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The Coupling Relationship between Building Morphology and Outdoor Wind Environment in the High-Rise Dormitory Area in China

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Abstract: A good outdoor wind environment can guarantee the safety and comfort of student activities. It is also conducive to building energy-saving and low-carbon goals. In this study, the high-rise dormitory area of a university was selected as a research object in the cold region. The study used a combination of numerical simulation and orthogonal tests to analyze the weighting of the influencing factors of the wind environment and to recommend the optimal design scheme. The results indicated that the building layout, building length, width, and height all had different degrees of influence on the outdoor wind environment of the dormitory area. For the slab-type high-rise dormitory, the influence weight of the layout was the strongest, followed by the building height, the width, and, finally, the length. The optimal scheme is a staggered layout with a building length of 50 m, width of 18 m, and height of 85.2 m. The wind environment in this situation performed well in winter and summer. For the tower-type high-rise dormitory, the influence weight of the building height was the greatest, followed by the width, the length, and then the layout. The optimal scheme is a staggered layout with a building length of 26 m, width of 24 m, and height of 85.2 m. The wind environment in this situation performed well. Overall, the study scrutinized the coupling relationship between building morphology and wind environment from the meso-level perspective. At the micro level, we constructed the design method for the dormitory building morphology by considering the wind environment performance as the target. It can assist designers in making decisions during the planning and design phases of project construction to facilitate the positive design of buildings.

Keywords: high-rise dormitory area; building morphology; outdoor wind environment; numerical simulation; orthogonal experimental design

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1. Introduction

In recent years, the scale of Chinese universities has been expanding and the construction of campuses continues to advance. To improve land utilization, buildings of university dormitories gradually change from traditional multi-story to high-rise. The dormitory area has rich and diverse building morphologies, and the overall layout is more concentrated compared to other building types. This feature causes some dormitory areas to encounter many problems, such as poor ventilation, accumulation of pollutants, and stifling heat in summer. When the layout of the building group is inappropriate, airflow confusion can occur inside the building [1]. Furthermore, outdoor wind speeds are often too high at the corners of high-rise buildings; thus, they can reduce wind comfort and safety for pedestrians [2]. All of the above problems can have an impact on the quality of the wind environment in the outdoor activity space of students. Researchers believe that optimizing the outdoor wind environment of high-rise buildings is inevitable for enhancing pedestrian comfort [3,4], building energy efficiency [4,5], and efficient dispersion of pollutants [6,7].

The outdoor wind effect is closely related to the climate zone in which the building is located. For example, in cold climate zones, the strong airflow deflecting downward from high-rise buildings in winter can be detrimental to pedestrians and needs to be mitigated by appropriate measures. However, in hot and humid climates, this element is an important way to enhance ventilation [8].

2. Literature Review

A large number of Chinese domestic and foreign scholars have conducted outdoor wind environment-related research in the area of building morphology. Such research focuses on specific aspects such as the building layout, building size, and building form. The representative literature is summarized in Table 1.

Table 1. Representative literature regarding building morphology and wind environment.

Factors	Building Type	Sub-Factors	Ref.	Method
Building layout	Residential building	Exploration of suitable building layout under different climate zones with given wind environment characteristics	[9–14]	Numerical simulation
		Influence of layout and plant arrangement on wind environment and thermal comfort	[15,16]	
		The relationship between layout and wind environment	[17–19]	
		The effect of layout on the wind environment	[20–22]	Numerical simulation + Wind tunnel test
		The relationship between the layout and wind environment of settlements with a high floor–area ratio	[23]	Numerical simulation + Field measurement
	Office building	Natural ventilation performance of closed office buildings with different layouts	[24]	Numerical simulation
Building size	Residential building	The influence of building width and height on the wind environment	[25]	Wind tunnel test
		The influence of building length and width on the wind environment	[26]	Numerical simulation
		The effect of building height on the wind environment	[27]	
	/	The influence of building height and volume on the dispersion of pollutants	[28]	
		The effect of building height on pedestrian wind comfort	[29,30]	
		The influence of building length, width, and height on wind environment	[31]	
	Office building	The relationship between the height, width, and location of the podium with the wind environment	[32]	Numerical simulation + Field measurement
	/	The effect of building height on wind environment comfort	[33]	
		Effect of building height on ventilation and dispersion of pollutants	[34]	Numerical simulation + Wind tunnel test
Building form	Campus building	The relationship between typical building forms and wind environment	[35]	Field measurement
	/	The mechanism of wind environment effect of different forms of high-rise buildings	[36]	Wind tunnel test
		The influence of building form on the wind environment of high-rise buildings	[37,38]	Numerical simulation + Wind tunnel test

"/" means that the building type is not defined.

In terms of building layout, Shui Tt et al. evaluated the wind environment of different building layouts by taking residential areas in severely cold regions as an example, and the study demonstrated that the hybrid and closed layouts are more suitable for residential areas in severely cold regions [20]. Zhang H et al. showed that, for high-rise residential buildings in tropical regions, the use of a courtyard layout in coastal cities can better cope with tropical cyclones [9]. Hu Yd et al. indicated that the point layout has the best ventilation in Shanghai during summer and transitional seasons, while the aligned layout is the best in winter [10]. In terms of building size, Gong C et al. demonstrated that building length has a significant impact on the wind environment, and the wind environment can be effectively improved when the length-to-width ratio is 3:1 and the staggered layout is used [26]. Tsang et al. took high-rise residential buildings as an example and showed that wider buildings tend to block the wind field, while taller buildings can improve the poor ventilation around the building [25]. In terms of building form, Xu X et al. constructed 40 models of high-rise buildings with different forms and employed wind tunnel tests to investigate the mechanism of the effect of building form on the pedestrian wind environment [36]. The literature review reveals that the research objects about outdoor wind environment are mainly residential areas. As a place where students gather, the wind environment quality of dormitory areas is important. However, it has not been studied sufficiently, especially in high-rise dormitory areas. Under the climate zoning of China, studies are often located in severely cold regions and hot summer and cold winter regions, and there are few investigations for cities in cold regions.

In terms of research methods, the three following main methods are utilized in the field of building wind environment: (1) wind tunnel tests [39,40], (2) field measurements [35], and (3) computational fluid dynamics (CFD) numerical simulations [41,42]. Field measurements can obtain first-hand data information, but there are some limitations in these measurements. The limitations are only for existing buildings, the process is time-consuming, and the number of test points is limited. Therefore, this method is often employed to support the results of wind tunnel tests and numerical simulations. For example, the literature [5,43,44] combined field measurements with fluent simulations, envi-met simulations, and orthogonal experimental designs, respectively. Wind tunnel testing is an earlier method for wind environment simulation, which is not extensively used at present because of the high test requirements and costs [45]. Compared with the first two methods, numerical simulation has the advantages of being convenient and cost-saving. In addition, this method can acquire detailed wind environment data for all points in the whole calculation domain [46], which is convenient for later data quantification and analysis. Therefore, CFD numerical simulation has become the mainstream method for wind environment research.

Based on the above analysis, the high-rise dormitory area of a Xi'an university in the cold region was selected as the research object. The study adopted a combination of numerical simulation and orthogonal tests. The influencing factors of the outdoor wind environment were analyzed, and the optimal design scheme that is adapted to the local climate was recommended. The results of the study can provide some methodological references for the design of wind environment in other similar climatic regions.

3. Research Methods

3.1. The Characteristics of College Dormitory Morphology in Cold Regions

Due to the differences in climate conditions, such as temperature, precipitation, and light, cities in different regions will form a specific building morphology. The morphologies of dormitory buildings in each university also differ depending on geographical location, environment, university scale, and construction period. This study was carried out by adopting the field visit and literature review method. We researched many cities in cold regions, which are representative cities with a high number of universities, including Beijing, Tianjin, Xi'an, Taiyuan, and 10 other urban areas. The details are shown in Figure 1. The two parts of ① and ② in the figure are located in southern Xinjiang and southern Tibet, respectively. We did not choose to research because of the low urban density, low population density, and low density of universities. The reference [47–50] investigated dormitory buildings in cold regions including Jinan, Lhasa, and Xi'an. It shows that the layout is mostly aligned and the building form is more regular. Among them, reference [47] investigated 77 university dormitories. The aligned layout accounted for 65% of the total sample and the rectangular form accounted for 79%. Due to space limitations, the representative morphologies of dormitories in 12 universities researched are presented in Table 2. It was found that (1) aligned type, staggered type, and enclosed type are the main layouts of dormitory buildings in the cold climate zone. Among them, the aligned type is the most commonly used type, followed by the staggered type, and the enclosed type is the least common. (2) Dormitory buildings in cold regions have a more regular form and a smaller body coefficient. Considering this kind of form can enhance the energy-saving effect of the building. The high-rise dormitory is divided into slab-type and tower-type. (3) The orientation of the buildings is mostly north–south, with a slight adjustment of individual orientation because of campus planning and road factors. (4) Owing to the limited land for the expansion of universities, the trend is to build high-rise dormitories.

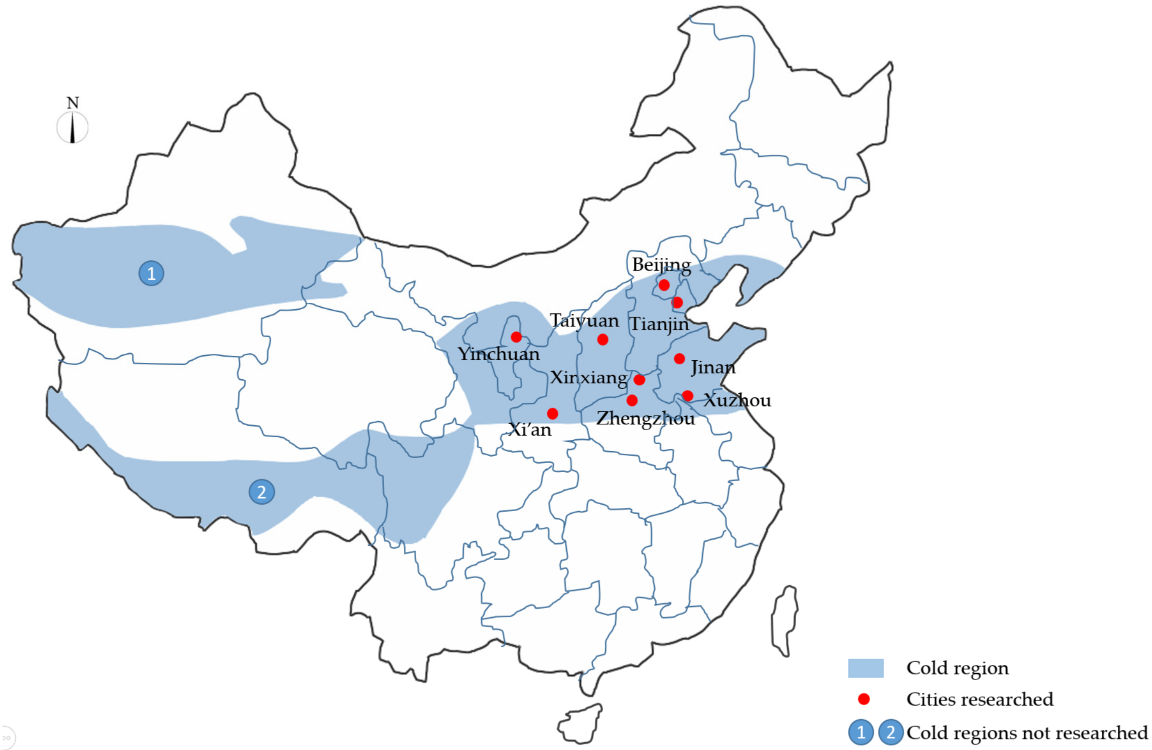


Figure 1. Distribution of cities researched in China.

3.2. Research Case

We selected study cases in the same city to ensure that the basic conditions of the wind environment are the same. Xi'an, located in the Shaanxi Province of China, belongs to the cold region of the building climate zoning [51]. Xi'an area ranks 6th in the number of universities in China, with about 871,400 people enrolled in higher education [52]. Therefore, we take the dormitory of the university in Xi'an area as a representative case study. There are four distinct seasons in Xi'an. The average temperature of the coldest month, January, ranges from −1.2 °C to 0.0 °C, and the average temperature of the hottest month, July, ranges from 26.3 °C to 26.6 °C. The wind environment data of the Xi'an area in winter and summer are summarized in Table 3 [53]. The Beaufort scale is an internationally accepted wind scale, as presented in Table 4. According to this standard, the wind speed in Xi'an is light breeze, which is small. Based on the climatic characteristics of the cold region, the planning and design of the dormitory area should meet both the wind protection requirements in winter and ventilation in summer. The regular building form is conducive to building energy saving. Furthermore, Xi'an belongs to the 7-level seismic intensity zone. Due to the limitation of the seismic intensity requirement, the building form is regular and without much variation.

Table 2. Typical university dormitory morphology in cold regions.

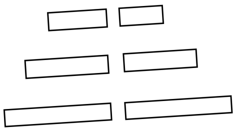
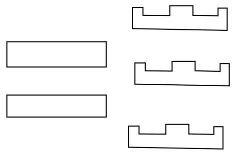
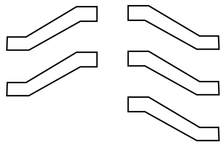
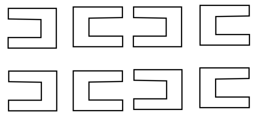
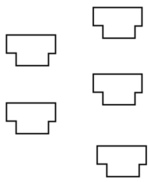
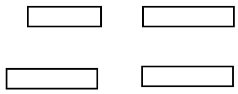
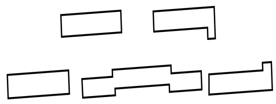
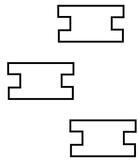
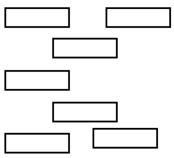
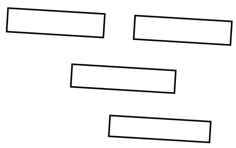
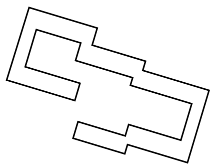
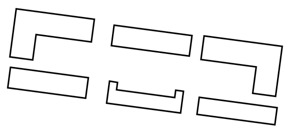
Tsinghua University	**Shanxi University (Wucheng Campus)**	**Shandong University of Construction**	**Hebei University of Technology (Hongqiao Campus)**
 Aligned layout	 Aligned layout	 Aligned layout	 Aligned layout
China University of Mining and Technology (College Road Campus)	Chang'an University (Weishui Campus)	BeihangUniversity (College Road Campus)	Shaanxi Normal University (Chang'an Campus)
 Aligned layout	 Aligned layout	 Staggered layout	 Staggered layout
Xi'an Jiaotong University (Xingqing Campus)	Zhengzhou University	Nankai University (Jinan Campus)	Henan Normal University (Western District)
 Staggered layout	 Staggered layout	 Enclosed layout	 Enclosed layout

Table 3. Wind direction, wind speed, and wind frequency in Xi'an.

Season	**Dominant Wind Direction**	**Average Wind Speed**	**Wind Frequency**	**Sub-Dominant Wind Direction**	**Average Wind Speed**	**Wind Frequency**
Summer	East North East	2.5 m/s	42.2%	Southwest	2.3 m/s	18.1%
Winter	East North East	2.2 m/s	37.5%	Southwest	2.0 m/s	25.1%

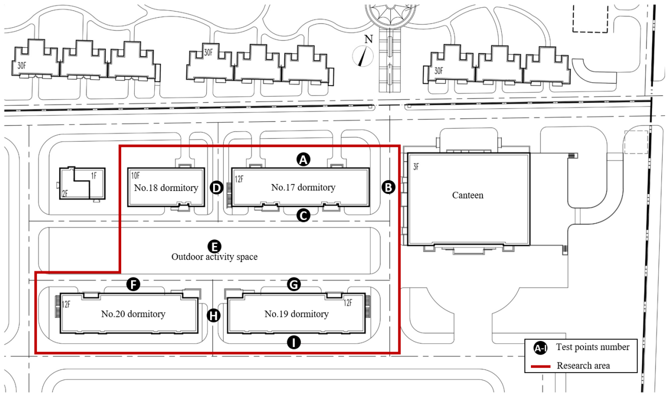
Table 4. Beaufort scale.

Beaufort Scale	**Description**	**Wind Speed (m/s)**	**Beaufort Scale**	**Description**	**Wind Speed (m/s)**
0	Calm	0–0.2	7	Near gale	13.9–17.1
1	Light Air	0.3–1.5	8	Gale	17.2–20.7
2	Light breeze	1.6–3.3	9	Strong gale	20.8–24.4
3	Gentle breeze	3.4–5.4	10	Storm	24.5–28.4
4	Moderate breeze	5.5–7.9	11	Violent storm	28.5–32.6
5	Fresh breeze	8.0–10.7	12	Hurricane	32.7–36.9
6	Strong breeze	10.8–13.8			

The research information of two types of high-rise dormitory buildings in Xi'an, namely slab dormitory buildings and tower dormitory buildings, is as follows. The high-rise dormitory area of the Weishui Campus of Chang'an University (CHD) is located on the west side of the campus and has four slab-type high-rise dormitory buildings (No. 17–20). The high-rise dormitory area of Chang'an Campus of Shaanxi Normal University (SNNU) is located in the southwest corner of the campus and includes tower-type and slab-type for master and doctoral students. The basic overview of the buildings in these two cases is shown in Table 5 and both examples are representative examples of high-rise dormitories.

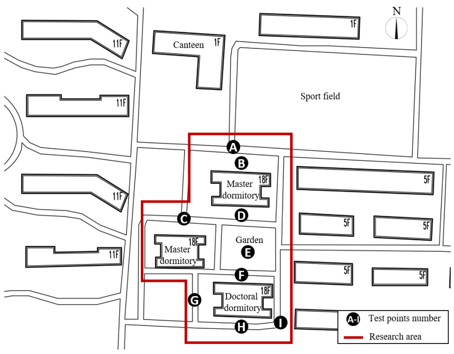
Table 5. Basic overview of typical cases and distribution of test point.

Case 1 CHD High-Rise Dormitory	
Orientation	15° S.E.
Number of floors and height	10F 40.2 m 12F 47.7 m
Building Form	Slab-type high-rise
Layout	Aligned



(a) Realistic view of the façade (b) General plan and distribution of test points

Case 2 SNNU high-rise dormitory	
Orientation	North
Number of floors and height	18F 71.1 m
Building Form	Tower-type high-rise
Layout	Staggered



(c) Realistic view of the façade (d) General plan and distribution of test points

3.3. Numerical Simulation and Orthogonal Test

To investigate the coupling relationship between the building morphology and outdoor wind environment in the high-rise dormitory area of the university and to explore the best strategy for optimization of the wind environment, the study case was simulated. The mainstream CFD numerical simulation method was utilized for this purpose. This method has the advantages of efficient simulation and accurate results [54]. The simulation parameters are presented in Table 6, where the meteorological parameters are selected from the outdoor calculation parameters in the Design Code for Heating, Ventilation, and Air Conditioning in Civil Buildings [55]. When the wind speed is 1–5 m/s, people feel comfortable [56] and, according to the Green Campus Evaluation Standard, the wind speed in the outdoor rest and activity area should be smaller than 2 m/s. Therefore, the comfortable wind speed range of 1–2 m/s was utilized as the evaluation standard.

To enhance the efficiency of the experiment, we adopted the method of orthogonal experimental design. The orthogonal experimental design is a branch of fractional analysis design and, compared with other test methods, the final results can be obtained by extracting only some representative case tests. The cases have the characteristics of "uniform dispersion, simplicity, and comparability". The orthogonal experimental design can effectively decrease the number of required studies. Furthermore, while orthogonal experimental design can infer the effects of factors from a small number of combinations of factors, it can also compare weights [56]. The technical processes involved in conducting this research are shown in Figure 2.

Table 6. Simulation parameter settings.

Paramater	Specific Setting	Paramater	Specific Setting
Model creation	BIM modeling into CFD simulation	Equation selection	Standard k-ε turbulence model
Computational domain	Length×width×height: 5X × 5Y × 3Z	Meteorological parameters	Wind direction: East–Northeast Wind speed: 1.9 m/s in summer, 1.4 m/s in winter
Number of iterations	1000	Grid division	building local encryption

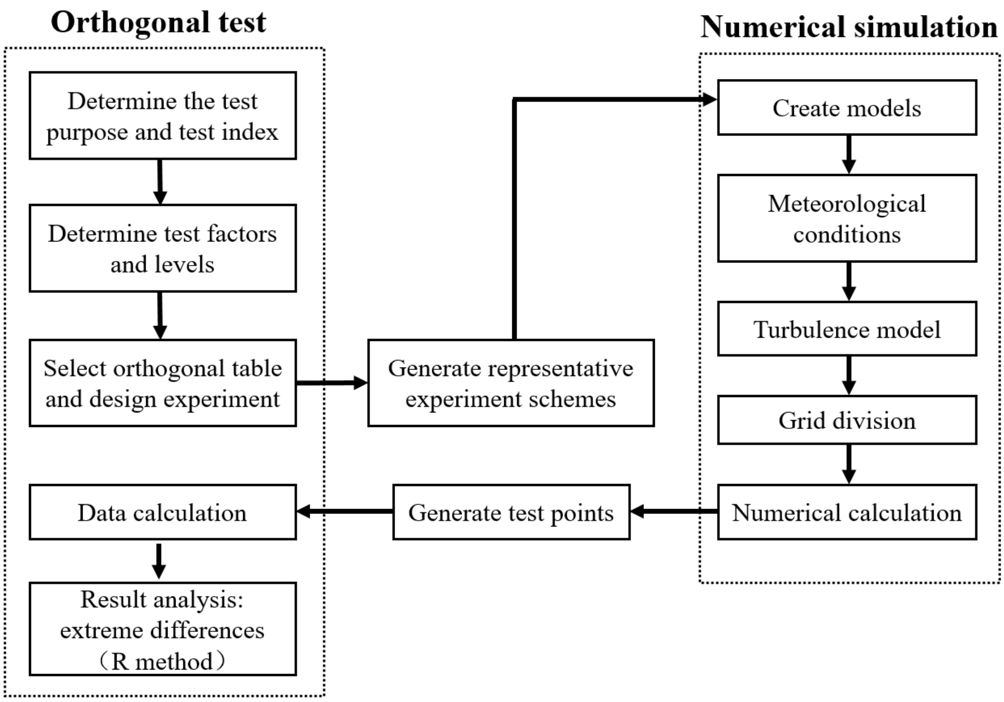


Figure 2. Related technical route.

4. Results and Analysis

4.1. Simulation Analysis of Outdoor Wind Environment

The dominant wind direction is the same in winter and summer in Xi'an, and the simulation results showed that the characteristics of the outdoor wind environment are similar in both seasons except for the wind speed values. Thus, the simulation results were analyzed by considering summer as the representative. The simulation results at the 1.5 m pedestrian height are exhibited in Figure 3.

From the wind speed simulation (diagrams (a) and (c)), it can be observed that the wind speed around CHD No. 17–18 dormitory buildings is smaller than 1 m/s. This is due to the wind-blocking effect of the buildings on the east and north sides. There is a wind speed stagnation area and the airflow in the dormitory area is more chaotic, which is considered to be affected by the staggered layout and the east side of the building. From the wind pressure simulation (diagrams (b) and (d)), it can be seen that the pressure difference between the front and rear of the building is small, leading to poor airflow movement. Compared with the tower-type high-rise with a staggered layout, the internal wind pressure in the slab dormitory area with an aligned layout is more stable.

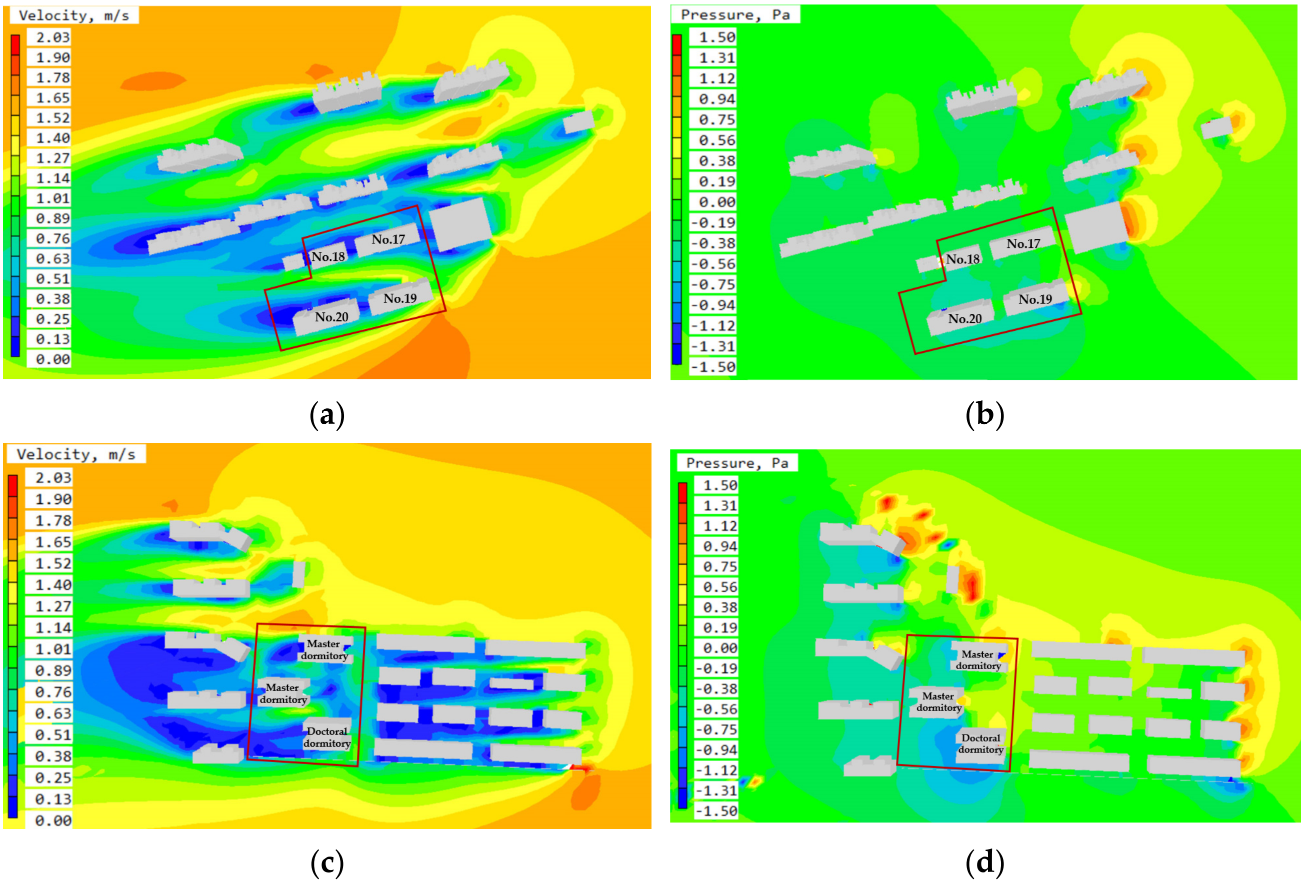


Figure 3. Wind environment simulation at pedestrian height: (**a**) wind speed simulation for CHD slab high-rise building, (**b**) wind pressure simulation of CHD slab high-rise building, (**c**) wind speed simulation for SNNU tower high-rise building, and (**d**) wind pressure simulation of SNNU tower high-rise building.

The results of the simulation analysis are summarized as follows:

(1) The wind environment characteristics are similar in winter and summer in Xi'an. The phenomenon of static wind can easily give rise to the deposition of pollutants, and the ventilation is poor and stifling in summer. The current wind environment requires urgent improvement.

(2) The wind shadow area of the high-rise dormitory building is large, so the wind comfort is not good. Moreover, the "corner effect" can easily result in high wind speed in some areas.

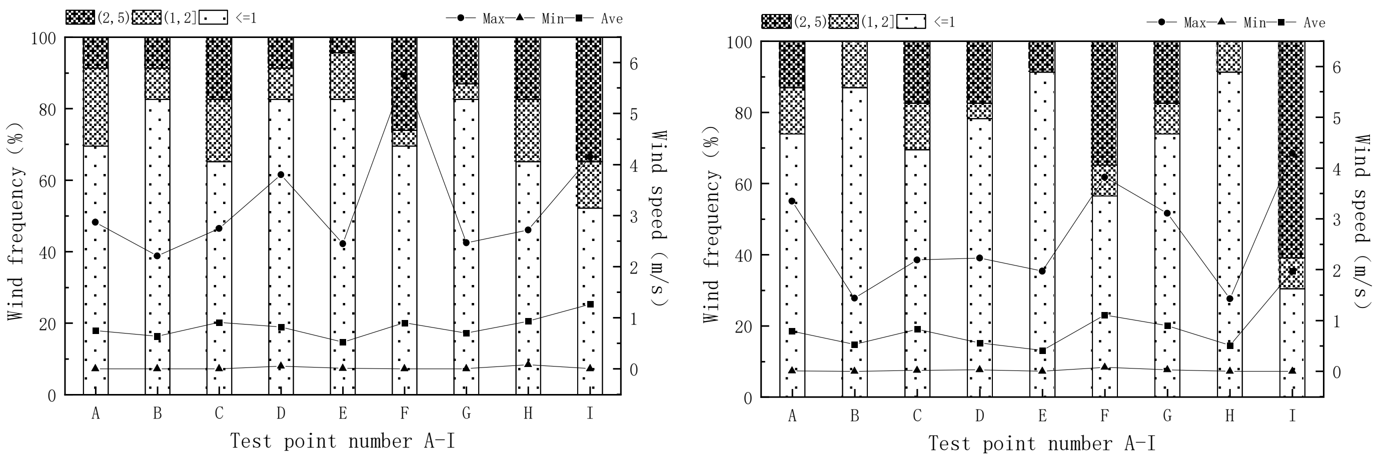
(3) The outdoor wind environment of the dormitory area with different morphologies differs greatly. The CHD slab-type high-rise dormitory adopts an aligned layout. The vortex and windless area can be easily formed, resulting in poor ventilation. The SNNU tower-type high-rise dormitory has a staggered layout, which has an unbalanced wind environment.

4.2. Analysis of Measured Data and Simulation Validation

Field measurements were carried out on 10 January and 28 June 2021 for the case of the CHD slab high-rise building. The test points were located at representative locations, including the windward side and leeward side, between adjacent buildings, and building corners of the building. The test instruments used were TES-1341 hot-wire anemometer and testo 410-1 impeller anemometer (Figure 4). The scheme of test point distribution is shown in figures (b) and (d) in Table 5. The wind speed test period was from 8:00 to 19:00 and the data were recorded every 0.5 h. The results are displayed in Figures 5 and 6. For the slab-type high-rise dormitory, the average outdoor wind speed in the dormitory area was smaller than 1 m/s in summer, except for test point I. For the tower-type high-rise dormitory, the average outdoor wind speed in the dormitory area was smaller than 1 m/s in summer, except for test point H. The overall ventilation was poor, leading to the poor diffusion of pollutants, which was not good for students' health. In winter, the maximum wind speed at test point I of the slab-type high-rise was 2 m/s. In addition, the maximum wind speed at test point H of the tower-type high-rise was 4.27 m/s. According to the Green Campus Evaluation Standard, the wind speed in outdoor rest and activity areas should be smaller than 2 m/s. The wind speed at this location is too high, which is not conducive to wind protection and warmth in winter.

(**a**) (**b**)

Figure 4. Testing instruments: (**a**) thermocouple anemometer and (**b**) impeller anemometer.

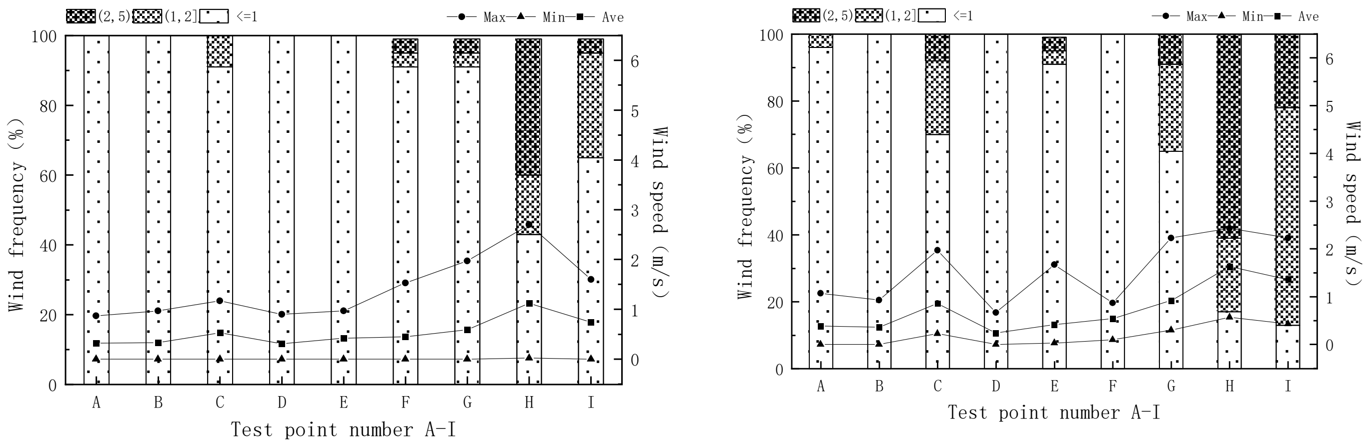


(**a**) (**b**)

Figure 5. All-day average wind speed of CHD slab-type high-rise dormitory, maximum wind speed, and wind frequency at each point: (**a**) summer; (**b**) winter.

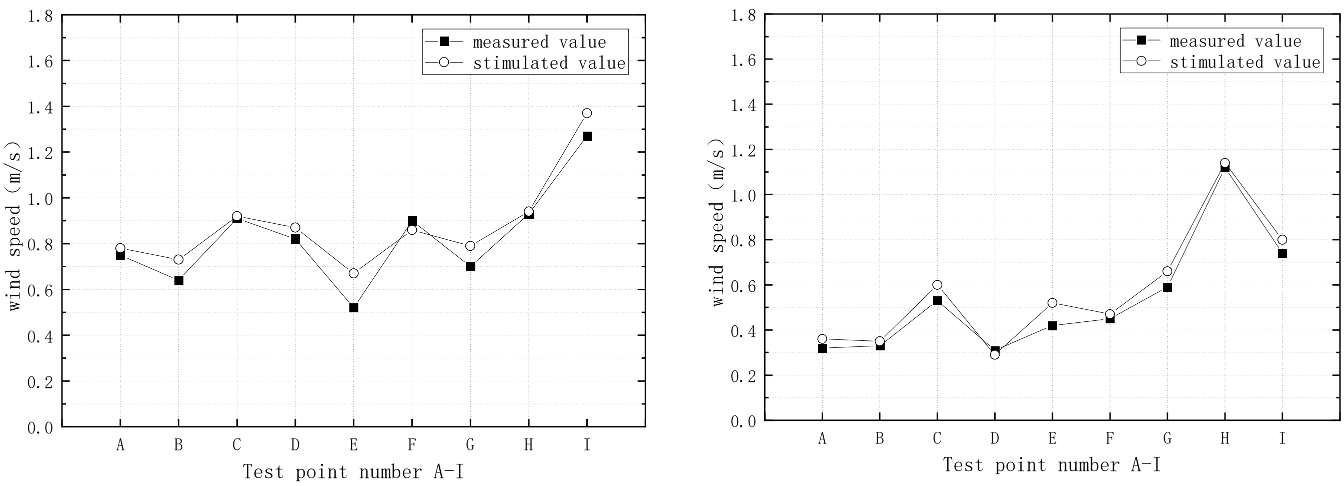
Because the average wind speed can better reflect the actual wind environment, we chose the measured average wind speed to validate the accuracy of the simulation. Taking the summer data as an example, the measured and simulated wind speed data were compared (Figure 7). It can be noticed that the overall trend of the data is consistent and the similarity of individual test points is high. Furthermore, we used Mean Absolute Percentage Error (MAPE) to validate the accuracy of the simulated value. The calculation was based on Equation (1), where X_{sim} is the simulated value, X_{med} is the measured value, and N is the number of measurements. For the slab-type high-rise dormitory, the MAPE was 8.93%. For the tower-type high-rise dormitory, the MAPE was 9.72%. They were within the reasonable error range. This indicated that the method of model establishment and simulation can reflect the real situation accurately. The error can be attributed to the influence of pedestrians, vegetation, and other factors during the actual measurement process.

$$\mathrm{MAPE} = \frac{\sum_{i=1}^{n} \frac{|X_{med} - X_{sim}|}{X_{med}}}{N} \tag{1}$$



(a) **(b)**

Figure 6. All-day average wind speed of SNNU tower-type high-rise dormitory, maximum wind speed, and wind frequency at each point: (**a**) summer; (**b**) winter.



(a) **(b)**

Figure 7. Comparison of measured value (average wind speed) and simulated value in summer: (**a**) CHD slab-type high-rise; (**b**) SNNU tower-type high-rise.

4.3. Orthogonal Experimental Design

Constraints need to be set for each building layout of the scheme, mainly including fire prevention, daylighting, and planning-related requirements (Table 7). The simulated wind direction was northeast–east (ENE) and the wind speed was 1.9 m/s, which is a typical wind speed in Xi'an.

Table 7. Constraints of the scheme.

Constraint Name	Binding Conditions	Based on
Dormitory design requirements	Dormitory building spacing should meet the requirements of fire prevention, sunlight, and other requirements as well as local urban planning and management regulations.	Dormitory Building Design Code (JGJ36-2016)
Fire prevention requirements	The minimum spacing between high-rise dormitories and high-rise civil buildings is 13 m.	Building Design Fire Code (GB-50016-2014)
Sunlight requirements	To ensure that the blocked building meets the sunshine requirement of ≥2 h on a cold day, the starting point of calculation is the sill surface of the ground floor (taking the value of 0.9 m).	Building Daylighting Standards
Hill wall spacing requirements	The minimum spacing between the hill walls of two high-rise civil buildings is 20 m.	Xi'an Urban Planning Management Regulations

The wind environment is influenced by many factors, such as layout, building size, topographic conditions, and wind direction. Among them, building layout and building size are the most important factors that can be easily optimized during planning and design [12]. Therefore, we selected four different influencing factors for high-rise dormitory buildings and then set three levels for each factor (Tables 8 and 9). Since tower-type high-rise is rarely enclosed in practical situations, this experiment did not consider this case.

Table 8. Influencing factors of outdoor wind environment of a slab-type high-rise dormitory.

	A. Building Layout	B. Building Length (m)	C. Building Width (m)	D. Building Height (m)
1	A_1 (Aligned layout)	B_1 (40)	C_1 (14)	D_1 (34.2)
2	A_2 (Staggered layout)	B_2 (50)	C_2 (16)	D_2 (55.2)
3	A_3 (Enclosed layout)	B_3 (60)	C_3 (18)	D_3 (85.2)

The letters represent factors and the numbers represent levels.

Table 9. Influencing factors of outdoor wind environment of a tower-type high-rise dormitory.

	A. Building Layout	B. Building Length (m)	C. Building Width (m)	D. Building Height (m)
1	A_1 (Aligned layout)	B_1 (26)	C_1 (24)	D_1 (34.2)
2	A_2 (Staggered layout)	B_2 (39)	C_2 (30)	D_2 (55.2)
3	—	B_3 (50)	C_3 (45)	D_3 (85.2)

The letters represent factors and the numbers represent levels.

We selected L9 (4 × 3) orthogonal table to guide the experimental design. The orthogonal experimental design of the slab and tower high-rise dormitory buildings is shown in Tables 10 and 11, respectively.

Table 10. Orthogonal test table of slab-type high-rise dormitory buildings.

Simulation Schemes	Factor A: Building Layout	Factor B: Building Length (m)	Factor C: Building Width (m)	Factor D: Building Height (m)
1. $A_1B_1C_1D_1$	A_1 (Aligned layout)	B_1 (40)	C_1 (14)	D_1 (34.2)
2. $A_1B_2C_3D_2$	A_1	B_2 (50)	C_3 (18)	D_2 (55.2)
3. $A_1B_3C_2D_3$	A_1	B_3 (60)	C_2 (16)	D_3 (85.2)
4. $A_2B_1C_3D_3$	A_2 (Staggered layout)	B_1	C_3	D_3
5. $A_2B_2C_2D_1$	A_2	B_2	C_2	D_1
6. $A_2B_3C_1D_2$	A_2	B_3	C_1	D_2

Table 10. *Cont.*

Simulation Schemes	Factor A: Building Layout	Factor B: Building Length (m)	Factor C: Building Width (m)	Factor D: Building Height (m)
7. $A_3B_1C_2D_2$	A_3 (Enclosed layout)	B_1	C_2	D_2
8. $A_3B_2C_1D_3$	A_3	B_2	C_1	D_3
9. $A_3B_3C_3D_1$	A_3	B_3	C_3	D_1

The letters represent factors and the numbers represent levels.

Table 11. Orthogonal test table of tower-type high-rise dormitory buildings.

Simulation Schemes	Factor A: Building Layout	Factor B: Building Length (m)	Factor C: Building Width (m)	Factor D: Building Height (m)
1. $A_2B_3C_3D_1$	A_2 (Staggered layout)	B_3 (50)	C_3 (45)	D_1 (34.2)
2. $A_1B_2C_2D_1$	A_1 (Aligned layout)	B_2 (39)	C_2 (30)	D_1
3. $A_2B_2C_1D_3$	A_2	B_2	C_1 (24)	D_3 (85.2)
4. $A_1B_1C_3D_3$	A_1	B_1 (26)	C_3	D_3
5. $A_1B_3C_2D_3$	A_1	B_3	C_2	D_3
6. $A_1B_1C_1D_1$	A_1	B_1	C_1	D_1
7. $A_1B_2C_3D_2$	A_1	B_2	C_3	D_2 (55.2)
8. $A_2B_1C_2D_2$	A_2	B_1	C_2	D_2
9. $A_1B_3C_1D_2$	A_1	B_3	C_1	D_2

The letters represent factors and the numbers represent levels.

The ratio of the long and short sides of the tower building is required to be smaller than 2. Scheme 9 did not satisfy this ratio; thus, the tower-type high-rise orthogonal test was adopted for Schemes 1–8.

4.4. Analysis of Orthogonal Experimental Design Results

Based on the orthogonal test table, we created 17 model schemes with different parameters. The outdoor wind environment of the dormitory buildings was simulated by CFD simulation. Due to space limitations, the simulation results of some schemes are displayed in Figure 8.

A total of 381 test points were chosen within each scheme. The principal selection is located on the windward side of the building, the leeward side, and between the hill walls of adjacent buildings for mean selection. The specific arrangement of test points is depicted in Figure 9.

The wind speed values at each simulated test point for high-rise dormitories are shown in Figure 10. It can be observed that the wind speed values of the test points located on the windward side of the building are generally larger than those on the leeward side and between the adjacent building walls. Figure 10a shows data for slab-type high-rise dormitories. Schemes 1–3 are aligned layouts. The overall wind speed uniformity is good. Test points 1–9 are located on the windward side of the building and, comparing three schemes, the increase in width causes a slight increase in wind speed at the test points on the windward side. Test points 10–18 are located on the leeward side of the building, and test points 19–24 are located between the hill walls of adjacent buildings. With the increase in building height and length, the wind speed increases on the leeward side and between the hill walls of adjacent buildings. Schemes 4–6 are staggered layouts and the overall wind speed is larger. Comparing three schemes, the overall wind speed is larger for the higher and wider building schemes. The maximum wind speed is at the windward test point 7 of Scheme 4, with a wind speed of 2.44 m/s. Schemes 7–9 are enclosed layouts. The overall wind speed of the enclosed layout is the smallest, which can easily result in poor ventilation. The smallest wind speed is at test point 14 of Scheme 7, with a wind speed value of 0.07 m/s. Furthermore, the fluctuation of wind speed value in the enclosed type is larger than that in the staggered and aligned types, suggesting that the wind environment is not well balanced. Figure 10b shows the data of tower-type high-rise dormitories. The building height of tower-type high-rise Schemes 3–5 is 85.2 m and, compared with the building height of 34.2 m and 55.2 m, the overall wind speed is larger. The maximum wind speed occurs at test point 7 of Scheme 4, with a wind speed of 2.34 m/s. The minimum wind speed occurs at test point 10 on the leeward side of Scheme 1, with a wind speed as small as 0.19 m/s.

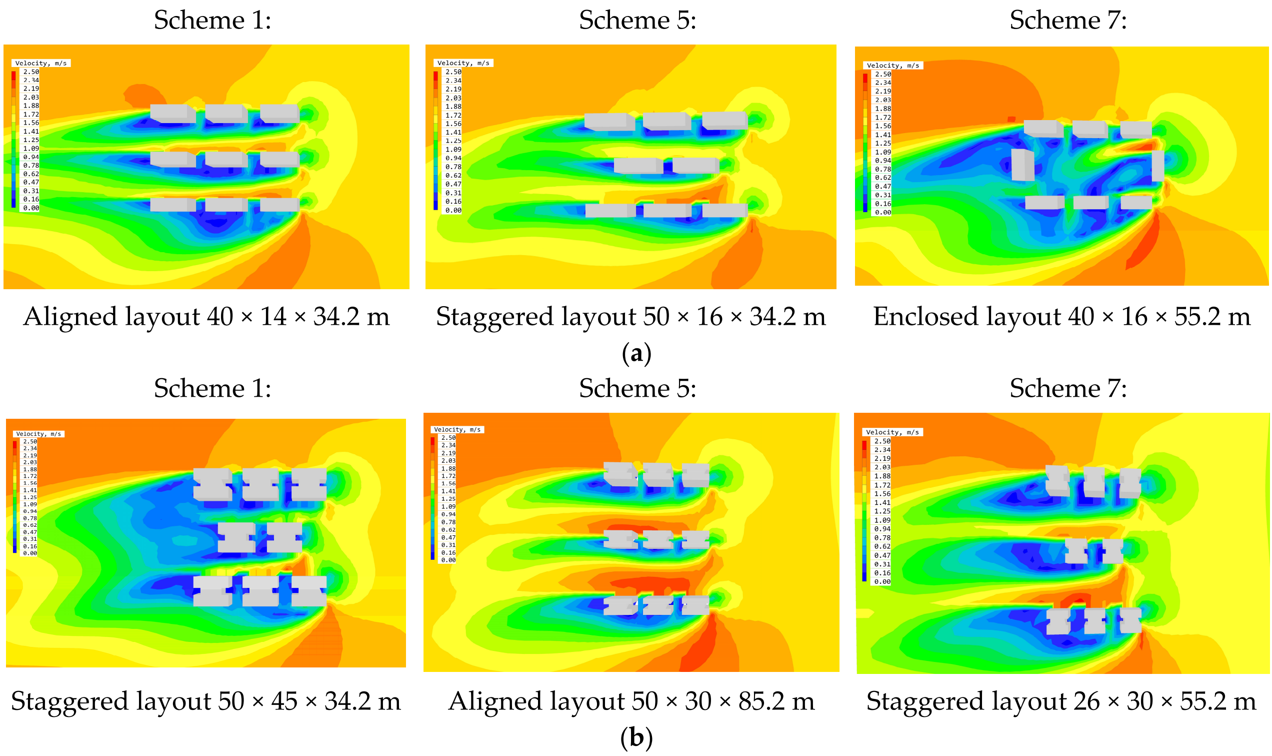


Figure 8. Simulation of wind speed at pedestrian height for each scheme of orthogonal test: (**a**) slab-type high-rise building; (**b**) tower-type high-rise building.

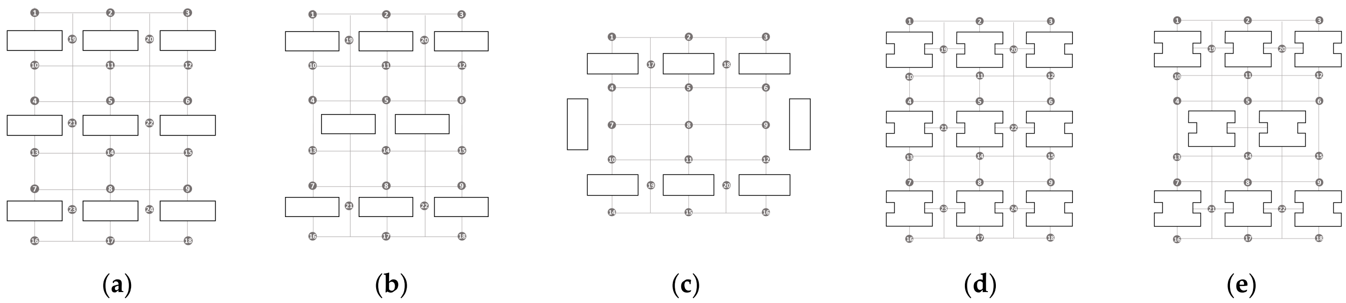
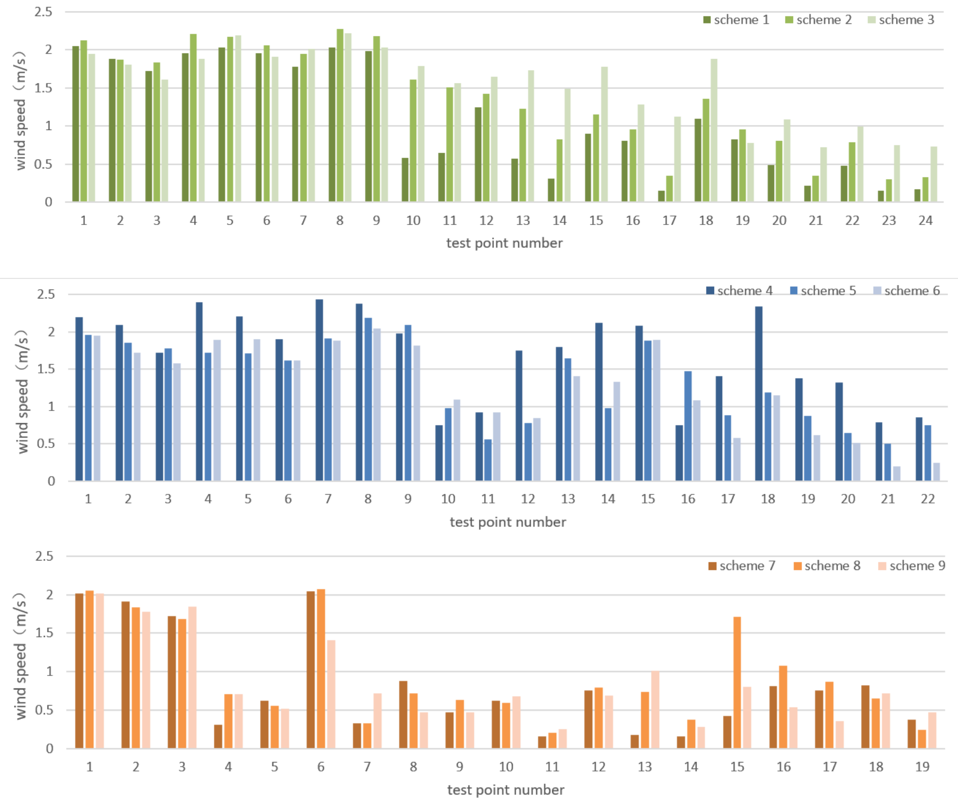
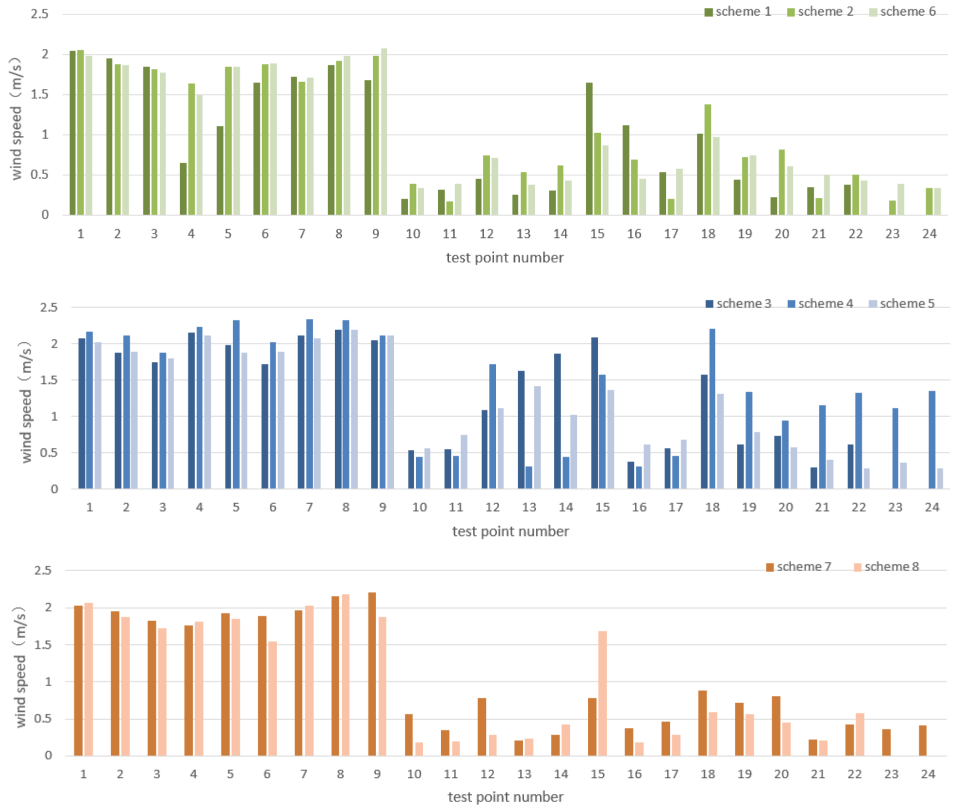


Figure 9. Layout diagram of simulation test points: (**a**) slab-type, aligned layout; (**b**) slab-type, staggered layout; (**c**) slab-type, enclosed layout; (**d**) tower-type, aligned layout; (**e**) tower-type, staggered layout.

The orthogonal test results were analyzed by the analysis of the extreme differences method, that is, R method. The method has the advantages of simple calculation, visualization, and practicality and includes two steps of calculation and evaluation (Figure 11). To recommend the optimal combination scheme, the K value can evaluate the optimal level of each influencing factor. The extreme difference in R-value is utilized to evaluate the weighting of the influencing factors. The greater the R-value, the greater the influence of the factor. The specific definitions of the parameters are shown in Table 12.



(**a**)



(**b**)

Figure 10. Wind speed values of simulated test points in high-rise dormitory area for each scheme: (**a**) slab-type high-rise building; (**b**) tower-type high-rise building.

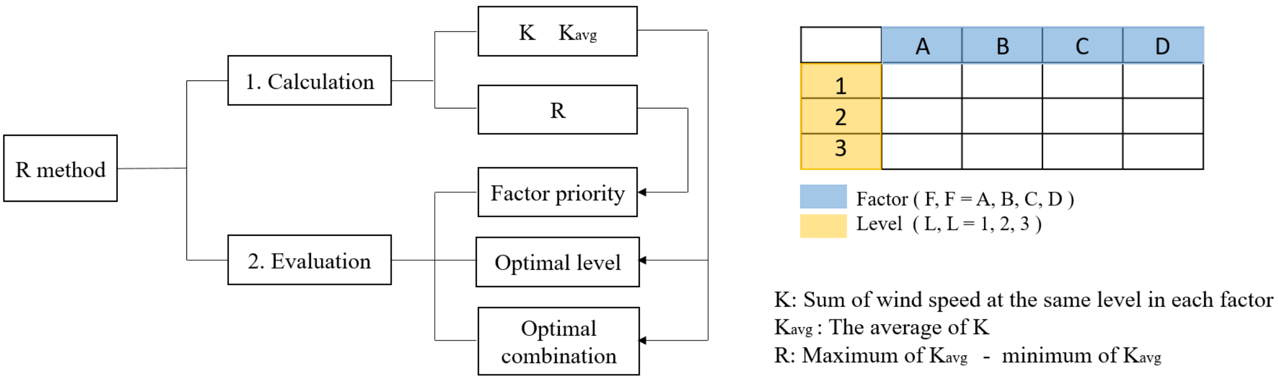


Figure 11. Method of extreme difference analysis.

Table 12. Specific definitions of parameters in the extreme difference analysis.

Parameter	Definition
V_x	Value of the result of the experiment No. x. (average wind speed)
K_{A1}	The value at the 1 level of the factor A
$K_{avg\ A1}$	The average of K_{A1}
Optimal level	The level of optimal K_{avg} for a factor
R_A	The range between the maximum and the minimum value of $K_{avg\ A1}$

The R calculation is shown as follows (Equation (2)):

$$\begin{array}{l} K_{A1} = V_1 + V_2 + V_3; K_{A2} = V_4 + V_5 + V_6; K_{A3} = V_7 + V_8 + V_9; \\ K_{avg\ A1} = \frac{V_{A1}}{3}; K_{avg\ A2} = \frac{V_{A2}}{3}; K_{avg\ A3} = \frac{V_{A3}}{3}; \\ R_A = \max\left(K_{avg\ A}\right) - \min\left(K_{avg\ A}\right). \end{array} \quad (2)$$

The same process calculated other K values of the factors.

By calculating average wind speed of each scheme, the simulation results of the orthogonal test for slab-type high-rise dormitory are acquired, as shown in Table 13. It can be noticed that the average wind speed of slab-type high-rise Scheme 4 is the largest and Scheme 7 is the smallest. Based on the simulation results, we calculated the K_{avg}, R, and optimization percentage, as shown in Table 14. According to the R and optimization percentage, we can evaluate the weighting of the influencing factors. The layout was the strongest, followed by the building height, the width, and, finally, the length. The optimization percentage of the layout is 69.6% when the enclosed type is changed to the staggered type. Therefore, the layout of slab-type high-rise dormitory buildings is the primary consideration when planning and designing. The next is the height and width of the buildings, and the building length has little influence on the wind environment. Wind speed comfort range is 1–2 m/s as the evaluation standard. The optimal combination of slab-type is $A_2B_2C_3D_3$, that is, a staggered layout with a building length of 50 m, width of 16 m, and height of 85.2 m.

Table 13. Simulation results of orthogonal test for slab-type high-rise buildings.

Simulation Schemes	A. Building Layout	B. Building Length (m)	C. Building Width (m)	D. Building Height (m)	(V) Average Wind Speed (m/s)
$A_1B_1C_1D_1$	1 (Aligned layout)	1 (40)	1 (14)	1 (34.2)	1.09
$A_1B_2C_3D_2$	1	2 (50)	3 (18)	2 (55.2)	1.36
$A_1B_3C_2D_3$	1	3 (60)	2 (16)	3 (85.2)	1.54
$A_2B_1C_3D_3$	2 (Staggered layout)	1	3	3	1.71
$A_2B_2C_2D_1$	2	2	2	1	1.36
$A_2B_3C_1D_2$	2	3	1	2	1.29

Table 13. *Cont.*

Simulation Schemes	A. Building Layout	B. Building Length (m)	C. Building Width (m)	D. Building Height (m)	(V) Average Wind Speed (m/s)
$A_3B_1C_2D_2$	3 (Enclosed layout)	1	2	2	0.80
$A_3B_2C_1D_3$	3	2	1	3	0.94
$A_3B_3C_3D_1$	3	3	3	1	0.83

The letters represent factors and the numbers represent levels.

Table 14. R table of orthogonal test for slab-type high-rise buildings.

	Levels	A. Building Layout	B. Building Length (m)	C. Building Width (m)	D. Building Height (m)
K	1	3.98	3.60	3.31	3.28
	2	4.36	3.66	3.70	3.45
	3	2.57	3.65	3.90	4.19
K_{avg}	1	1.328	1.199	1.103	1.092
	2	1.452	1.220	1.235	1.149
	3	0.856	1.218	1.298	1.396
Optimal level		A_2	B_2	C_3	D_3
R		0.596	0.021	0.195	0.304
Optimization percentage		69.6%	1.8%	17.7%	27.8%

By calculating the average wind speed of each scheme, the simulation results of the orthogonal test for the tower-type high-rise dormitory are acquired, as shown in Table 15. It can be noticed that the average wind speed of tower-type high-rise Scheme 4 is the largest and Scheme 1 is the smallest. Based on the simulation results, we calculated the K_{avg}, R, and optimization percentage, as shown in Table 16. According to the R and optimization percentage, we can evaluate the weighting of the influencing factors. The building height was the strongest, followed by the width, the length, and then the layout. The optimization percentage of the building height is 31.9% when the height changes from 34.2 m to 85.2 m. Therefore, the building height of tower-type high-rise dormitory buildings is the primary consideration when planning and designing. The next is the width and length of the buildings, and the layout has little influence on the wind environment. Wind speed comfort range is 1–2 m/s as the evaluation standard. The optimal combination of tower-type is $A_1B_1C_1D_3$, that is, an aligned layout with a building length of 26 m, width of 24 m, and height of 85.2 m.

Table 15. Simulation results of orthogonal test for tower-type high-rise buildings.

Simulation Schemes	A. Building Layout	B. Building Length (m)	C. Building Width (m)	D. Building Height (m)	(V)Average Wind Speed (m/s)
$A_2B_3C_3D_1$	2 (Staggered layout)	3 (50)	3 (45)	1 (34.2)	0.99
$A_1B_2C_2D_1$	1 (Aligned layout)	2 (39)	2 (30)	1 (55.2)	1.05
$A_2B_2C_1D_3$	2	2	1 (24)	3 (85.2)	1.39
$A_1B_1C_3D_3$	1	1 (26)	3	3	1.46
$A_1B_3C_2D_3$	1	3	2	3	1.23
$A_1B_1C_1D_1$	1	1	1	1	1.03
$A_1B_2C_3D_2$	1	2	3	2	1.06
$A_2B_1C_2D_2$	2	1	2	2	1.04

The letters represent factors and the numbers represent levels.

Table 16. R table of orthogonal test for tower-type high-rise buildings.

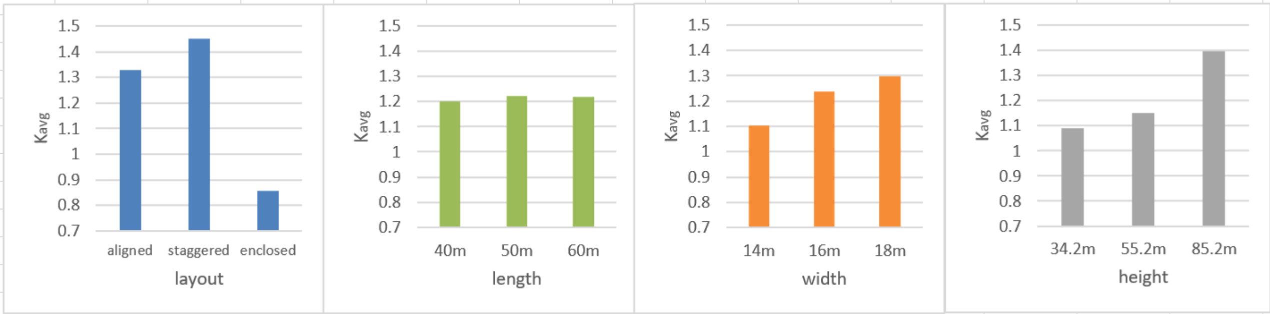
	Levels	A. Building Layout	B. Building Length (m)	C. Building Width (m)	D. Building Height (m)
K	1	5.82	3.51	2.42	3.08
	2	3.41	3.49	3.32	2.09
	3	/	2.22	3.49	4.06
K_{avg}	1	1.163	1.171	1.209	1.026
	2	1.138	1.165	1.106	1.045
	3	/	1.110	1.164	1.353
Optimal level		A_1	B_1	C_1	D_3
R		0.026	0.054	0.104	0.327
Optimization percentage		2.3%	4.9%	9.4%	31.9%

4.5. Coupling Relationship and Optimal Scheme Validation

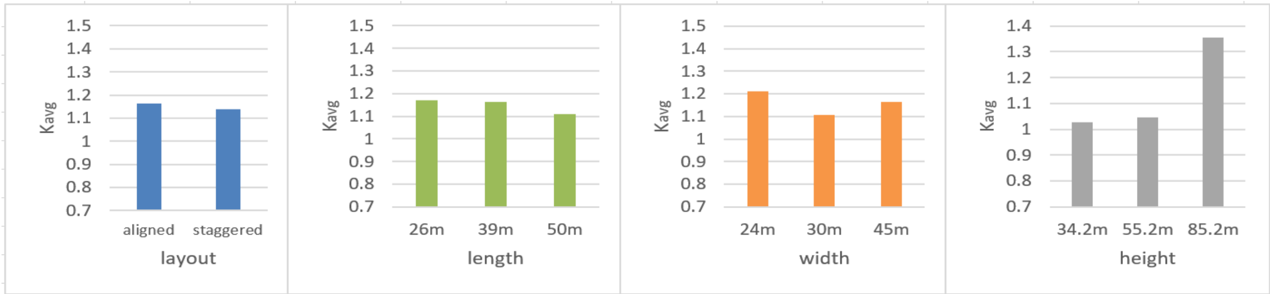
The wind speed in cold regions should meet the relevant requirements of the wind environment in the Evaluation Standard for Green Building. In the Environmental Livability chapter, there should be no vortex area or windless area in the pedestrian activity area of the site under typical wind speed in summer. In addition, under typical wind speed and wind direction conditions in winter, the wind speed needs to be smaller than 5 m/s at an elevation of 1.5 m in the pedestrian area around the building. Moreover, the wind speed at the outdoor rest area should be smaller than 2 m/s. According to relevant studies, people feel comfortable when the wind speed is larger than 1 m/s [57]. Therefore, the wind speed range of 1–2 m/s is defined as the comfortable wind speed range. The coupling relationship analysis is carried out based on this.

According to the results of the orthogonal test, the relationship between the influencing factors and the wind environment was acquired, as shown in Figure 12. For the slab-type high-rise dormitory, the staggered and aligned layouts are significantly better than the enclosed layout. The staggered layout is optimal, with an average wind speed of 1.45 m/s, which meets the standard and is comfortable. Therefore, during the planning and design phase, the staggered layout should be given priority for the slab-type high-rise dormitory. The average wind speed of the enclosed layout scheme is 0.86 m/s, which is not in the range of comfortable wind speed. It is generally not recommended. The average wind speed increases and then decreases with the length of the building. The wind environment is optimal at a length of 50 m. However, the variation in building length does not have a significant influence on wind speed. The wind speed increases with the increase in building width. The wind environment is optimal when the building width is 18 m and the average wind speed is 1.3 m/s. The wind speed increases with the increase in building height. The wind speed increases significantly when the height increases from 55.2 m to 85.2 m. The wind environment is optimal at a height of 85.2 m, with an average wind speed of 1.4 m/s.

For the tower-type high-rise dormitory, the influence of building layout on wind speed is not obvious. Aligned-type is better than staggered-type. Moreover, the layout should be considered in conjunction with the overall planning and roads. The wind speed is negatively correlated with the length of the building and the wind speed decreases with the increase in the length of the building. The wind environment is optimal at a length of 26 m. The average wind speed decreases and then increases when the building width increases from 24 m to 45 m. The wind environment is optimal at a width of 24 m and the average wind speed is 1.21 m/s. The average wind speed increases with the increase in building height. The wind speed increases significantly when the height increases from 55.2 m to 85.2 m. The wind environment is optimal when the building height is 85.2 m and the average wind speed is 1.35 m/s, which is in agreement with the standard and the wind environment is comfortable.



(**a**)



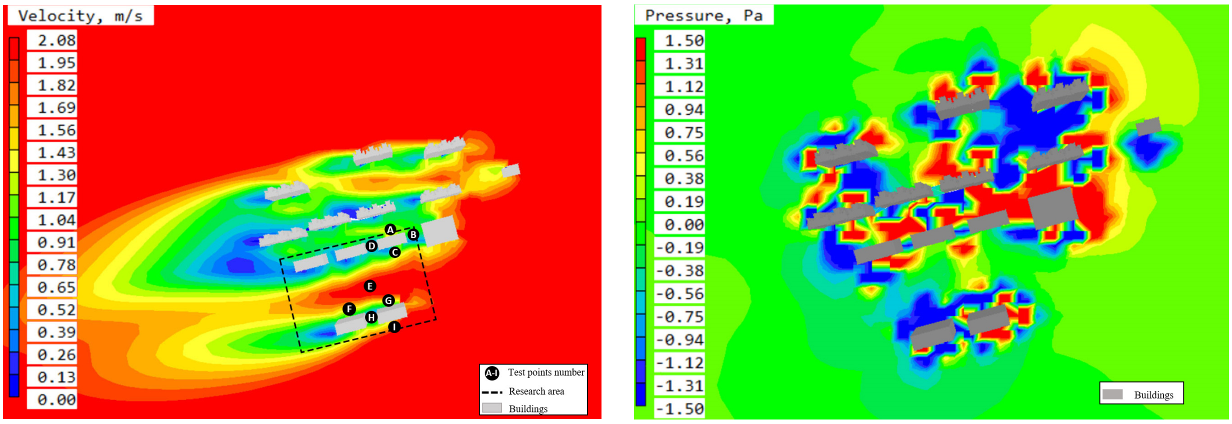
(**b**)

Figure 12. Influencing factors and wind environment relationship: (**a**) slab-type high-rise building; (**b**) tower-type high-rise building.

According to the above analysis, the optimal combination of slab high-rise dormitory was applied to the case CHD slab high-rise dormitory for simulation validation. That is, a staggered layout with a building length of 50 m, width of 16 m, and height of 85.2 m. No change in other factors such as the surrounding buildings was included in the case. The wind speed and pressure simulation results of the recommended scheme are shown in Figure 13. The speed selection position of the recommended scheme is the same as the position tested before. The wind speed data are shown in Table 17. The average wind speed of the original scheme is 0.83 m/s and the average wind speed of the recommended scheme is 1.43 m/s. According to the standard, the overall wind speed increases and the comfort level increases. Furthermore, the wind pressure difference between the front and rear of the building of the recommended scheme increases. The maximum wind pressure difference is 2.85 Pa. It is in agreement with the requirement of the pressure difference in the green building standard, that is, the wind pressure difference between the windward side and the leeward side of the building should not be greater than 5 Pa. The appropriate increase in the wind pressure difference can promote airflow movement. It is conducive to improving the outdoor wind environment of the dormitory area. Overall, we applied the recommended scheme to a real case for simulation. It can be found that the overall outdoor wind environment has been effectively improved.

Table 17. Comparison of wind speed data between original and recommended schemes.

Test Point Number	A	B	C	D	E	F	G	H	I
Original scheme wind speed (m/s)	0.75	0.64	0.91	0.82	0.52	0.90	0.70	0.93	1.27
Recommended scheme wind speed (m/s)	1.43	0.98	0.82	0.96	2.12	1.86	1.88	0.79	2.08



(**a**) (**b**)

Figure 13. Wind speed and pressure simulation of CHD slab high-rise recommended scheme. (**a**) Wind speed simulation; (**b**) wind pressure simulation.

5. Conclusions

The typical morphology of dormitory areas in cold regions was extracted by combing a large number of cases. The wind environment simulations and orthogonal tests were carried out on representative cases in Xi'an. The coupling relationship between two forms of high-rise dormitory buildings, in terms of layout, building length, width, and height, and outdoor wind environment was investigated and optimization strategies were put forward. We found that, with the development of dormitory buildings to high-rise ones, the accompanying outdoor wind environment problem should be paid attention to. In terms of research method, numerical simulation combined with the orthogonal test was utilized, which could substantially enhance the test efficiency. In practical application, it can be employed to compare schemes and guide the optimal design at the early stage of project design, which is helpful to promote the positive design of the building. Our study demonstrated the important influence of planning on the wind environment around the building. Furthermore, the study highlighted the importance of the assessment of the wind environment of alternative schemes during the design phase of large-scale projects, such as dormitory complexes.

The model created in this study through the numerical simulation is an ideal model under a typical morphology. The influences of vegetation, topography, and other building-related factors that may be influential in the real environment were not considered. The study was conducted only for cold regions in the geographical space, without considering other climate zones. In the study period, only the winter and summer wind environments were analyzed and the transition season was not involved. To address the above limitations, a more comprehensive study will be performed subsequently.

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