 380 m (Figure 2). On this basis, by altering a single design variable, its impact on the mean WSR of the whole area is compared. Design variables include ABH, BD, FAR, ED, HF and MBH. Table 2 lists the variation range of each design variable.

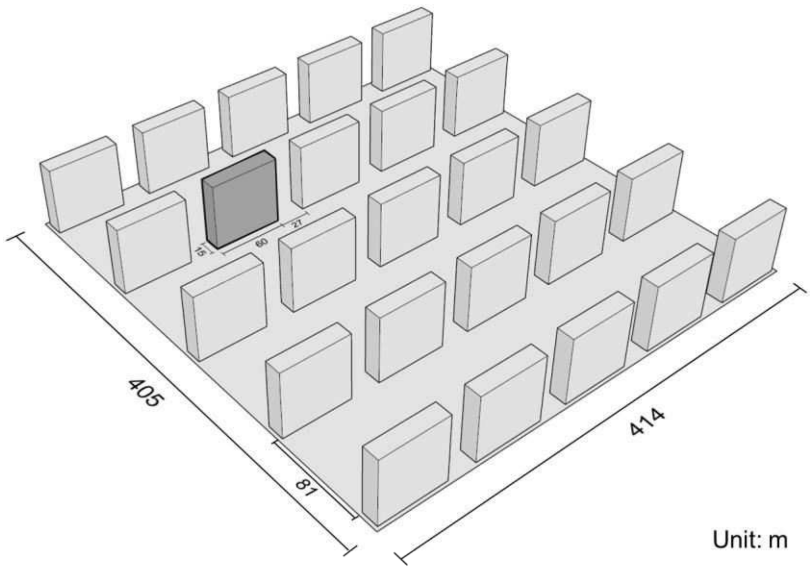

Figure 2 Basic model

Table 2 Range of morphological parameters

MBH	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m
ABH	10 m	20 m	30 m	40 m	50 m	60 m		
HF	10 m	20 m	30 m	40 m	50 m	60 m	70 m	
FAR	0.403	0.805	1.342	1.879	2.147	2.684		
BD	4.9%	8.7%	13.5%	24.3%	35.6%	51.9%		
ED	0.092	0.276	0.378	0.568				

The data of air temperature, relative humidity, WS and wind direction on June 21, 2019 measured by HOBO U23-001, UAV and on-board equipment are used as input values of the simulation software (such as Table 3). The accuracy of the simulation software is verified by the measured and simulated data of Xi'an finance and economics campus. As shown in Figure 3, the average relative error between the measured and simulated WS is 13.5%.

Table 3 Setting of simulation parameters

Start date	June 21, 2019
Start time	00:00
Simulation time	48 h

Wind speed at 10 m	5.3 m/s
Wind direction (0° is north)	67.5°
Air temperature	18.9~28.9 ℃
Relative humanity	42.0~80.0%

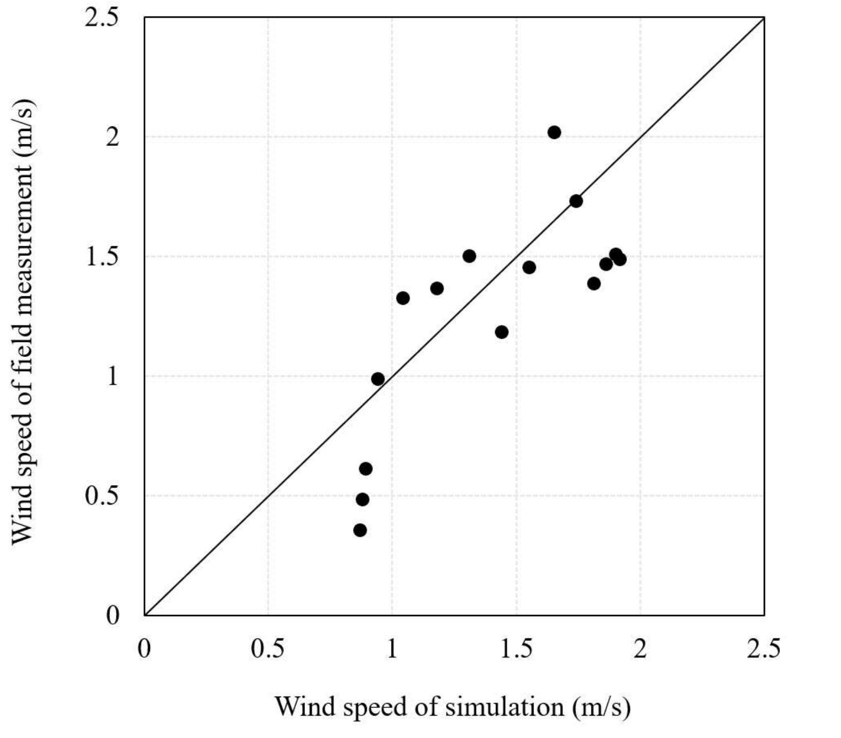

Figure 3 Correlation between measured and simulated results of vertical WS

3. Results

3.1 Surface wind profile difference between urban built-up area and open area

Figure 4 shows the WS distribution characteristics at different heights of Zishui Park. In general, the mean WS increases with the rising height. Specifically, the minimum and maximum of the mean WS measured at the heights of 1.5 m (the pedestrian level) and 100 m are 1.07 m/s and 3.98m/s, respectively. From 1.5 m to 12 m, the WS surges with the rising height, and increases by 2m/s every 10 m increase in height. At the height of 12 m to 100 m, the WS increases slowly with the increasing height. The WS increases by 0.01 m/s with every 10 m increase in height. This may be attributed to the fact that there are many trees and artificial facilities in Zishui Park, and these obstacles near the ground slow down the WS.

The WS distribution characteristics at different heights of Shijiaxingcheng Community are shown in Figure 5. In general, the mean WS increases along with the height. Specifically, the minimum and maximum of the mean WS measured at the heights of 1.5 m and 80 m are 0.56 m/s and 2.56 m/s, respectively. In the height range of 1.5 m to 12 m, the WS increases rapidly with the increasing height. Each 10 m of increase in height raises the WS by 1m/s. In the height range of 12 to 36 m, by contrast, the WS dwindles with the rising height. The WS decreases by 0.06 m/s for every 10 m of height increase. In the range of 36 to 100 m, the WS increases slowly with the height, and by 0.19 m/s every 10 m of increase in height.

It can be seen that the WS in the residential area below building heights are significantly lower than those in the park area. The mean WS measured below 35 m in the residential area and park are 1.2 m/s and 1.8 m/s, respectively. Residential buildings reduce WS by about 0.6 m/s.

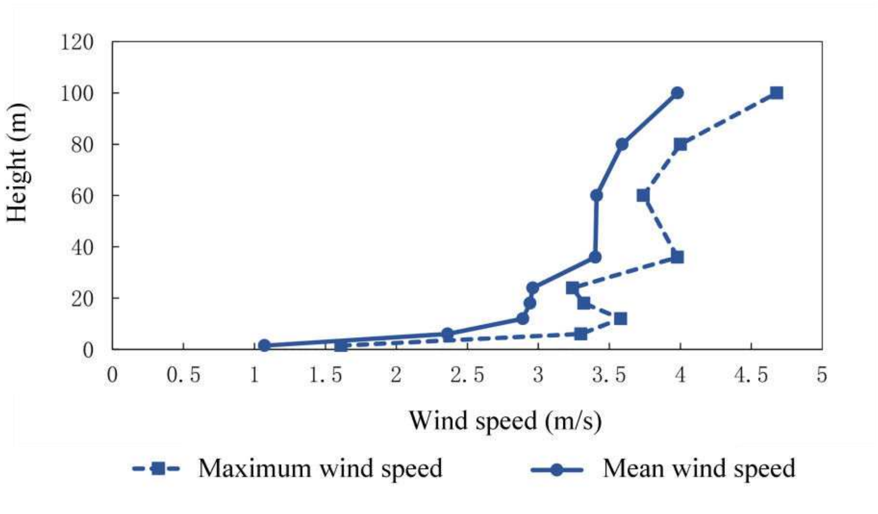

Figure 4 The WS at different heights in Zishui Park in Xi'an

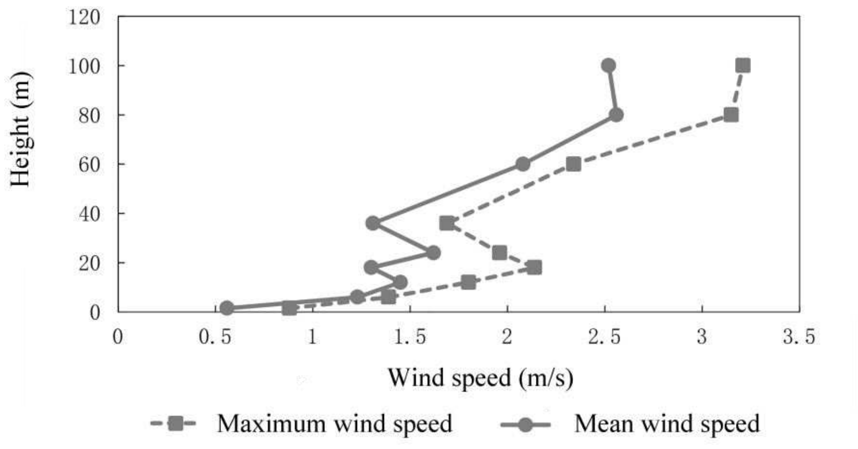

Figure 5 The WS at different heights at Shijiaxingcheng in Xi'an

3.2 Single factor correlation between vertical wind environment and morphological index

This part will further explore the influence of residential area form on the ventilation efficiency at the pedestrian level and in vertical direction, and summarize the reasons for the difference in vertical wind profile in the residential area through single factor analysis and multi-factor analysis. The results are divided into two parts: the WSR at the pedestrian level (1.5 m) and the vertical WSR at different heights.

3.2.1 Impact of ABH on WSR

1）Relationship between WSR and ABH at the pedestrian level

As shown in Figure 6, as the average height rises, the area of low WS region gradually increases. Specifically, when the average height is 10 m, the average horizontal WSR at the pedestrian level reaches the maximum of 0.609, and then decreases slowly with the increasing ABH. In addition, with the increase of the average height, the maximum WS increases slowly. When the average height is 60 m, the maximum WS reaches 5.87 m/s, and the minimum WS varies from 0.02 to 0.06, but its correlation with the average height is small. It can be seen that the ventilation efficiency at the pedestrian level dwindles with the increasing average height, which will lead to the occurrence of accelerated winds.

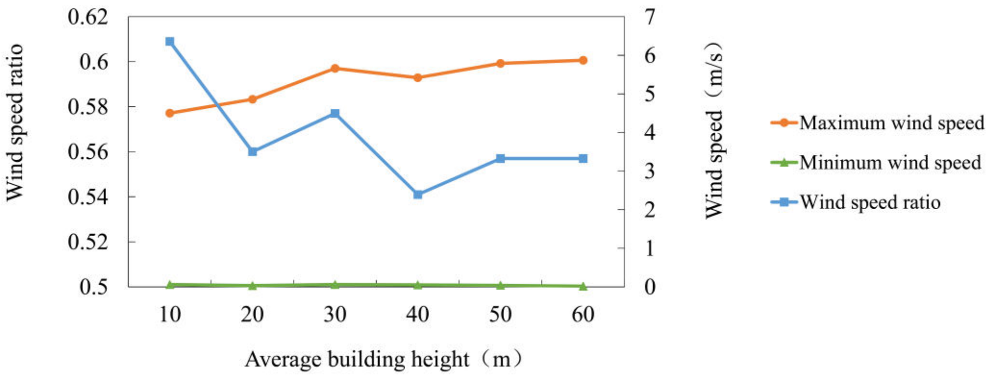

Figure 6 Correlation between mean WSR and ABH

2) Relationship between WSR and ABH at different height levels

As shown in Figure 7, the mean WSR at different horizontal heights increases with the rising height. This indicates that the built-up area obstructs the mean WSR to different degrees. At the same horizontal height, different ABHs have no obvious correlation with the mean WSR, but when the horizontal height is greater than 20 m, the average height exerts a growing attenuation effect on the mean WSR. In the vertical direction, the increase rate of the mean WSR increases with the rising height, showing a trend of first decreasing and then increasing. Specifically, when the mean WSR is below 0.65, the increase rate of the mean WSR gradually decreases with the increasing height, but after it reaches 0.65, the increase rate of the mean WSR gradually increases in different scenes.

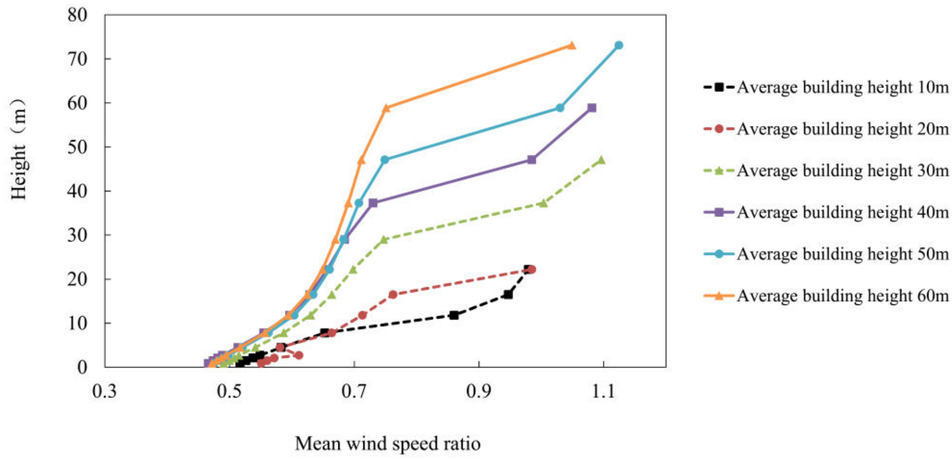

Figure 7 Correlation between the ABH and the mean WSR in the vertical direction

3.2.2 Impact of BD on WSR

1) Relationship between WSR and BD at the pedestrian level

As shown in Figure 8, with the increase of BD, the low WS area at the pedestrian height around the building gradually increases, and gradually approaches the static WS. Specifically, when the BD is 4.9%, the WSR of the average pedestrian height level is 0.592, which then dwindles with the increasing BD. Moreover, the maximum WS increases along with the BD. When the BD is 51.9%, the maximum WS reaches 5.92 m/s, and the minimum WS varies between 0.03 and 0.19, and they are not significantly correlated with the BD. It can be seen that the BD has a negative correlation with the WSR at the average pedestrian height and a positive one with the maximum WS. The increase in BD reduces the ventilation efficiency at the pedestrian height level, and leads to greater WS.

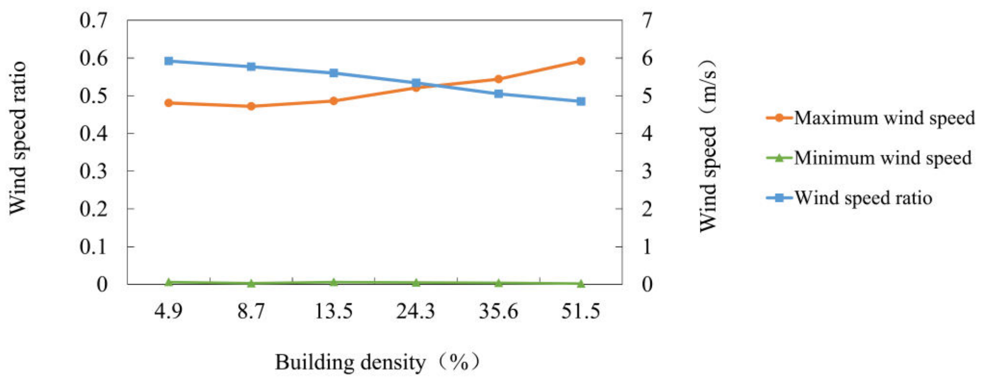

Figure 8 Correlation between the mean WSR at the pedestrian level and BD

2) Relationship between WSR and BD at different height levels

It can be seen form Figure 9 that the mean WSR at different horizontal heights increases with the increasing height. At the same horizontal height, the increase rate of the mean WSR below height of 20 m decreases with the rising BD because the building height is 20 m. Below 20 m, owing to the obstruction of the buildings, the smaller the mean WSR and the denser the built-up area, the greater the obstruction to the wind. When the vertical height is greater than 20 m, the increase rate of the mean WSR has little correlation with the increasing

BD, but in the case of a BD of 51.9%, the increase rate of the mean WSR is the largest. For every 1 m increase in the vertical height, the mean WSR rises by 0.17.

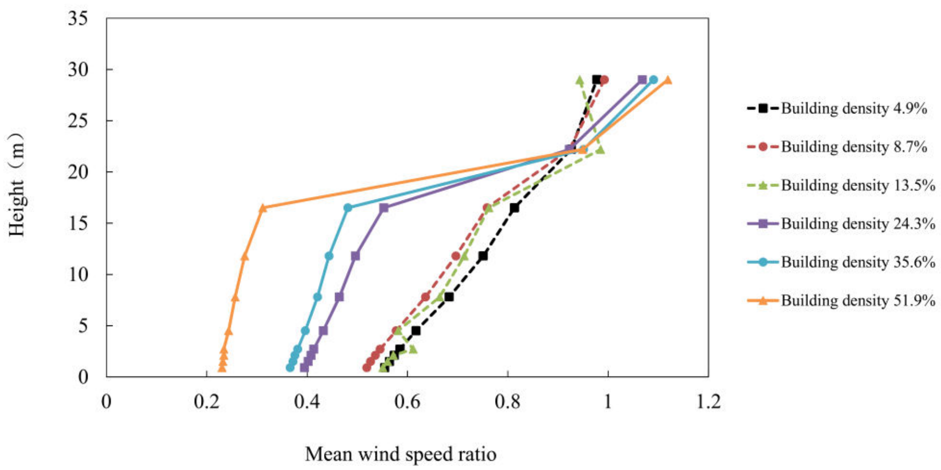

Figure 9 Variation curve between different BD and mean WSR in the vertical direction

3.2.3 Impact of FAR on WSR

1) Relationship between WSR and FAR at the pedestrian level

As shown in Figure 10, when the FAR is 0.403, the mean WSR at the pedestrian level reaches the maximum of 0.609, and then decreases slowly as the FAR increases. The maximum WS rises with the increasing FAR. When the FAR is 2.684, the maximum WS is 5.87 m/s, and the minimum WS changes between 0.02 and 0.06. Furthermore, with the increase of FAR, the mean WSR at the pedestrian height level gradually declines, which will lead to greater WS.

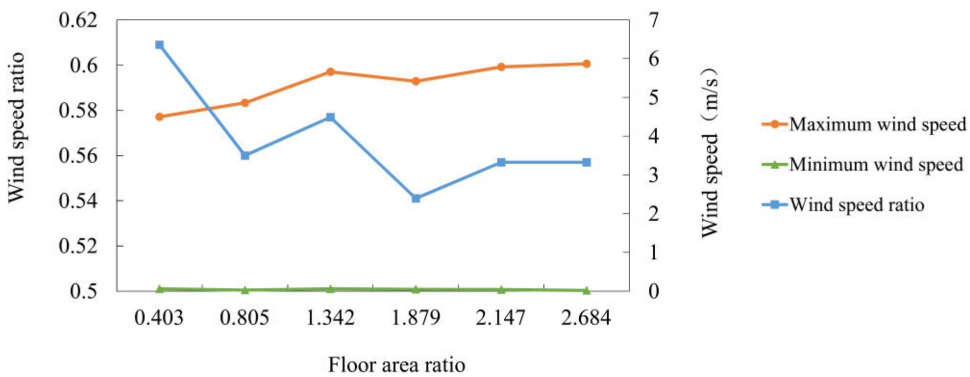

Figure 10 Correlation between mean WSR at the pedestrian level and FAR

2) Relationship between WSR and FAR at different height levels

As shown in Figure 11, the mean WSR increases along with the vertical height, which indicates that the built-up area on the surface hinders the WS. On the one hand, at the same height level, the correlation between different FARs and the mean WSR is slight. On the other hand, the mean WSR decreases first and then increases with the change of height. When the mean WSR is below 0.7, the increase rate of the mean WSR decreases with the rising height. But after the mean WSR reaches 0.7, the increase rate of the mean WSR in different FAR scenarios rises gradually with the vertical height.

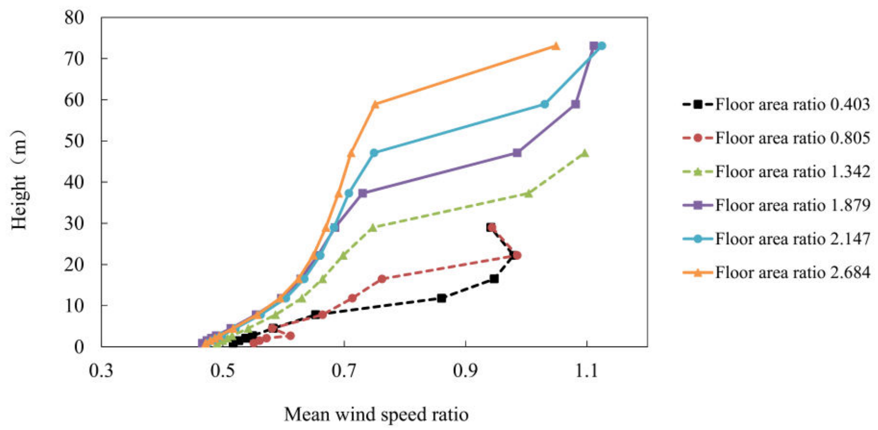

Figure 11 Correlation between the change of FAR with the average height and the mean WSR

3.2.4 Impact of ED on WSR

1) The relationship between mean WSR and the ED at the pedestrian level

As shown in Figure 12, as the ED rises, the area of low WS in the center of the site increases gradually. Specifically, when the closure is 0.092, the mean WSR is 0.630, which then dwindles with the increasing ED. In addition, when the ED is 0.378, the maximum WS drops to the minimum of 5.74 m/s, and the minimum WS ranges between 0.03 and 0.05. Furthermore, the ED is negatively correlated with the mean WSR at the pedestrian level, which indicates that the increase in the ED will reduce the ventilation performance at the pedestrian height level in the residential area.

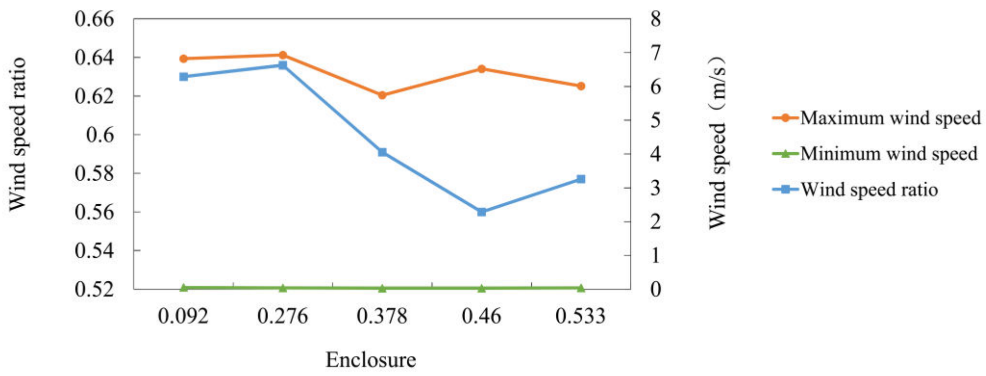

Figure 12 Correlation between the mean pedestrian level WSR and ED

2) Relationship between WSR and ED at different height levels

It can be seen from Figure 13 that the mean WSR of each scene increases along with the vertical height. When the vertical height is smaller than 30 m, at the same horizontal height, the larger the ED, the smaller the mean WSR. In the vertical direction, the increase rate of the mean WSR declines with the increasing ED. The increase rate of the mean WSR is the largest at the ED of 0.092. When the vertical height increases by 1 m, the increase rate of the mean WSR is about 0.0104 and it is the smallest when the ED is 0.533. Every 1 m increase in the vertical height raises the mean WSR by about 0.00775. Under 30 m, the larger the ED, the greater the wind blocking effect of the scene. The increase in ED will lead to a general reduction in the ventilation efficiency around residential buildings.

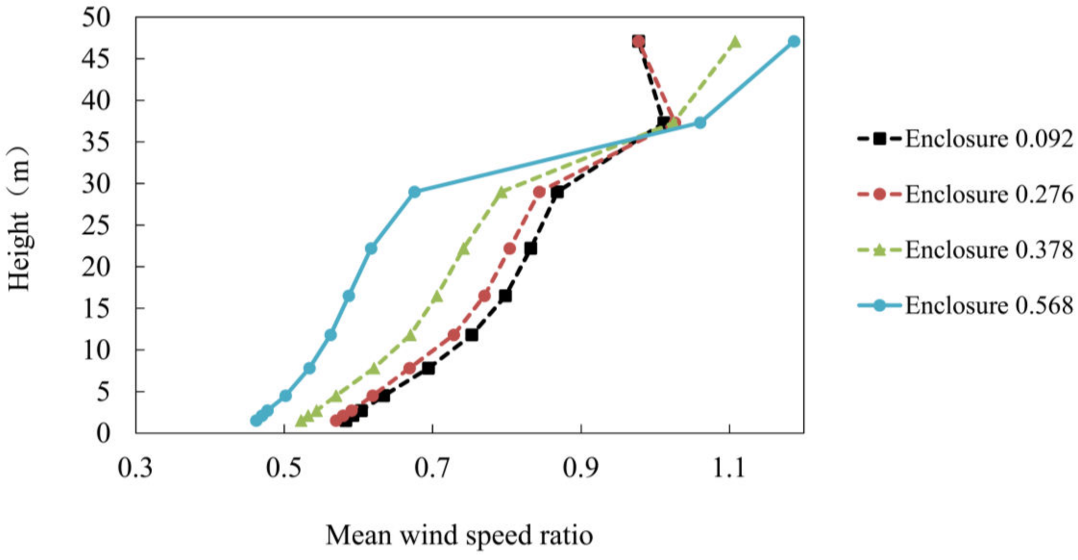

Figure 13 Correlation between the mean WSR and different EDs in the vertical direction

3.2.5 Impact of HF on WSR

1) Relationship between the mean WSR and HF at the pedestrian level

As shown in Figure 14, mean WSR decreases with the rising HF at the pedestrian level. When the HF is 10, the ratio of mean WS at the pedestrian height level is 0.560, which then decreases slowly with the increasing HF. The maximum WS increases slowly with the rising HF. When the HF is 70, the maximum WS reaches the maximum of 5.57 m/s, and the minimum WS always ranges between 0.03 and 0.09, showing a descending trend. It can be seen that the HF has a negative correlation with the mean WSR at the pedestrian level and the minimum WS of the site, and a positive relationship with the maximum WS of the site. It shows that the construction of high-rise residential buildings will reduce the ventilation efficiency at the pedestrian level, and result in high WS.

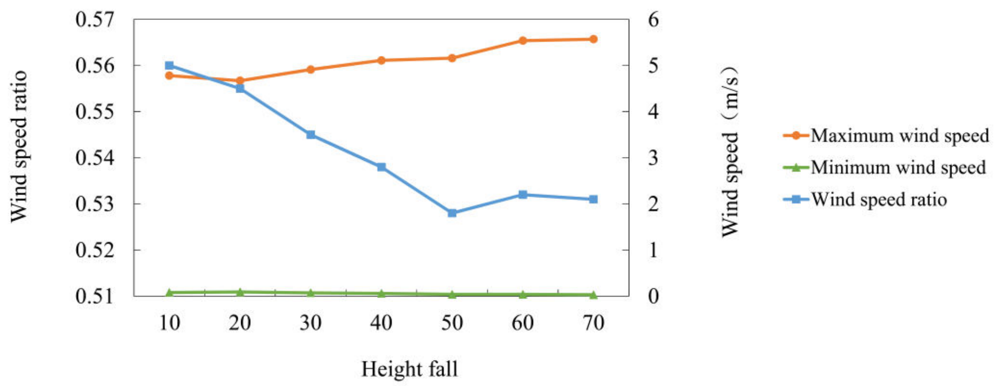

Figure 14 Correlation between the mean WSR at the pedestrian level and HF

2) Relationship between vertical WSR and HF

Figure 15 shows that the mean WSR of each scene increases with the rising vertical height, except for the scene with a HF of 10 m. When the vertical height is below 20 m, the correlation between different HF and the mean WSR at the same horizontal height is weak. For every 1 m increase in vertical height, the mean WSR corresponding to different HF increases by about 0.018. When the vertical height is greater than 20 m, the increase in the HF will cause a reduction in the mean WSR. When the HF is 70, the increase rate of the mean WSR is the largest. Each 1 m increase in the vertical height will lead to an increase of 0.0027 in the mean WSR. The possible reason is that the wind is hindered by four high-rise buildings. It is thus can be concluded that the variation of the HF impacts the mean WSR mostly in the area above the average height of the site. The larger the HF, the more obvious the blocking effect of high-rise buildings on the wind.

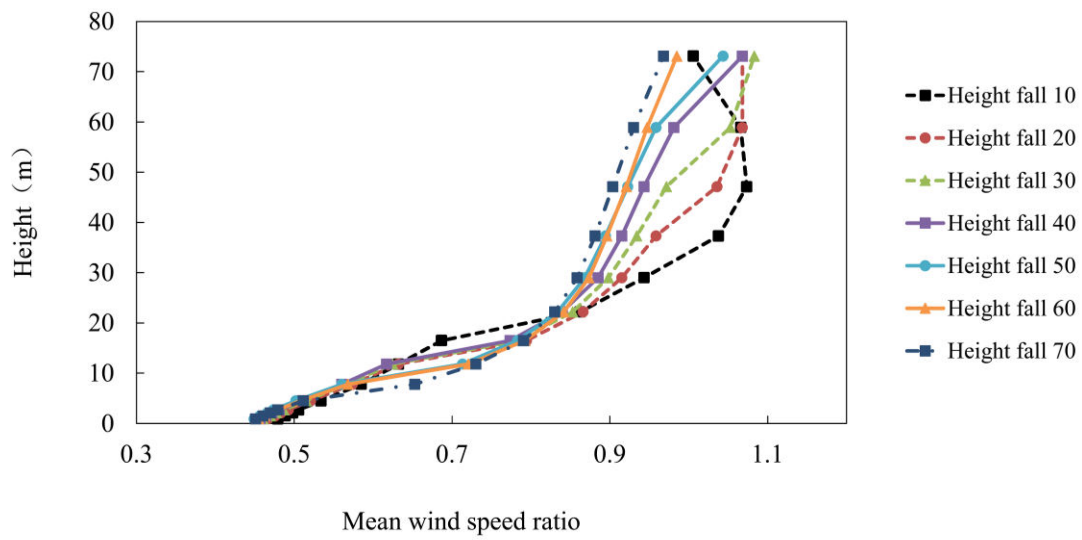

Figure 15 Correlation between the mean WSR and different HF in the vertical direction

3.2.6 Impact of MBH on WSR

1) Relationship between mean WSR and MBH at the pedestrian level

It can be seen from Figure 16 that with the increasing MBH, the area of the low WS region gradually increases, and so does the area affected by the high speed winds around the highest building. Specifically, when the MBH is 30 m, the mean WSR at the pedestrian level is 0.560, which then dwindles with the rising maximum height. The maximum WS first decreases from 4.71 to 4.42 m/s, then slowly to 4.97 m/s, during which the minimum WS varies from 0.03 to 0.08. Conclusions can thus be drawn that the MBH has a negative correlation with the mean WSR at the pedestrian level, while has little correlation with the maximum WS or the minimum WS.

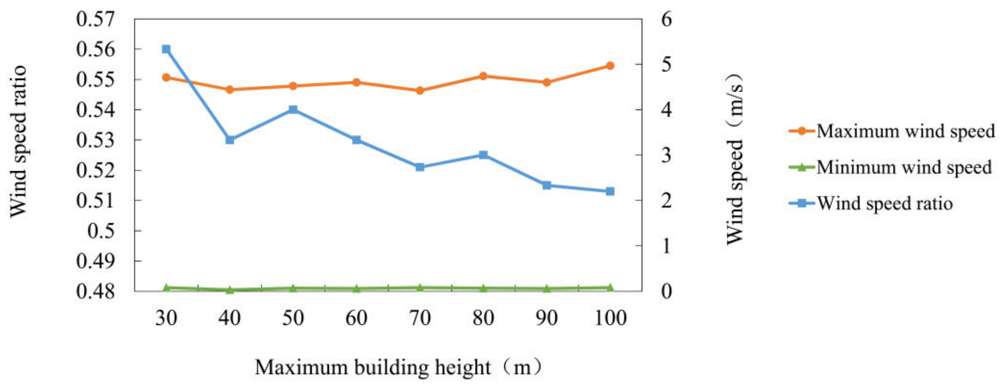

Figure 16 Correlation between the mean WSR at the pedestrian level and MBH

2) Relationship between WSR and MBH at different height levels

Figure 17 shows that, in general, the mean WSR of each scene increases along with the vertical height, and the correlation between the maximum height and the mean WSR is weak at any horizontal height. When the vertical height is below 20 m, the increase rate of the mean WSR in different scenes tends to be equal. For every 1 m increase in the vertical height, the mean WSR of each scene increases by about 0.014. When the maximum height is 100 m, the mean WSR is relatively large. When the vertical height is above 20 m, the correlation of the maximum height with the mean WSR is weak. When the maximum height is 80 m, the increase rate of the mean WSR is the lowest. Every 1 m increase in vertical height raises the mean WSR by about 0.012. Thus, there is no significant correlation between the maximum height and the mean WSR, and the ABH of the site is the dividing line that affects the change rate of the mean WSR in the vertical direction.

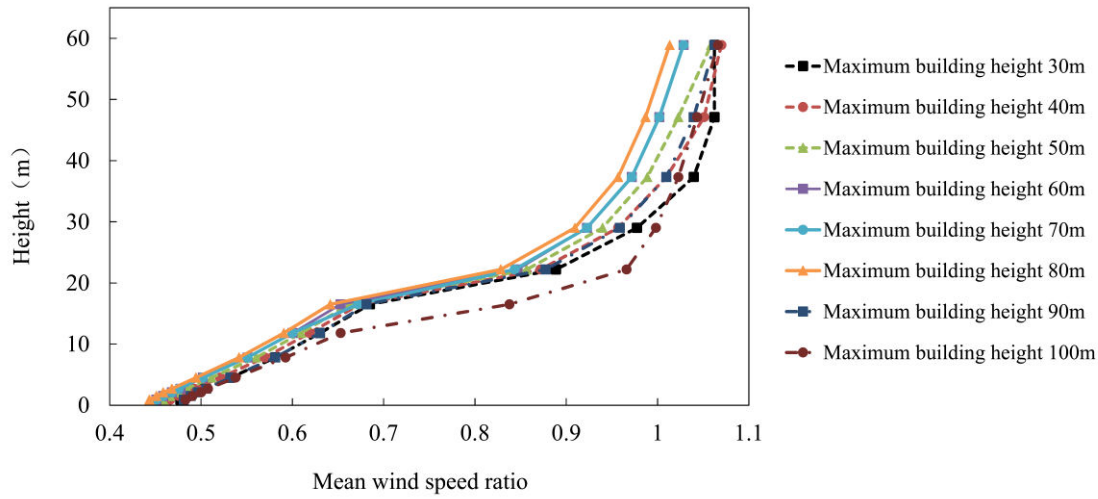

Figure 17 Correlation between the MBH and the mean WSR of different sites in the vertical direction

3.3 Multi-factor correlation between vertical wind environment and morphological index

The single factor analysis of wind environment in residential area is insufficient. Therefore, based on the previous sections, the prediction formulas for the mean WSR at the pedestrian level and vertical wind environment are established respectively.

1) Multiple linear regression formula for WSR at the pedestrian level

The results of the 37 scenarios simulated aboves are integrated (According to Table 2), and the regression equation of the average pedestrian horizontal mean WSR is obtained through SPSS software. Due to the differences in the order of magnitude and unit of each index, the following regression equation and R^2 are finally obtained by standardizing the data:

$$\mathrm{U1} = 0.42\mathrm{FAR} - 0.269\mathrm{E} - 1.96\mathrm{ABH} - 0.72\mathrm{BD} - 4.186\mathrm{HF} + 3.467\mathrm{MBH}\ (\mathrm{R}^2 = 0.855) \quad (1)$$

In formula (1), U1 is the mean WSR at the pedestrian level in the residential area under the specific form combination, ABH is the ABH, FAR denotes the FAR, BD is the BD, E is the ED of the residential area, HF is the HF, and MBH is the MBH. It can be seen that R^2 is 0.855, indicating that the sample regression effect is good; F test statistic $f = 28.565$, and associated probability $p < 0.001$, which indicates that there is a linear regression relationship between the independent variable and the dependent variable; the independent variables with an associated probability p below 0.05 include average height ($P < 0.013$), BD ($P < 0.001$), HF ($P < 0.005$) and maximum height ($P < 0.015$). This implies that the WSR at the pedestrian level has a significant linear relationship with the average height, BD, HF and the maximum height. The influence degree of each index in descending order is as follows: the HF > the MBH > the ABH > the BD > the FAR >the ED.

2) Multiple linear regression formula for vertical WSR prediction

The simulation results of the above 381 scenarios are taken as the basic data and standardized to obtain the following regression equation and R^2:

$$U2 = 0.883VH - 0.252ABH - 0.112FAR - 0.07BD - 0.036E - 0.637HF + 0.519MBH (R^2 = 0.801) \quad (2)$$

In formula (2), U2 is the mean WSR at any horizontal height in the residential area under the specific combination of forms, VH is the vertical height. It can be seen that the coefficient R^2 is 0.801, which indicates that the regression effect of the sample is good; the statistic of F test is $f = 212.42$, and the associated probability is $p < 0.001$, indicating that there is a linear regression relationship between the independent variable and the dependent variable. Furthermore, the vertical height ($P < 0.001$) is the only the independent variable with an associated probability (p) of below 0.05, which indicates that there is a significant linear relationship between the vertical height and the WSR of any horizontal plane. The relationship between other building shape indexes and vertical WSR is insignificant. The influence degree of each index in decreasing order is: VH > HF > MBH > ABH > FAR > BD > ED.

4. Discussions

This paper aims to establish the relationship between ventilation efficiency and building morphology of residential area. The following will be further discussed in combination with relevant research.

The present study shows that, the mean WSR at the pedestrian height level has a significant linear correlation with the average height, BD, HF and the MBH. Some scholars also studied the relationship between the WSR at the pedestrian level and building morphology. Kubota, in a wind tunnel experimental study on the relationship between WS and BD in Japanese detached houses, concluded that the higher the BD, the smaller the mean WSR (M. M. Kubota T, Tominaga Y, et al, 2008). As in the case study of Feng et al., the WSR at the pedestrian level is negatively correlated with the average height (Feng W, 2020). Yang et al. found that the increase in ED is not conducive to the diffusion of air pollutants in the built-up area (Yang J, 2020). The results of this paper also demonstrate that the increase in ED will reduce the ventilation efficiency of residential area, which is not conducive to the air circulation in residential area or blocks. Yang et al. simulated the summer monsoon environment in Xinjiekou area of Nanjing, and through multiple linear regression analysis, found that the WSR at the pedestrian level has a negative correlation with BD and ED, but a significant, positive linear correlation with average height (Yang, 2016). Nonetheless, the results of this study show that the mean WSR at the pedestrian level will decrease the increasing average height because of the blocking of wind by the buildings. This may be ascribed to the different building geometries, building densities, building intervals, WS and directions adopted in Yang’s simulation and this study. Adamek et al. pointed out that the presence of high-rise buildings in urban space will increase the near-surface WS (Adamek K, 2017). It can be concluded that the WSR at the pedestrian height level is negatively correlated with the BD, the average height and the ED, yet positively related to the MBH. In practice, planners and designers can refer to these research results to improve the safety and comfort of the wind environment in residential areas.

In terms of the vertical wind profile, the single factor analysis results show that the increase in each single indicator of building morphology will lead to the reduction in ventilation efficiency. The results of multi-factor analysis demonstrate that the mean WSR has a significant positive correlation with the vertical height, and an insignificant linear relationship with other building morphology indicators. The relevant studies focus mostly on the scale of city. The research results of Liu et al. proved that the wind profiles in urban center and rural area are quite different, and so are the degrees to which WS increases with the height from the ground (Liu, 2011). Grimmond and Oke et al. reported that the horizontal component of wind profile becomes smaller due to the blocking of urban built-up area

(Grimmond C S B, 1999). In the present study, by observing the shape of the wind profile, it can be seen that the wind in the area with buildings is greatly blocked and the ventilation efficiency is reduced, while the WS in the area without buildings is significantly increased. Yuan et al. studied the ways to improve the ventilation in high-density cities, and by comparing the differences in vertical wind profiles, proposed a strategy to improve the ventilation at the pedestrian level by separating single buildings and reducing the overall building coverage of the site. This strategy is consistent with the principle of reducing the BD and ED of residential area in this paper, because the increase in these two indicators will reduce the WSR at any height level (N. E. Yuan C, Norford L K, 2012). To sum up, the existence of urban built-up area inevitably reduces the near-surface ventilation efficiency. In response to this, planners and architects need to fully consider the regional meteorological conditions and building morphology.

5. Conclusions

Based on one typical determinant residential area, the present paper, through field measurement and numerical simulation method, discusses the influencing factors of the ventilation efficiency at different height levels in the residential area. The main conclusions are as follows:

1) The mean WS measured below 35 m in residential area and park are 1.2 m/s and 1.8 m/s, respectively. Residential buildings reduce WS by about 0.6 m/s. This shows that the presence of residential buildings greatly reduces the inflow of wind. Thus, is particularly important to optimize the layout of residential buildings to let more winds in.

2) The results of single factor analysis show that the mean WSR at the pedestrian height level has a negative correlation with each of the indicators studied.

3) The results of multi-factor analysis show that the ventilation performance at different heights is positively related to the building height and the MBH. The HF has the greatest influence on the WSR at all heights in the residential area. This indicates that to improve the ventilation efficiency among buildings, the height difference should be minimized.

4) The research can provide data support for the establishment and improvement of wind

environment standards in residential areas, and provide a reference method for optimizing the ventilation efficiency in different regions, especially in static wind areas

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Author contributions Wei Feng and Meng Zhen designed the experiments, Qishu Zou carried out field measurement, Wei Ding ran simulations, analyzed the results, and wrote the manuscript. The authors read and approved the final manuscript.

6. Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication All the authors have read and approved the manuscript for publication.

Competing interests The authors declare no competing interests.

Data availability Data will be sent based on request.

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Figures

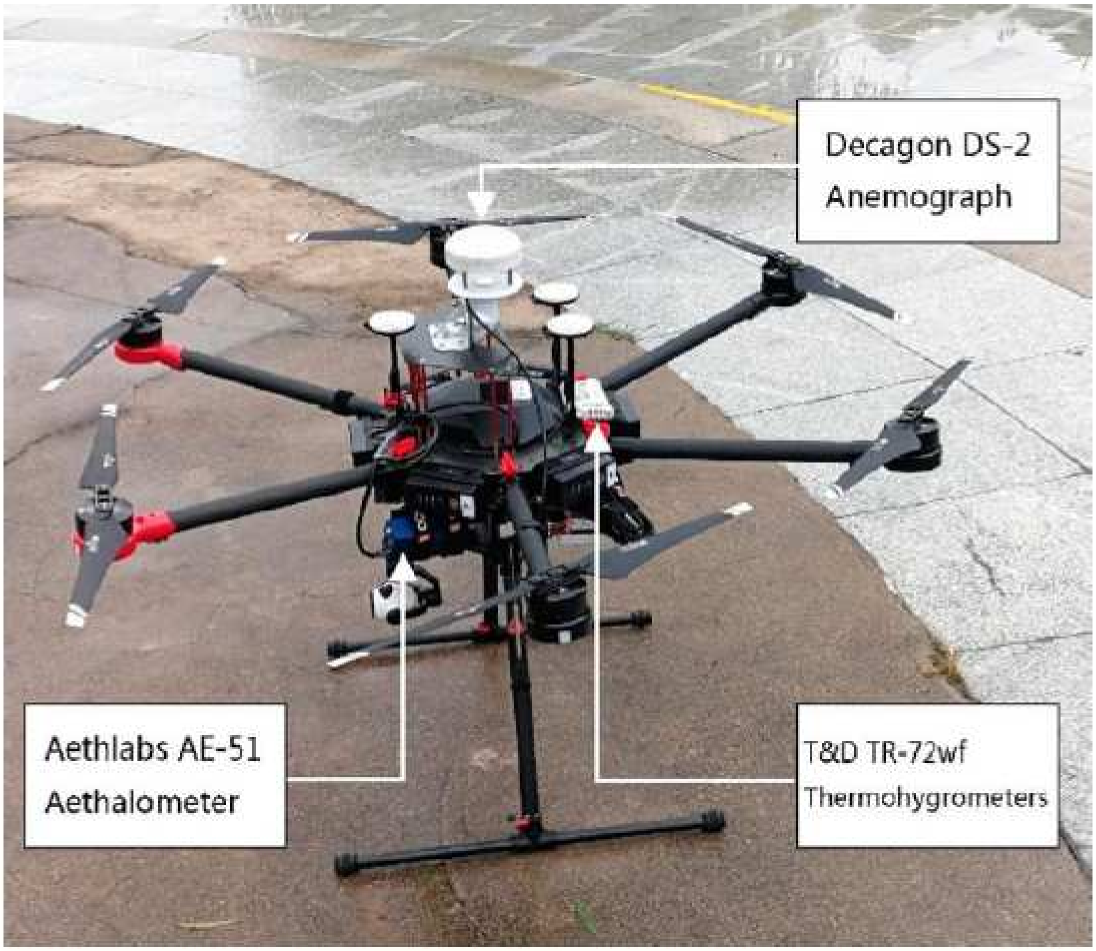

Figure 1

UAV and test equipment (Zhen M, 2019)

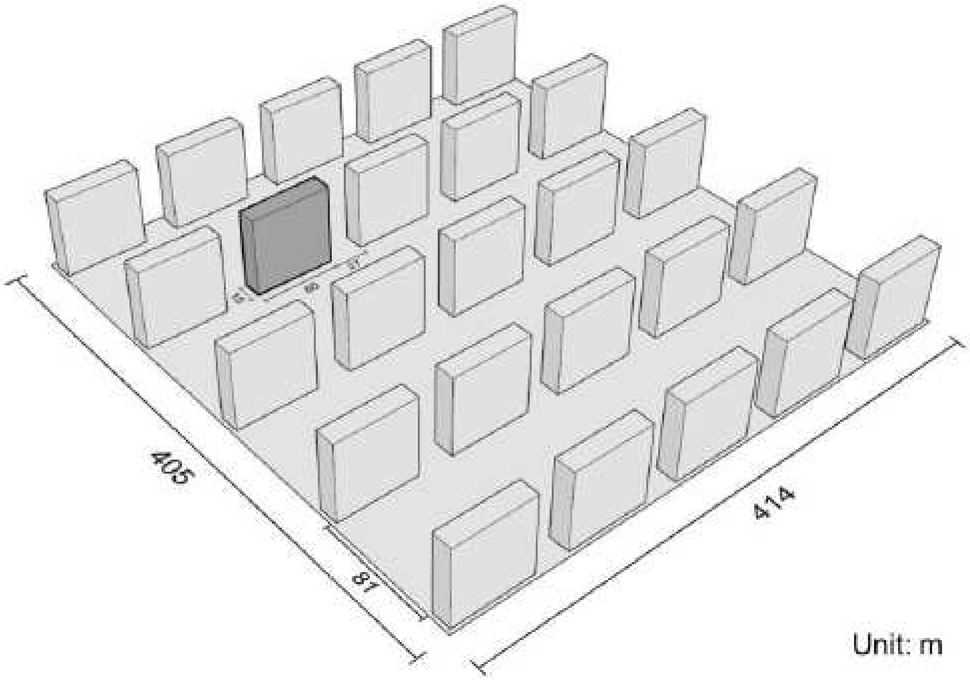

Figure 2

Basic model

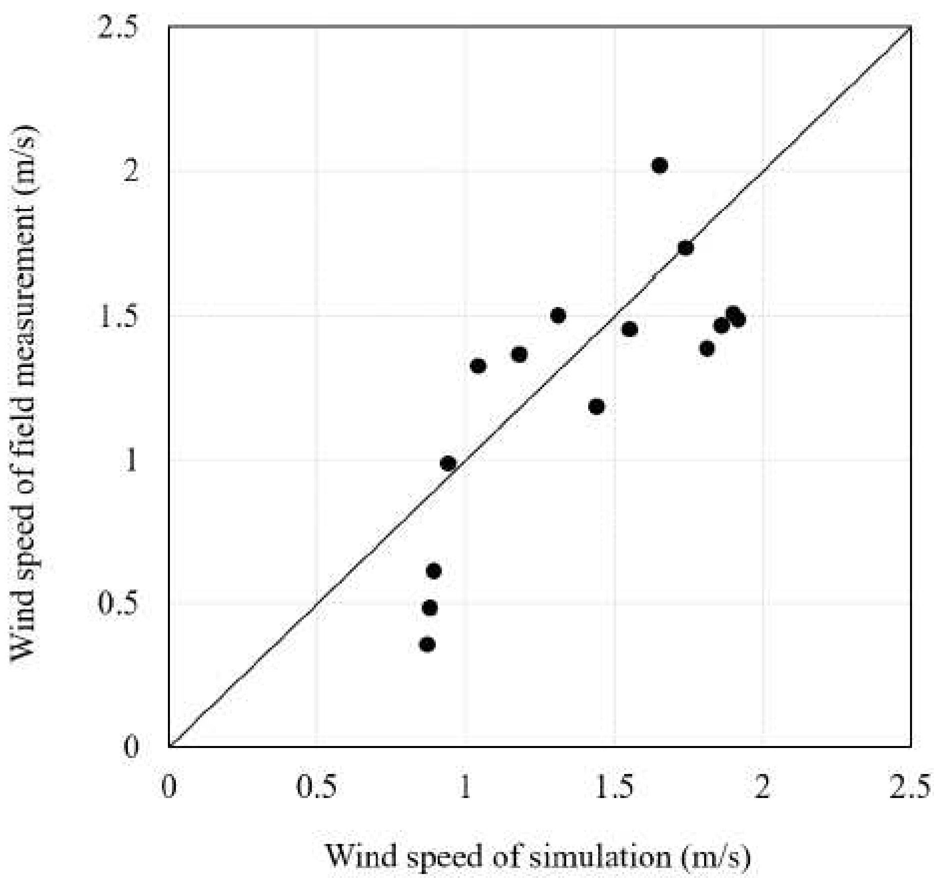

Figure 3

Correlation between measured and simulated results of vertical WS

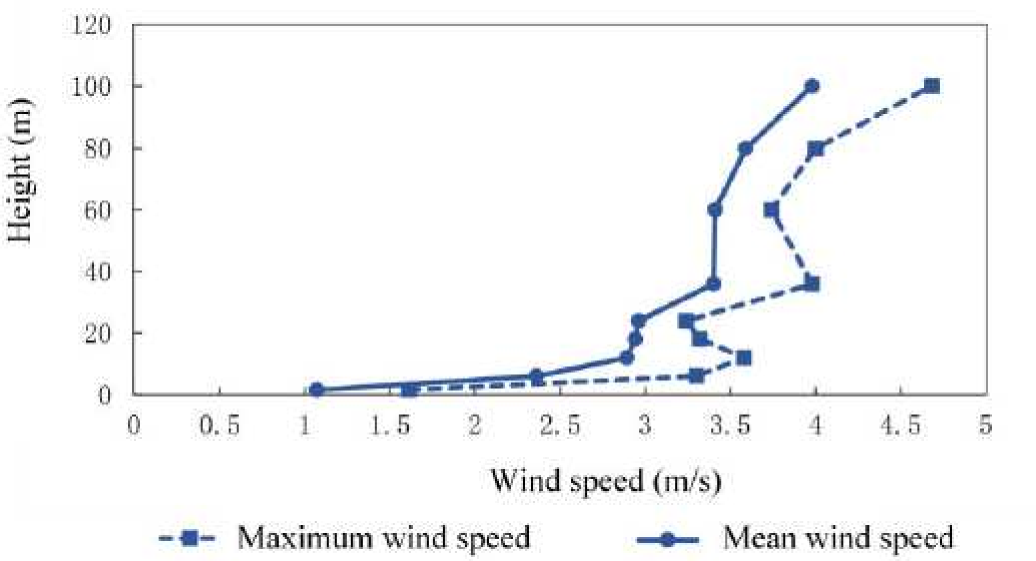

Figure 4

The WS at different heights in Zishui Park in Xi’an

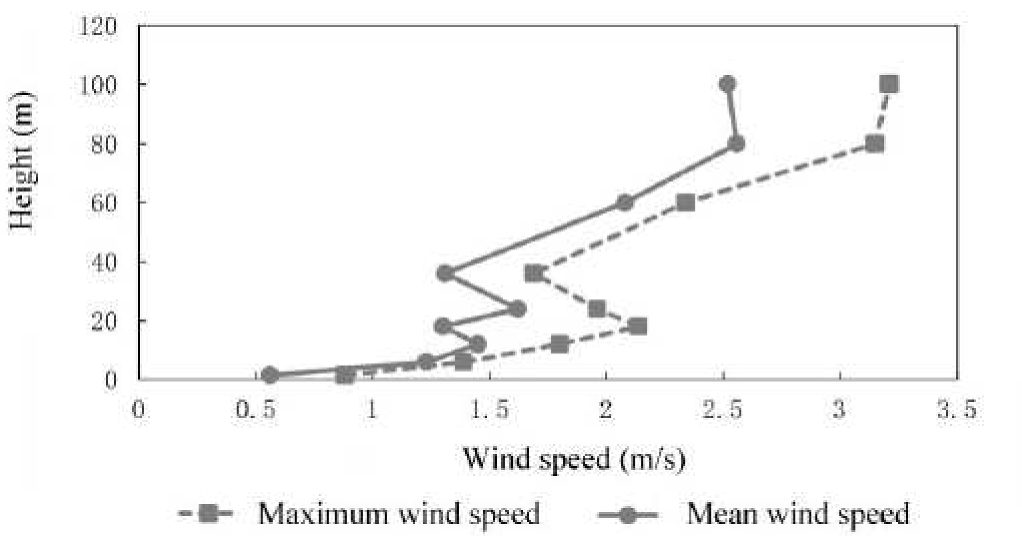

Figure 5

The WS at different heights at Shijiaxingcheng in Xi’an

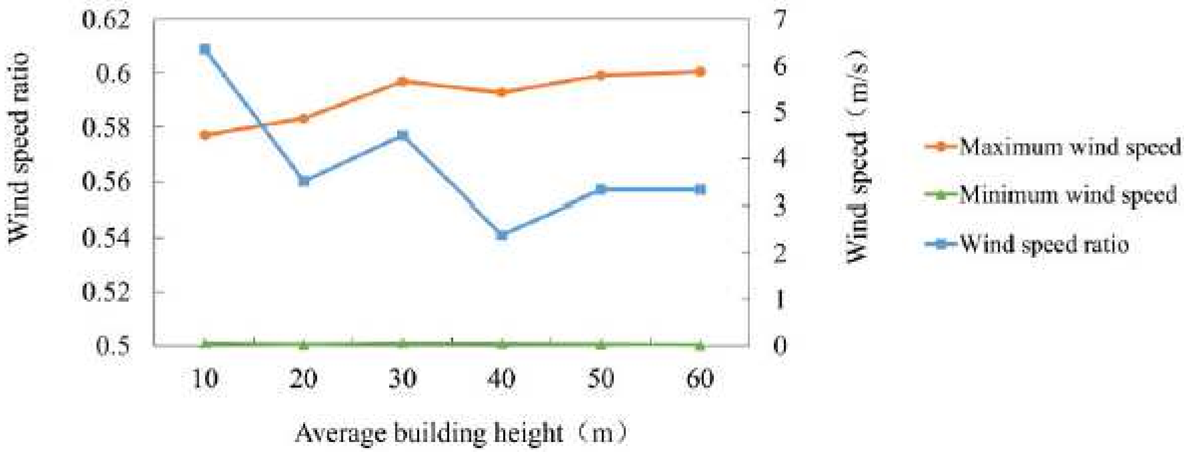

Figure 6

Correlation between mean WSR and ABH

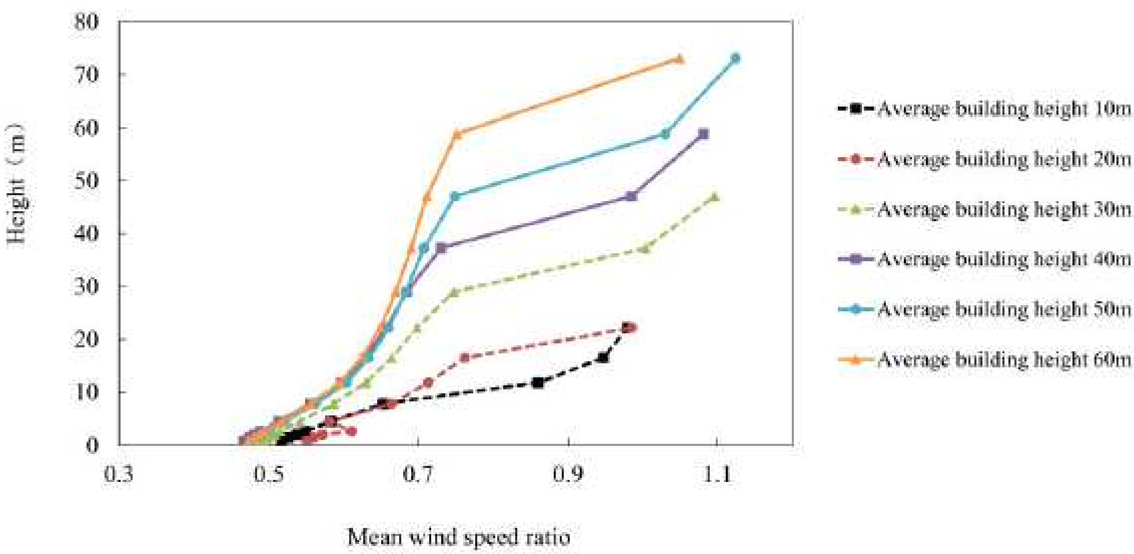

Figure 7

Correlation between the ABH and the mean WSR in the vertical direction

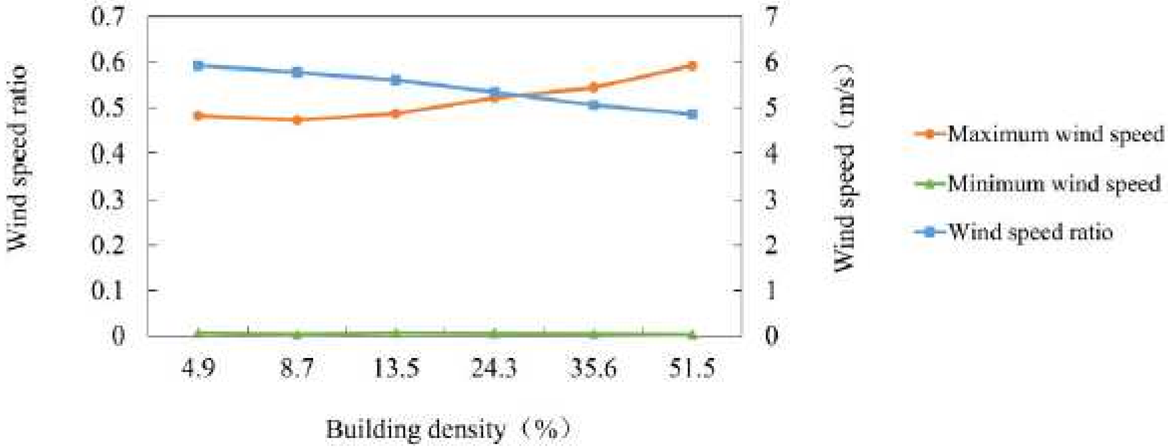

Figure 8

Correlation between the mean WSR at the pedestrian level and BD

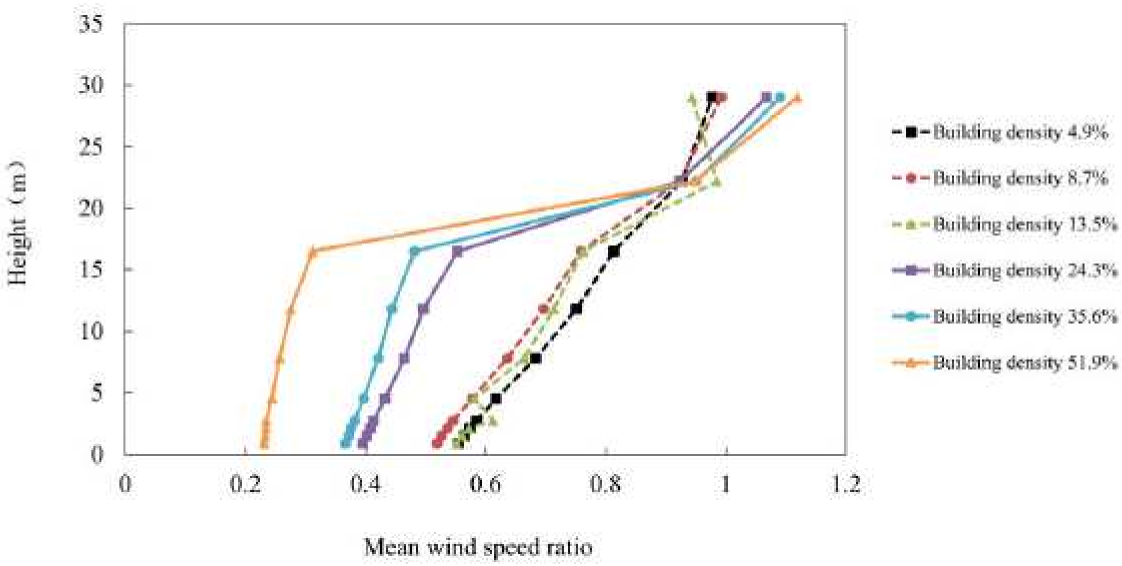

Figure 9

Variation curve between different BD and mean WSR in the vertical direction

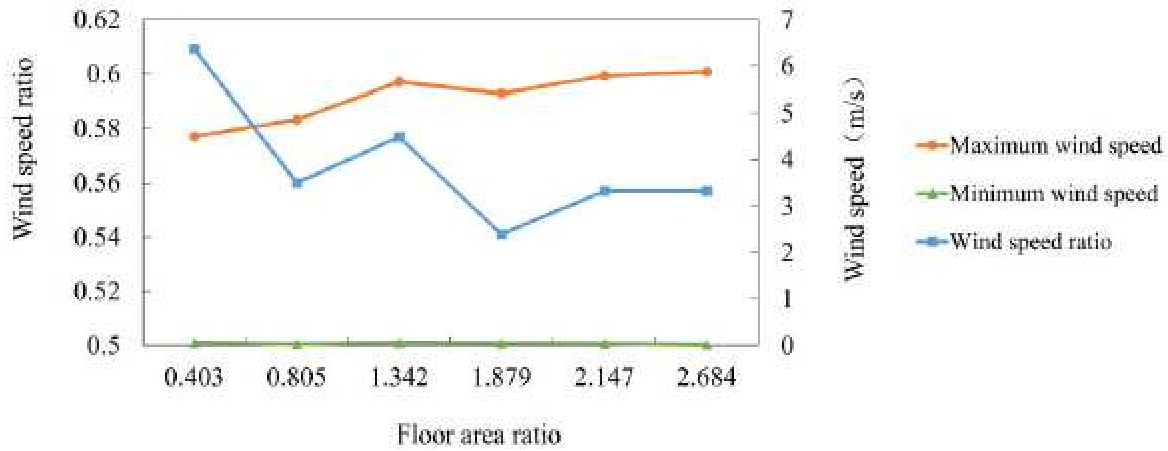

Figure 10

Correlation between mean WSR at the pedestrian level and FAR

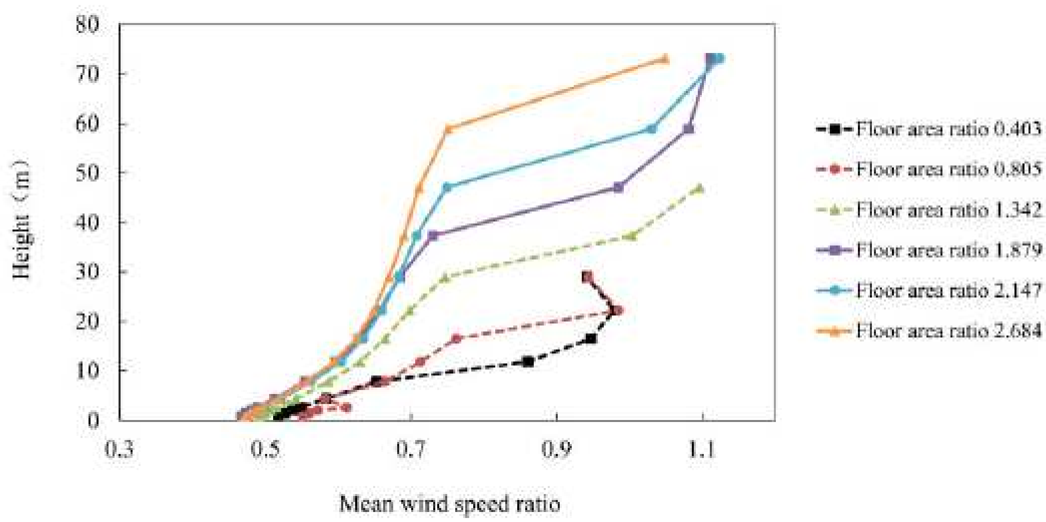

Figure 11

Correlation between the change of FAR with the average height and the mean WSR

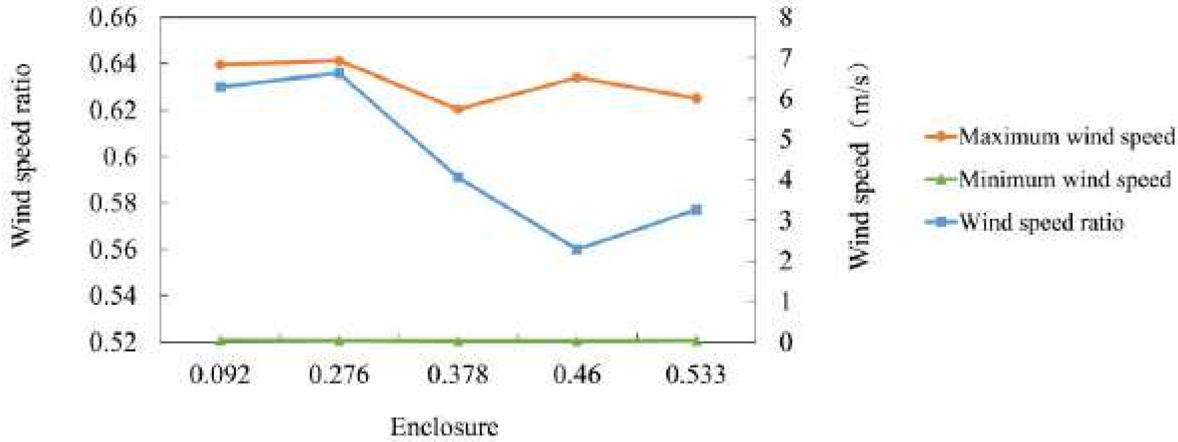

Figure 12

Correlation between the mean pedestrian level WSR and ED

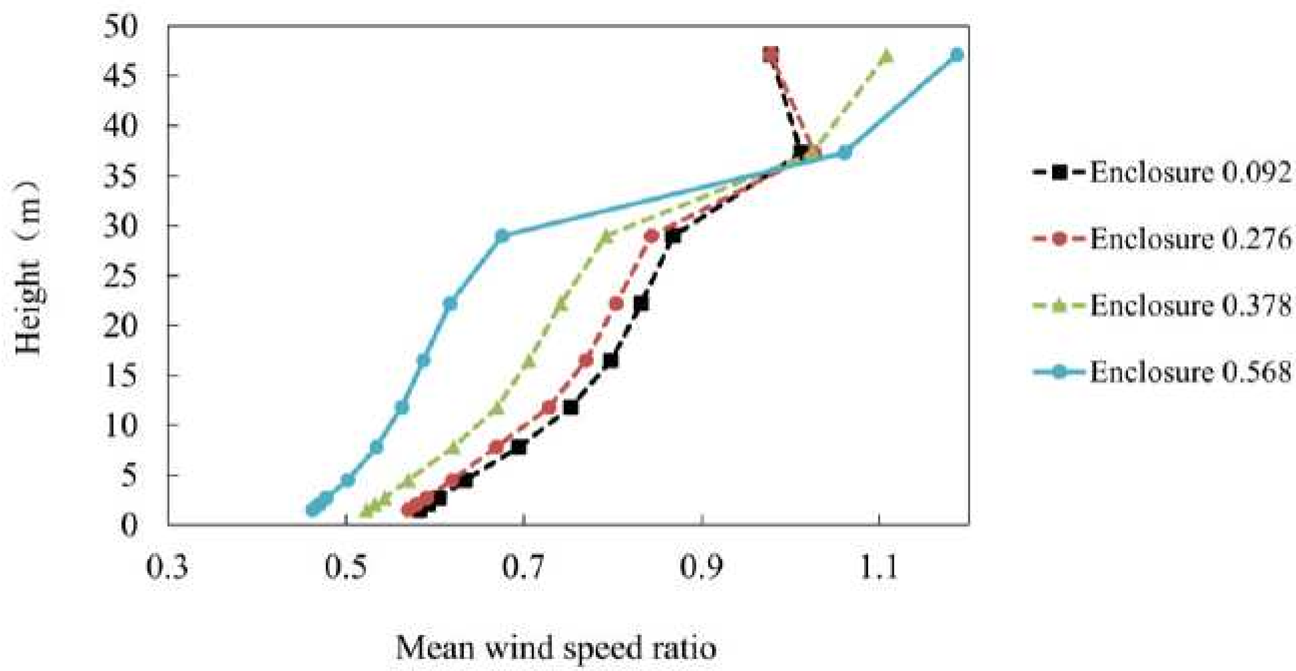

Figure 13

Correlation between the mean WSR and different EDs in the vertical direction

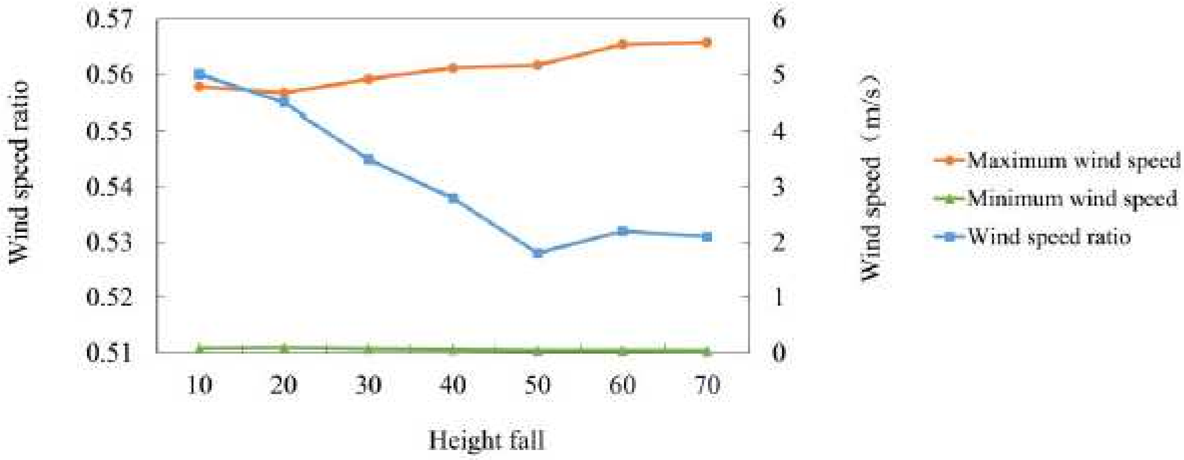

Figure 14

Correlation between the mean WSR at the pedestrian level and HF

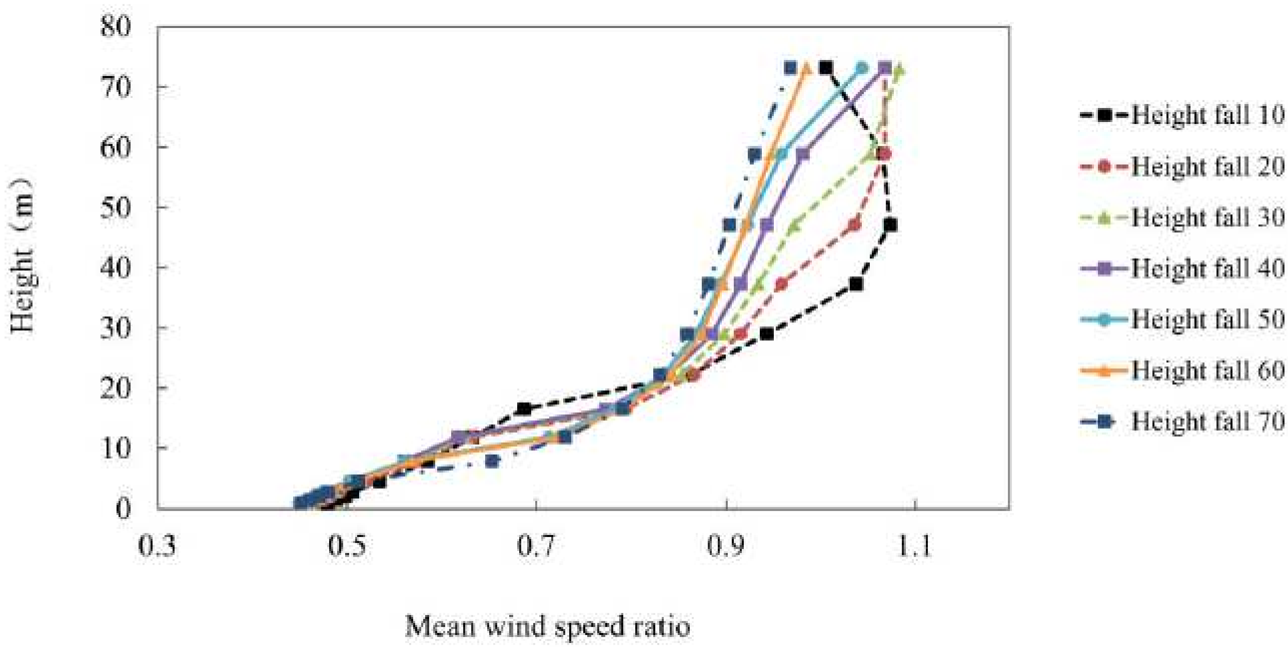

Figure 15

Correlation between the mean WSR and different HF in the vertical direction

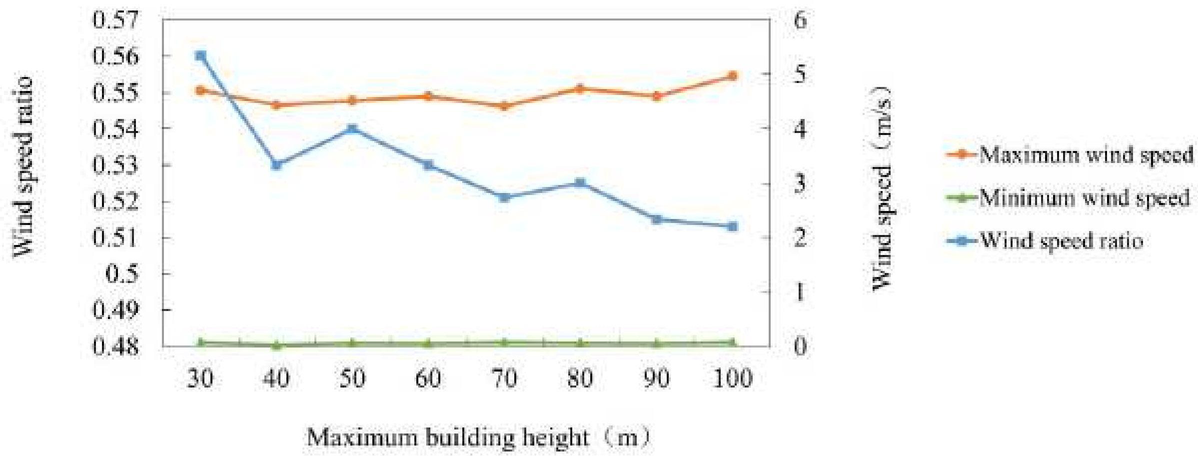

Figure 16

Correlation between the mean WSR at the pedestrian level and MBH

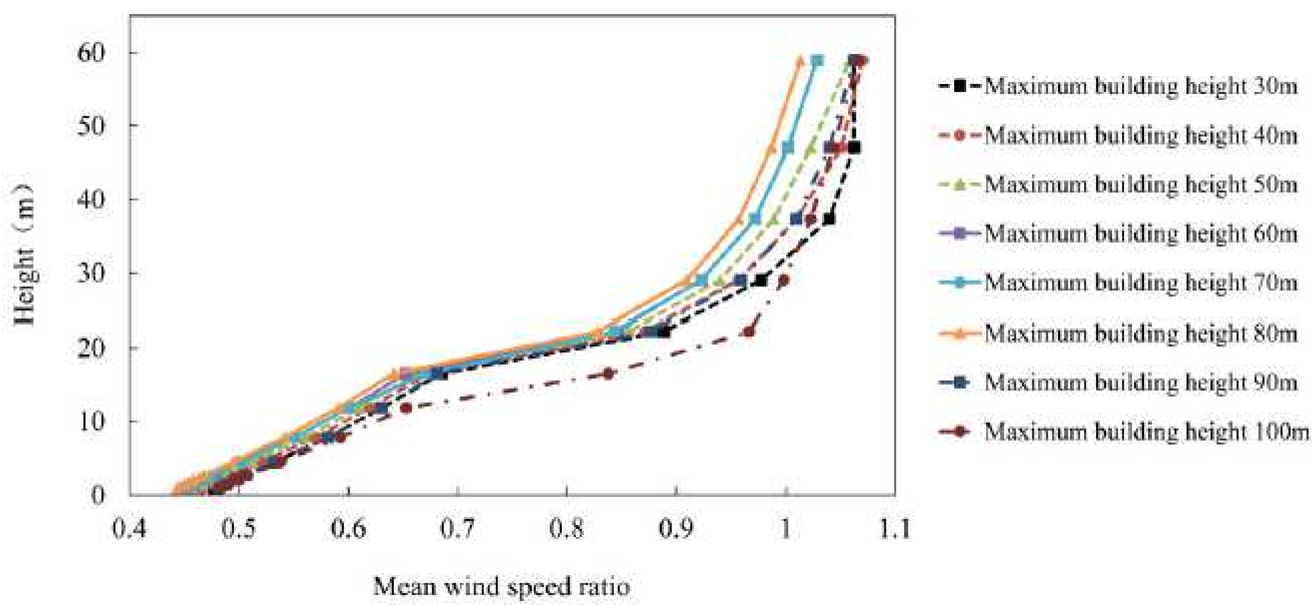

Figure 17

Correlation between the MBH and the mean WSR of different sites in the vertical direction