Research on the Influence of Ground Surface on Wind Environment in Shanghai Urban Squares

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Abstract: In order to reveal correlation between ground surface of urban squares and wind environment, the wind speed and wind direction of 20 plots were monitored during summer and winter in Shanghai Nation Anthem Square (NA square), Shanghai Knowledge and Innovation Community square (KIC square) and Shanghai Haisu Greenbelt Square (HSG square). The variations of wind speed and wind direction with different elevation, material, slope, slope form, topographic feature and aspect were surveyed. The difference of air flow in a variety of squares’ ground surface in summer and winter were analyzed. Furthermore, the design strategies of microclimate regulation were proposed for future squares planning with the seasonal preferences of wind environment.

Keywords: urban squares; ground surface; elevation; slope; aspect; wind environment

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The plaza base surface is one of the core elements in shaping the plaza's spatial configuration [1], serving as the foundation for its spatial functions and various activities. In his work ‘Yuan Ye’, Ji Cheng emphasized the importance of varied base surface forms by stating: "The plaza base need not adhere to a fixed orientation; the terrain naturally determines its elevation... By selecting the most suitable terrain and designing the plaza accordingly," [2] highlighting the significance of base surface variation. Base surface composition is a pivotal element in landscape architecture design. Variations in elevation, slope direction, slope shape, and topographic features on urban squares not only delineate spatial zones, enhance site functionality, and improve landscape appeal, but also alter the radiation balance on the base surface [3], influence near-surface airflow, and optimize the plaza's wind environment [4].

The wind environment is influenced by topographic structures and slope orientations. Any changes in terrain affect airflow patterns [5], enabling it to guide, concentrate, obstruct, or alter air currents, while also blocking

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heat and moisture exchange between mountainous areas and surrounding regions—impeding the dissipation of summer heat and the intrusion of winter cold in urban or settlement areas [6]. Research on terrain's impact on wind environments spans three scales: large-scale studies (e.g., the influence of African topography on the Indian summer monsoon [7]); medium-scale studies (e.g., mountain climates [8], urban microclimates [9], and the effects of airport surroundings on wind conditions [10,11]); and small-scale investigations where topography's impact on wind dynamics and microclimates has long been a focus for landscape designers. These studies range from qualitative analyses of terrain's effects on microclimates [12] to quantitative examinations of spatial vertical configurations in open spaces [13,14], ground surface morphology [15], enclosure characteristics [16], and airflow microcirculation [17].

Building on this foundation, to elucidate the impact of plaza ground surface variations on wind conditions, this study conducted continuous field measurements and quantitative analyses over winter and summer at three urban plazas in Shanghai. It examines how elevation differences, slope angles, slope profiles, slope orientations, and topographic features influence wind environments within small-scale spaces, aiming to provide a theoretical basis for wind environment design in urban plazas.

1. research technique

1.1 Research Area

Shanghai is located between east longitude 120°52′ and 122°12′, and north latitude 30°52′ and 31°53′, characterized by a subtropical maritime monsoon climate with hot summers, cold winters, and distinct seasons. In architectural climate zoning, it falls under the category of a hot summer and cold winter region [18,19]. According to statistical data analysis from the Shanghai Meteorological Center, the highest temperatures typically occur in July and August, while the lowest temperatures are recorded in January and December. Over the 23-year period from 1991 to 2013, the average temperatures in July and August were 28.6℃ and 28.1℃, respectively, with maximum temperatures reaching 40.6℃ and 41.2℃; the average temperatures in January and December were 4.3℃ and 7.0℃, respectively, and the lowest temperatures were consistently-8.5℃.

1.2 experimental design

The testing sites are all located in Shanghai's central urban area: the National Anthem Memorial Square and Chuangzhi Tiandi Square in Yangpu District, and the Haisu Green Space Square in Changning District (Figure 1). All three squares exhibit distinct topographic variations, with the National Anthem Memorial Square being an elevated plaza, while Chuangzhi Tiandi Square and Haisu Green Space Square are sunken plazas. Four field experiments were conducted to investigate the impact of plaza surfaces on wind conditions.

Figure 1: Location map of the test site

1) Experiment 1: The effect of elevation difference on wind speed (see Figure 2).

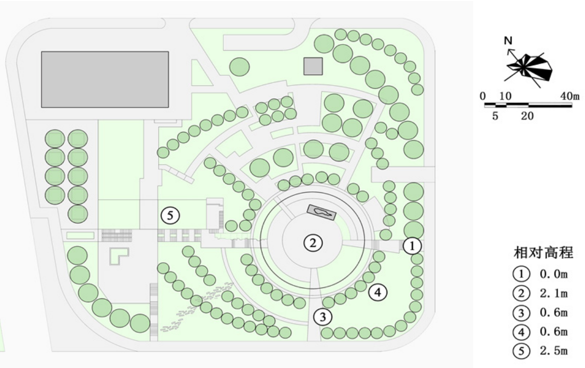

Figure 2: Layout plan of measurement points at the National Anthem Memorial Square

The experimental testing site was the National Anthem Memorial Square. The experiment consisted of three main sections: 1) Comparing daily wind speed variations at measurement points 1 (designated as the elevation reference level with a relative elevation of 0 m), 2 (relative elevation of 0.6 m), and 3 (relative elevation of 2.1 m) on hard surfaces versus measurement points 4 (relative elevation of 0.6 m) and 5 (relative elevation of 2.5 m) on the lawn, to investigate how elevation changes affect wind speed in elevated areas; 2) Comparing wind speed differences between measurement points at varying elevations during winter and summer to examine seasonal variations in elevation's impact on wind speed; 3) Comparing the effects of hard surfaces versus grasslands on wind speed—and their seasonal variations—at identical elevation differences (points 2 and 4) or similar elevation differences (points 3 and 5).

2) Experiment 2: Effect of slope gradient and shape on wind speed (Figure 3)

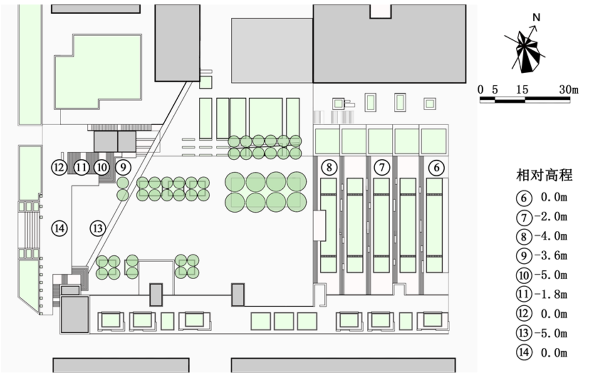

Figure 3: Measurement Point Layout Diagram of Chuangzhi Tiandi Plaza

The experimental testing site was the Chuangzhi Tiandi Plaza, and the experiment consisted of two main parts: 1) Comparing wind speed variations between a gentle slope with a 11° gradient (measuring points 6, 7, 8) and a steep slope with a 28° gradient (measuring points 10,11,12), as well as the difference in wind speed between the slope top and bottom, to investigate the effect of slope gradient on wind speed in the plaza;

2) Comparing wind speed differences between the slope top and the slope surface for two slope configurations—a steep ramp (measuring points 13 and 14 located above and below a 5m elevation difference) and a stepped slope (measuring points 9 and 12)—to examine the influence of slope shape on wind speed in sunken plazas.

3) Experiment 3: The effect of slope orientation on wind direction (see Figure 4)

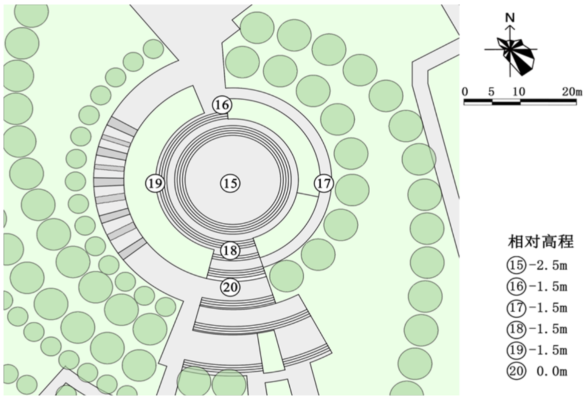

Figure 4: Layout plan of measurement points at Haisu Green Space Square

The experimental testing was conducted at Haisu Green Square. Measurement points were established at the center of the sunken plaza (Point 15) and on slopes with relative elevations of 1 m, oriented toward the east (Point 19), south (Point 16), west (Point 17), and north (Point 18). The original wind direction data were obtained by recording the instantaneous wind direction occurrence frequency every 10 minutes over 18 days during both winter and summer, to investigate the influence of slope orientation on wind direction within the sunken plaza.

4) Experiment 4: The Impact of Square Topography Characteristics on Wind Speed

The experiment was conducted at three test sites: the National Anthem Memorial Square, Chuangzhi Tiandi Square, and Haisu Green Space Square. Specifically, the National Anthem Memorial Square is an elevated plaza with a height difference of 2.1 m; Chuangzhi Tiandi Square is a sunken plaza with a height difference of 5 m; and Haisu Green Space Square is also a sunken plaza with a height difference of 2.5 m (see Figure 5). Wind speed differences were compared between the elevated section (Measurement Point 2) and the non-elevated section (Measurement Point 1) of the National Anthem Memorial Square during both winter and summer, versus the sunken section (Measurement Point 15) and the non-sunken section (Measurement Point 20) of Haisu Green Space Square. Similarly, wind speed differences were analyzed between the sunken section (Measurement Point 9) and the non-sunken section (Measurement Point 6) of Chuangzhi Tiandi Square during the same seasons, compared with those of Haisu Green Space Square. The study examined the impact of elevated and sunken plazas on wind speed, as well as the effects of sunken plazas at different scales.

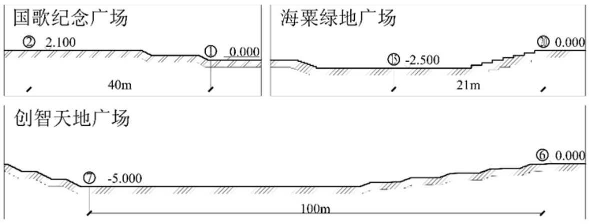

Figure 5: Cross-sectional view of the square

1.3 measuring and test instruments

The microclimate measurement instrument is the WatchDog Model 2900ET compact weather station manufactured by Spectrum Technologies (USA), with its detailed parameter specifications listed in Table 1. The primary field measurement equipment includes the Swiss-made Leica D810 laser rangefinder, the Swiss-made Haglof Vertex IV ultrasonic altimeter-rangefinder, and a tape measure.

Table 1 Detailed Configuration Table of Weather Stations

wind speed		wind direction	
measuring range	0 km/h, 3--241 km/h	measuring range	0-360°
Initial wind speed	3 km/h	certainty of measurement	±4°
certainty of measurement	±3 km/h, ±5%	resolution ratio	1°
resolution ratio	0.1 km/h		

1.4 test method

The microclimate tests were conducted on clear and cloudless days, with continuous day-night data collection at 10-minute intervals. The testing periods covered February 7–8 and July 14–August 5, 2015, as well as January 1–16,2016, during periods of moderate cloudiness and similar air temperatures. Each season involved nine days of testing at the Haisu Green Space Plaza; except for the two-day test at the Chuangzhi Tiandi Plaza on February 7–8, 2015, all other test sites underwent three days of testing. Data were collected at a height of 2.0 m, measuring wind speed and wind direction.

1.5 interpretation of result

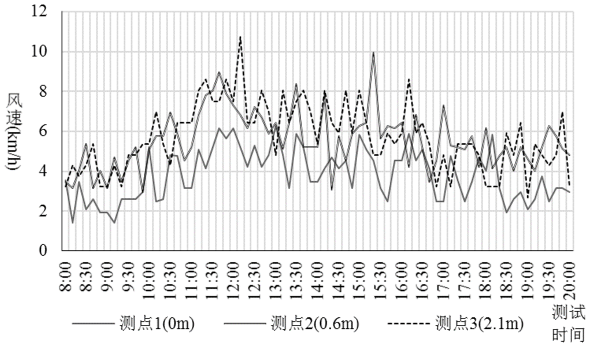

Figure 6 Daily variation of wind speed at different elevations

1.6 The Effect of Altitude Difference on Wind Speed in the Square

The daily variation charts of summer wind speed at different elevation measurement points (Figure 6) reveal the following patterns: 1) Wind speed exhibits daily fluctuations characterized by morning increases and evening decreases (with 10-minute data intervals resulting in frequent variations). Wind speeds are lowest in the early morning and evening, highest at noon, with the daily maximum occurring at midday. The meteorological mechanism explains this as follows: Daily wind speed variations primarily depend on turbulent exchange dynamics. During daytime, intensified turbulent exchange enhances air mixing between upper and lower layers, increasing ground-level wind speeds; by afternoon, convective and turbulent activities peak, reaching maximum ground wind speeds; subsequent weakening of turbulence reduces turbulent exchange between layers, leading to decreased ground wind speeds; at night, turbulent exchange nearly ceases, resulting in minimum ground wind speeds or even calm conditions [20].2) The maximum wind speeds and wind speed range at all three measurement points show a direct correlation with elevation differences—higher elevations correspond to greater maximum wind speeds and wider wind speed ranges. This phenomenon occurs because, as illustrated in Figure 7, airflow moving from lower to higher elevations experiences compression that converges airflow lines and accelerates upward movement, whereas airflow moving from higher to lower elevations experiences dispersion of airflow lines, reducing wind speed [21].

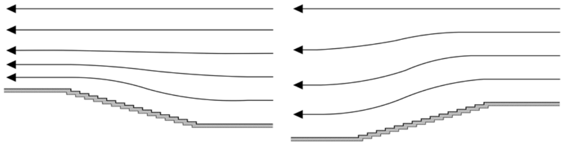

Figure 7: Diagram illustrating the effect of elevation on airflow patterns

The differences in daily average wind speeds at measurement points with varying elevation differences between winter and summer (Figure 8) indicate that the average wind speed is proportional to the elevation difference, with higher average wind speeds in summer than in winter. On hard surfaces, the wind speed difference among measurement points is smaller in summer than in winter, suggesting that elevation differences have a lesser impact on average wind speed in summer. In contrast, on grasslands, the wind speed difference among measurement points is significantly greater in summer than in winter, indicating a stronger influence of elevation differences on average wind speed—this is primarily due to the distinct growth characteristics of vegetation on grasslands during the two seasons.

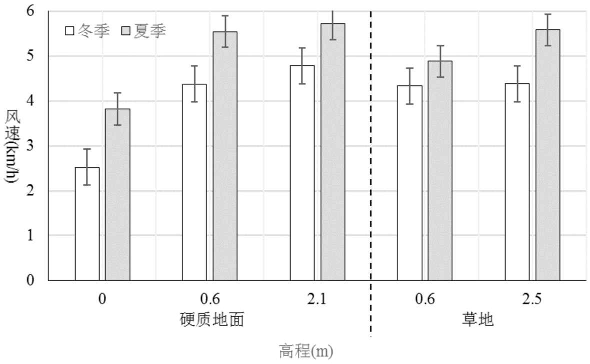

Figure 8 Comparison of daily average wind speeds at different elevations and ground surface materials

As shown in Figure 7, the following observations are made: 1) When the elevation difference is the same (both 0.6 m), the wind speed at measurement point 4 on the grassland is lower in both winter and summer compared to that at measurement point 3 on the hard surface. This is due to the rough surface texture of the grassland versus the smooth surface of the hard ground: wind velocity increases when flowing from a smooth surface to a rough one [21], while decreasing when flowing from a rough surface to a smooth one; 2) In winter, as grass plants wither and enter dormancy, surface roughness decreases, resulting in a wind speed difference between points 3 and 4 of only 6.89% of that observed in summer, indicating that surface texture significantly influences wind speed; 3) When the elevation difference between the grassland and the hard surface is greater, the combined effects of the proportional relationship between elevation difference and wind speed, along with surface roughness's obstructive effect on airflow, lead to lower wind speeds at point 5 in both seasons compared to point 2, demonstrating that wind speeds are higher on hard pavements than on rough grasslands.

1.7 The Impact of Slope Angle and Shape on Wind Speed in the Square

The wind speed values at each 10-minute interval during the 72-hour summer testing period on both the gentle slope (slope of 11°) and the steep slope (slope of 28°) within the Chuangzhi Tiandi Plaza were compiled and plotted as a box plot in Figure 9. The upper edge, upper quartile, median, lower quartile, and mean values for the gentle slope were all higher than those for the steep slope. Additionally, the mode calculation revealed a wind speed of 6 km/h on the gentle slope versus 4 km/h on the steep slope, further confirming the higher wind speeds on the gentle slope. The lower wind speeds on the gentle slope can be attributed to the following: As shown in Figure 10, airflow on the gentle slope flows closely along the ground surface. When airflow moves from low to high elevations, it is compressed, causing airflow lines to converge and accelerating upward movement; conversely, when airflow moves from high to low elevations, the lines diverge, reducing wind speed. Thus, wind speeds on the gentle slope are primarily influenced by airflow patterns. In contrast, airflow on the steep slope does not fully conform to the ground surface. Sudden changes in the underlying terrain generate counter-directed vortices under the dominant airflow, resulting in lower wind speeds compared to the gentle slope.

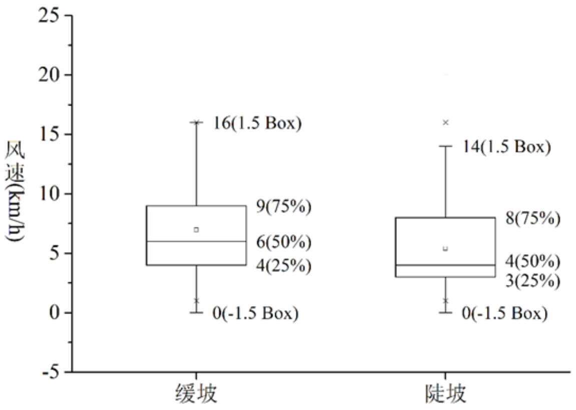

Figure 9 Comparison of daily wind speed distributions at different slopes

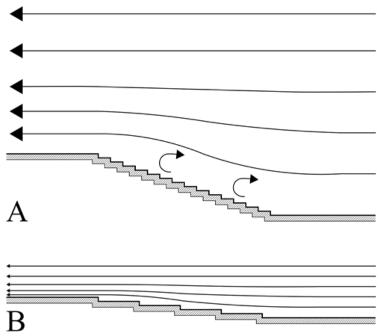

Figure 10: Diagram illustrating the effect of slope gradient on airflow (A represents a steep slope, B represents a gentle slope)

The analysis of the difference between wind speeds at the slope summit and base during winter and summer (Figure 11) reveals: 1) In summer, the average wind speed on gentle slopes is higher than that on steep slopes, while the difference between the summit wind speed and the ground-level wind speed on steep slopes exceeds that on gentle slopes, indicating that steep slopes exhibit not only lower wind speeds but also a greater influence on wind speed compared to gentle slopes; 2) In winter, the wind speed difference between the summit and base of steep slopes is lower than that of gentle slopes, measuring only 0.69 km/h, suggesting that steep slopes have a smaller impact on wind speed than gentle slopes.

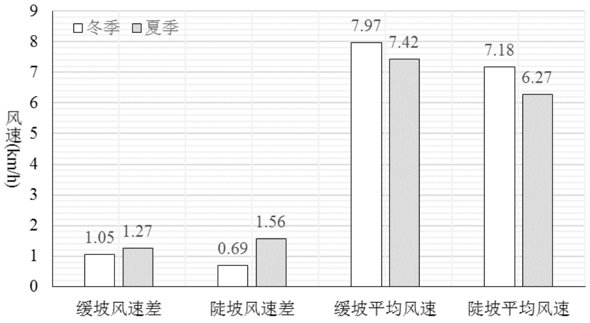

Figure 11 Comparison of wind speed differences and average wind speeds at different slopes

As shown in Figure 12, the wind speed differences and average wind speeds at the slopes 'tops and bases reveal that during winter, the average wind speeds for both slope types are comparable. The steep ramp slope exhibits an average wind speed only 0.33 km/h slower than the stepped slope, while its wind speed difference is 1.03 km/h higher. This indicates that in sunken plazas, the steep ramp slope exerts a stronger wind-diminishing effect on internal wind speeds compared to the stepped slope. Figure 13 elucidates the underlying mechanisms: 1) When airflow moves from the slope base to the summit, the airflow at the steep ramp's top (Figure 13-A1) accelerates due to topographic elevation, whereas the airflow at the base forms an unstable, weak lee eddy (Bolster eddy) flowing against the general direction—a significant velocity disparity exists between the slopes 'tops and bases. In contrast, the stepped slope (Figure 13-B1) demonstrates smaller velocity differences caused by upward acceleration due to its elevated terrain. 2) When airflow moves from the summit to the base, the steep ramp's abrupt depression creates an unstable, weak lee eddy (Lee eddy) beneath the cliff, delaying the dispersion of primary airflow lines compared to the stepped slope (Figure 13-B2), resulting in a greater wind speed difference between the steep ramp's top and base.

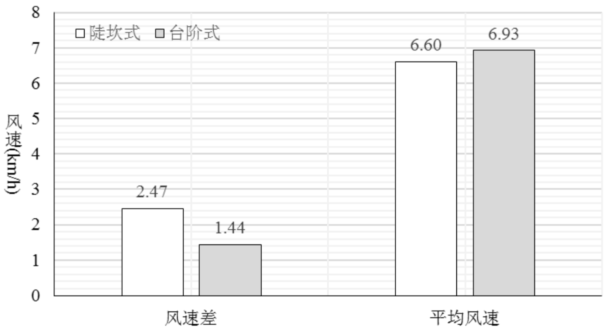

Figure 12 Comparison of wind speed differences and average wind speeds for different slope profiles

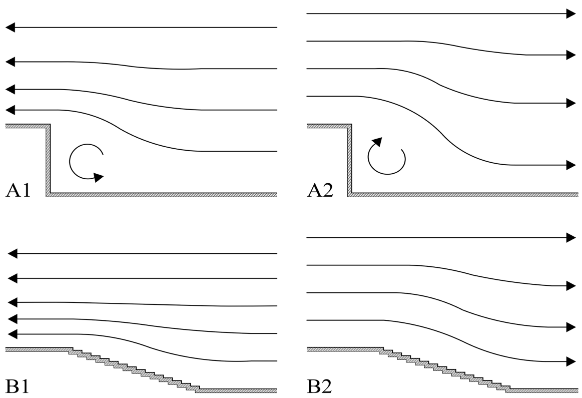

Figure 13: Diagram illustrating the impact of slope shape on airflow (A: steep ramp type; B: stepped type)

The Influence of the Slope Direction on the Wind Direction at the Square

In undulating terrain, wind directions exhibit significant variability due to local circulation effects and the influence of topography on general circulation patterns. This variation is particularly pronounced on clear days when general circulation is weak, with the most pronounced differences in wind direction observed between different areas during periods of intense local circulation [22]. Additionally, wind directions change rapidly and do not maintain a consistent direction [23]. Therefore, the instantaneous wind direction frequency at each monitoring point every 10 minutes is used as the primary wind direction indicator. The radar charts in Figure 14 are arranged according to the spatial positioning of monitoring points within the square. Haishu Green Space Square is a circular sunken plaza. As shown in the charts, during winter: the dominant wind direction on the eastern slope is east; on the western slope, it is westward; on the southern slope, it is south; while the dominant wind direction on the northern slope and the plaza center is southeast. Throughout the observation period, the prevailing wind direction in the square was southeast. Winds entered the plaza from the northern slope on its southern side, resulting in predominantly southeast winds on the northern slope and plaza center. As these winds ascended along the steps or slopes, they accelerated upward airflow, aligning the dominant wind directions on the eastern, southern, and western slopes with their respective slope orientations.

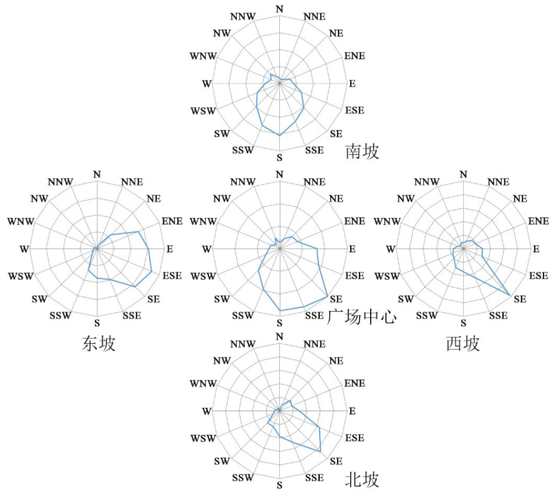

Figure 14: Analysis of the Impact of Winter Slope Orientation on Wind Direction

As shown in Figure 15, during summer, the prevailing wind direction on the southern slope is south, while that on the eastern slope is easterly—similar to the factors influencing the prevailing wind directions on the eastern, southern, and western slopes in winter. The prevailing wind direction on the western slope, northern slope, and the center of the square is all southeast, reflecting the influence of the prevailing wind direction in the test area.

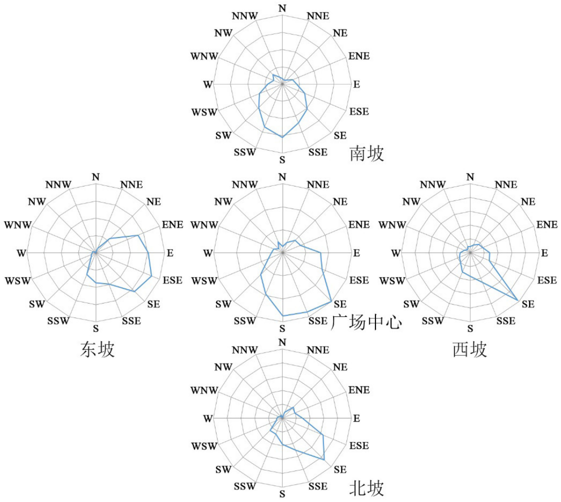

Figure 15: Analysis of the impact of summer slope orientation on wind direction

1.8 The Impact of Square-shaped Topographic Features on Wind Speed

Figure 16 shows the wind speed difference between the interior and exterior of the Winter and Summer National Anthem Memorial Square and the Haisu Green Space Square during the testing period from 8:00 to 20:00. Analysis reveals that due to the acceleration effect of elevation differences on airflow, the indoor wind speed in the elevated square is higher than the outdoor wind speed in winter, but lower in summer; whereas in the sunken square, the indoor wind speed is lower than the outdoor wind speed in both seasons, as the sunken space slows air movement and reduces wind speed.

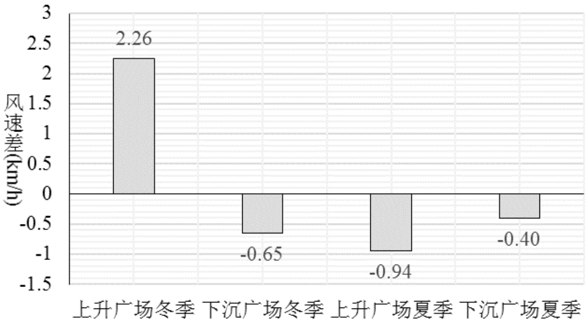

Figure 16 Comparison of wind speeds in the rising and descending plazas

Figure 17 shows the daily (24-hour) wind speed difference between the interior and exterior of the two sunken plazas—the Dongxia Chuangzhi Tiandi Plaza and the Haisu Green Space Plaza—during the testing period. Analysis reveals that: 1) Regardless of season or plaza size, the internal wind speed in sunken plazas is lower than that outside; 2) The wind speed difference between the interior and exterior is greater in larger-scale sunken plazas than in smaller-scale ones; 3) In larger-scale plazas, the summer wind speed difference is greater than in winter, whereas in smaller-scale plazas, the winter difference exceeds the summer difference.

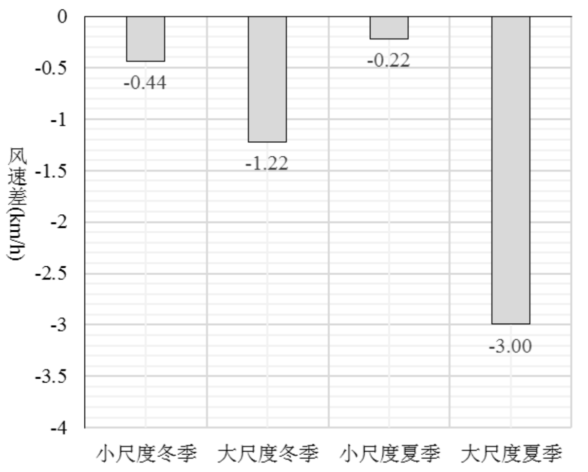

Figure 17 Comparison of wind speeds in sunken plazas at different scales

2. Conclusion and Discussion

2.1 Conclusion

Through field measurements conducted during winter and summer at 20 monitoring points across three squares in Shanghai, this study investigated the effects of elevation differences, ground materials, slope angle and shape, and topographic features on square wind speeds, as well as the influence of slope orientation on wind direction. The following conclusions were drawn.

1) Wind speed values in urban squares exhibit fluctuating patterns, but the overall daily variation shows a unimodal trend: lower speeds in the morning and evening, and higher speeds at noon.

2) The varying surface roughness of plaza foundations differently affects wind speed. At the same elevation difference, wind speeds on hard surfaces exceed those on grassy areas. When the foundation elevation varies, the height difference influences site wind speeds: greater elevation differences result in higher maximum wind speeds, wider wind speed ranges, and higher average wind speeds. On hard surfaces, the impact of elevation differences on wind speed is less pronounced in summer than in winter. On grassy areas, however, the effect of elevation differences on wind speed is stronger in summer due to the seasonal growth patterns of grass vegetation.

3) In sunken plazas, wind speeds on steep slopes are lower than those on gentle slopes, and wind speeds beneath steep steps are lower than those beneath terraces. In compact, relatively enclosed sunken plazas, airflow accelerates along the direction of steps or increasing gradients, aligning the prevailing wind direction with the slope orientation.

4) In winter, the internal wind speed at the elevated plaza exceeds that of the exterior, whereas in summer it is lower. The internal wind speed at the sunken plaza is consistently lower than the exterior in both seasons. Considering people's seasonal preferences—favoring wind in summer and windless conditions in winter—the internal wind environment of the sunken plaza is most desirable in winter. In contrast, both the internal wind conditions of the sunken plaza in summer and those of the elevated plaza in both seasons are inferior to those outside the plazas.

5) The wind speed difference between the interior and exterior of larger sunken plazas is greater than that of smaller ones.

In larger sunken plazas, the summer wind speed difference between interior and exterior is greater than in winter; in smaller ones, the winter difference exceeds the summer difference. Considering seasonal preferences for wind conditions, larger sunken plazas provide better wind environments in winter, while smaller ones offer superior conditions in summer.

2.2 Discussion

The design of a microclimate-adaptive plaza should create as many comfortable zones as possible to accommodate varying climatic conditions throughout the year. Since people have different preferences for wind conditions in winter and summer—desiring ventilation and cooling in summer versus wind protection and insulation in winter—the plaza should address these needs accordingly.

1) For wind protection during winter, the primary approaches involve employing both wind barriers and wind diversion techniques at the prevailing wind direction points to mitigate the impact of cold winds on the plaza. Wind barriers utilize vertical surfaces and corner steps for direct obstruction, while wind diversion leverages the superior wind-reducing effects of steep slopes compared to gradual slopes—by designing appropriate slope shapes and gradients based on the plaza's specific topography to minimize wind speed upon its entry. Additionally, airflow is directed away from the wind source by incorporating buildings [24] and vegetation [25].

2) Regarding summer ventilation: The primary approach involves employing air induction and cooling methods at the direction of the prevailing summer wind to enhance wind strength or direct airflow onto the plaza. Air induction utilizes varying slope shapes and gradients to amplify or reduce wind speed, or employs the "narrow tube effect" to accelerate incoming airflow, thereby improving plaza ventilation during summer. Cooling is achieved by installing fountains or other water features at these locations to reduce the temperature of incoming airflow [26], leveraging the synergistic cooling and ventilation effects of water bodies [27].

The urban square's ground surface is significantly affected by the wind environment; therefore, this paper focuses solely on analyzing the relationship between the ground surface and the wind environment. The relationships between the ground surface and microclimate indicators—including relative air humidity, solar radiation, air temperature, ground temperature, and atmospheric pressure—were not examined in detail. Future research could analyze the relationship between the square's ground surface and the microclimate through both field measurements and simulations of wind, humidity, and thermal conditions, investigate its underlying mechanisms, and develop theoretical frameworks, methodologies, and technical approaches for designing squares optimized for microclimate suitability.

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