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# The Influence of High-Rise Buildings on Pedestrian-Level Wind in Surrounding Street Canyons in an Urban Renewal Project

**Tzu-Ling Huang [1], Chien-Yuan Kuo [2], Chun-Ta Tzeng [1] and Chi-Ming Lai [3,*]**

[1] Department of Architecture, National Cheng Kung University, Tainan 701, Taiwan; saiyoki@gmail.com (T.-L.H.); ctmt@mail.ncku.edu.tw (C.-T.T.)
[2] Architecture and Building Research Institute, Ministry of the Interior, New Taipei City 23143, Taiwan; kcy@abri.gov.tw
[3] Department of Civil Engineering, National Cheng Kung University, Tainan 701, Taiwan
* Correspondence: cmlai@mail.ncku.edu.tw; Tel.: +886-6-2757575 (ext. 63136)

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**Abstract:** The pedestrian wind environment in a street canyon is affected by a multitude of factors, including the height and geometric shape of the surrounding buildings, the street width, the wind direction, and speed. Wind-tunnel tests were performed to determine the effects of constructing high buildings in an urban renewal project in New Taipei City, Taiwan on the pedestrian wind environments in the surrounding street canyons. The results show that replacing the original low-rise buildings with high-rise buildings could decrease the wind speed and natural ventilation potential in certain surrounding street canyons. The flow fields generated by approaching winds in various street canyons are highly complex in this practical case study. Thus, the pedestrian wind patterns in the street canyons cannot be interpreted in terms of channeling and shielding effects alone, as is typically reported in the literature.

**Keywords:** urban renewal; pedestrian wind environment; street canyon; high-rise building; wind-tunnel testing

## 1. Introduction

The effect of a high-rise building on the surrounding microclimate is an important design consideration in addition to safety and aesthetics. For example, strong ground-level winds generated around high-rise buildings may affect pedestrian safety and comfort.

Pedestrian wind environments have been actively studied since the 1960s. These studies on the effects of buildings on the surrounding pedestrian-level wind fields can generally be categorized into those on a single high-rise building [1–5] and those on building clusters. Tamura et al. [4] performed wind-tunnel tests to investigate the effects of several parameters (i.e., the building height H, the building width B, the aspect ratio H/B, and the approaching flow profile) on pedestrian-level wind fields surrounding single rectangular-plan high-rise buildings. The downwash airflow generated by the buildings within the boundary layer flow significantly affected the surrounding pedestrian-level wind field. Both the area and wind intensity of strong-wind regions increased with H, albeit at lower rates beyond a defined H value. At a fixed H, decreasing the aspect ratio (i.e., by increasing the width of the windward side of the building) weakened the downwash and Venturi effects.

Kuo et al. [2] used wind-tunnel tests to investigate the characteristics of the pedestrian-level wind environment in street canyons under different conditions, including different street widths, podium heights, and approaching wind directions. The results showed that a higher podium creates stronger wind speeds within the street canyon.

The pedestrian-level wind field characteristics in a building cluster are affected by the building morphological characteristics. A complex airflow is produced from the interaction of many factors. The channeling effect increases the wind speed in a street canyon to create unpleasant gusts. The outdoor air inflow direction, the street canyon width, and the building height on the sides of the street canyon all affect the street canyon wind field characteristics.

Blocken et al. [6] described three types of wind flow in inter-building passages of various widths: resistance, interaction, and isolation flow. Increased wind speeds in a passage occur only at pedestrian height, whereas wind speeds at other passage heights are only 8% higher than those in the free flow (that is, in the absence of buildings). Thus, the Venturi effect does not operate for wind fields in passages. Blocken et al. [7] designed diverging and converging configurations of two high-rise buildings and performed wind-tunnel tests using the wind speed profiles of rural areas. The wind speeds were higher in the diverging passage than the converging passage and increased with the street canyon width. This result contradicts results obtained from previous studies on parallel street canyon passages. Li et al. [8] validated the wind network index based on wind-tunnel test results for the spatial average velocity, the surface pressure on individual buildings, and the total drag force. The wind network index was found to effectively identify the effect of the building layout on the wind field. The road distribution affects the street canyon morphology and thereby the urban wind environment. He et al. [9] used wind-tunnel tests and computational fluid dynamics (CFD) simulations to show that non-orthogonal road networks can channel horizontal airflows more easily than orthogonal road networks.

Real urban morphologies have been used in several studies to determine wind field characteristics in large street canyons [8–12]. Ramponi et al. [10] used CFD to investigate urban outdoor ventilation for different wind directions and equal and unequal street widths. Depending on the wind direction, the main street could promote or deteriorate the ventilation efficiency of the downstream area. Biao et al. [11] proposed the use of urban spatial indices (openness, area, and shape) to determine urban wind field characteristics. An et al. [12] used CFD to verify the urban ventilation and air pollutant dispersion effects of a void design of high-mass high-rise buildings.

Building heights along riverbanks are often maximized to obtain the best landscape views and increase total floor areas. Towering, massive buildings along riverbanks can beautify city skylines. However, from a wind environment perspective, massive buildings are likely to produce strong winds in corners and weak winds in downstream street canyons. Excessively strong and weak winds both negatively impact urban microclimates. In Taiwan, some county and city governments have used urban design specifications to reduce external wind obstruction from newly constructed buildings and consider convection to be effective for ventilation and heat dissipation in the built environment.

Few studies investigating the wind environment issue in urban renewal impact have been reported. In this context, the objective of the present study is to provide insights into the impact of demolishing original low-rise buildings and constructing high-rise buildings on the pedestrian wind environments in the surrounding street canyons for which little information is available. Wind-tunnel tests were performed to analyze the environmental wind fields based on the morphology of original low-rise buildings subjected to urban renewal area and the post-urban renewal morphology of high-rise buildings. The results for the two different morphologies are used to determine the effects of increasing building heights on the pedestrian-level wind fields in the surrounding street canyons.

## 2. Materials and Methods

In this study, wind-tunnel tests were performed based on an actual urban renewal project. An 800-m-diameter urban street area was investigated, including the urban renewal area and the surrounding existing buildings. A wind-tunnel test model with a 3.2 m diameter was generated at a scale of 1/250. The pre-urban renewal original buildings are approximately 10 m in height and classified as low-rise buildings (the blue regions in Figure 1a). During urban renewal, these buildings will be demolished, and high-rise buildings approximately 90 m in height will be constructed at the same site (the red regions in Figure 1b).

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

**Figure 1.** Wind-tunnel test model. (**a**) Before urban renewal; (**b**) after urban renewal.

Irwin probes [13] were used to measure wind speeds in the wind-tunnel tests. The Irwin probe is a simple and omnidirectional piece of equipment that serves as a surface wind sensor for measuring both the mean wind speed and low frequency fluctuations of pedestrian-level winds in wind-tunnel testing. The Irwin probe has been proven to be satisfactory for practical use in wind-tunnel studies [14–16]. The calibration for the used Irwin probes has been done, using the Cobra Probes (Turbulent Flow Instrumentation Pty Ltd., Victoria, Australia) and hotwire anemometers. Good agreement can be observed between the Irwin probe and hotwire anemometer measurements under 16 different wind velocities [2].

A total of 42 Irwin probes were placed within the urban renewal site (the area surrounding the buildings to be renewed) and the target street canyons. Figure 2 shows the placement of the Irwin probes, the street canyons (labeled as C1–C9), and the buildings to be renewed (blue regions). Table 1 summarizes the characteristics of each street canyon, including the length (L) and the height/width (H/W) ratio (i.e., the ratio of the height of the buildings to the street canyon width) of each street canyon and the approaching wind directions for winds generated parallel or perpendicular to the target street canyons. The direction of a wind from due north to due south is 0°. The wind direction increases clockwise. The main purpose of observing winds parallel to the street canyons is to examine the channeling effect. A wind generated parallel to a treet canyon may cause the wind speed in the street canyon to increase. Generally, a channeling effect is present when the angle between the direction of a street canyon and the direction of an approaching wind is ±30°. The purpose of observing winds perpendicular to street canyons is to examine the shielding effect. When the angle between the direction of an approaching wind and the direction of a street canyon is ±30°, the street becomes a canyon that acts as a shield from the approaching wind.

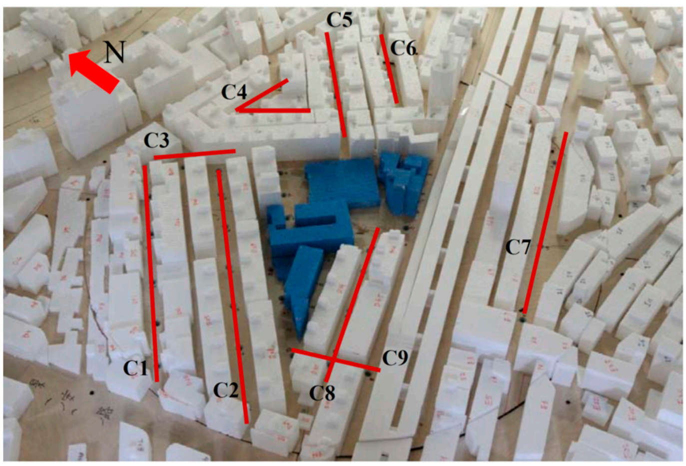
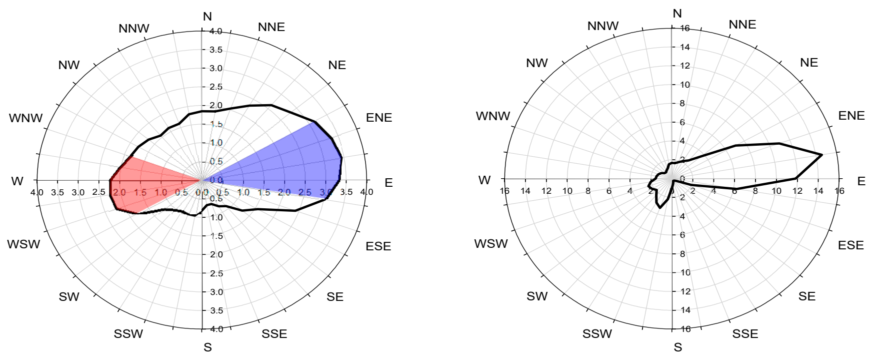



**Figure 2.** Placement of Irwin probes within street canyons C1–C9.

**Table 1.** Characteristics of street canyons.

| Street Canyon No. | Wind Speed Measuring Points | Characteristics of Street Canyon | Directions of Winds Parallel to Street Canyon (°) | Directions of Winds Perpendicular to Street Canyon (°) |
|---|---|---|---|---|
| C1 | 1–6 | L: 168 m<br>H/W: 1.3 and 0.7 | 40–100 and 220–280 | 140–200 and 320–20 |
| C2 | 8–14 | L: 175 m<br>H/W: 1.3 | 40–100 and 220–280 | 140–200 and 320–20 |
| C3 | 6, 7, and 14 | L: 52 m<br>H/W: 1.4 and 0.8 | 320–20 and 140–200 | 40–100 and 220–280 |
| C4 | 15–18 | L: 145 m<br>H/W: 1.4 and 1.3 | 90–150 and 270–330 | 0–60 and 180–240 |
| C5 | 19–21 | L: 70 m<br>H/W: 1.35 | 40–100 and 220–280 | 140–200 and 320–20 |
| C6 | 22–24 | L: 62.5 m<br>H/W: 1.5 | 40–100 and 220–280 | 140–200 and 320–20 |
| C7 | 25–28 | L: 145 m<br>H/W: 1.4 and 1.1 | 70–130 and 250–310 | 330–40 and 150–220 |
| C8 | 29–31 | L: 80 m<br>H/W: 1.1 and 0.8 | 70–130 and 250–310 | 330–40 and 150–220 |
| C9 | 31–33 | L: 45 m<br>H/W: 1.1 and 0.8 | 330–40 and 150–220 | 70–130 and 250–310 |

The urban renewal site is located in the Xinhe section of the Zhonghe district of New Taipei City, Taiwan. Figure 3 shows the hourly wind speed and wind direction data acquired at meteorological stations near the urban renewal site over a 10-year period from 2003 to 2013. The data are divided into 10° intervals. There are 36 wind directions. Low wind speed data (<0.3 m/s) were excluded from the analysis. No measurements were taken during typhoons. Figure 3a shows the mean wind speed distribution in each wind direction. Clearly, the mean wind speed is highest (3.4 m/s) at 80° and lowest (0.68 m/s) at 160°. Figure 3b shows the probability distribution of each wind direction. Among the wind directions, 80° has the highest probability of occurrence (14.56%), and 150° has the lowest probability of occurrence (0.28%).



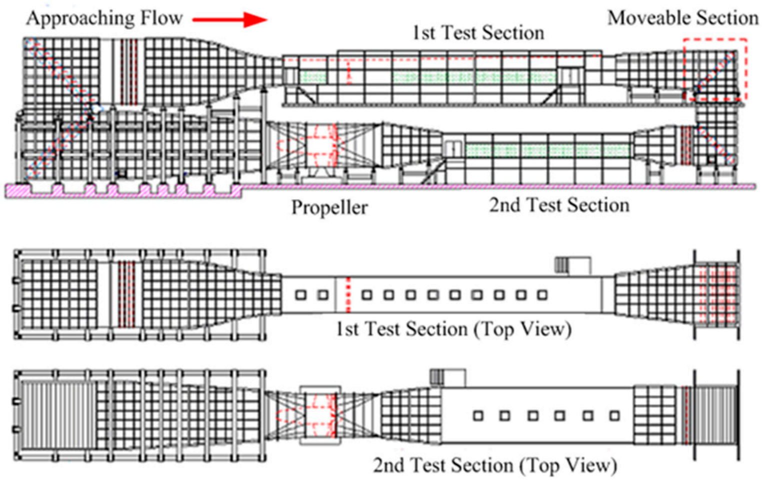

(**a**) (**b**)

**Figure 3.** Wind speed and wind direction data acquired at meteorological stations near the urban renewal site for 2003–2013. (**a**) Mean wind speed for various wind directions; (**b**) after urban renewal probability of each wind direction.

The experiments were conducted at the Wind-tunnel Laboratory of the Architecture and Building Research Institute, Ministry of the Interior, Taiwan on the Gueiren Campus of National Cheng

Kung University. As shown in Figure 4a, a closed wind-tunnel with two test sections was used. The pedestrian-level wind flow testing in this study was conducted using the second rotating disc of the first test section. This test section was 36.5 m long, 4 m wide, and 2.6 m high with a maximum wind speed of 30 m/s.

In accordance with Taiwanese regulations, the wind flow above suburban terrain was simulated using a series of 1.6-m spoiler and roughness elements to produce a mean wind speed profile for the approaching turbulent wind flow in the wind-tunnel with a power law exponent of 0.25. The building models were fabricated at a length scale of 1/250. Figure 4b,c show the normalized mean wind speed, $U_{mean}/U_{\delta}$, and the turbulence intensity of the approaching wind, respectively. $U_{mean}$is the mean wind speed at a height z, and $U_{\delta}$ is the mean wind speed at the height of the modeled atmospheric boundary layer ($\delta$ = 1.6 m).

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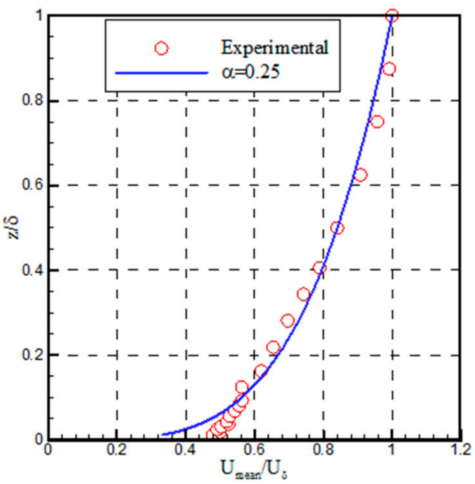


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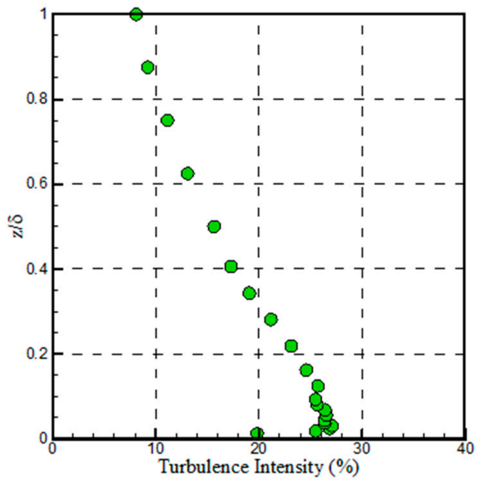



(**c**)

**Figure 4.** Wind-tunnel diagrams and approaching wind profile in wind-tunnel [2]. (**a**) Schematic (left) and photo (right) wind-tunnel; (**b**) mean speed profile; (**c**) mean speed profile.

## 3. Results and Discussion

The effects of urban renewal on the pedestrian wind environments in the street canyons are discussed here. In Figures 5–7, the purple squares and light green triangles show the pre- and post-urban renewal pedestrian-level wind speeds in the street canyons, respectively.

The street canyon C1 is 168 m long with H/W ratios of 1.3 and 0.7. Winds approaching from 40°–100° and 220°–280° generate winds parallel to C1, and winds approaching from 140°–200° and 320°–20° generate winds perpendicular to C1. Figure 5a shows the changes in the pedestrian-level wind speeds in C1 after urban renewal. Clearly, the wind speeds are considerably lower after urban renewal than before urban renewal. This result can be explained in terms of the impact of the new high-rise buildings, as shown by the red regions in Figure 5a. In particular, before urban renewal, a pedestrian-level wind field is generated by an approaching wind at 10°–110°. After urban renewal, the new high-rise buildings reduce all the wind speeds in this area to below 1 m/s. Evidently, the new high-rise buildings significantly affect urban ventilation quality.

Figure 5b shows the changes in pedestrian-level wind speeds in C2. The wind speed distributions before and after urban renewal are highly similar. After urban renewal, non-significant local changes in wind fields occur for wind speeds higher than the human comfort level (1 m/s). There is a slight increase in pedestrian-level wind fields after urban renewal for those approaching from 170°–250°, as shown by the red regions. However, Figure 3b shows that winds approaching from 170°–250° have a very low probability of occurrence. Thus, urban renewal is not very likely to increase pedestrian-level wind speeds. Under other conditions, new high-rise buildings constructed for urban renewal produce a decrease in wind speeds.

Figure 5c shows the changes in the pedestrian-level wind speeds in C3. There is a peak wind speed before and after urban renewal. Before urban renewal, the peak wind speed occurs for 60° winds. Figure 3b shows a high probability of winds approaching from 60° (as indicated by a red arrow), that is, 60° winds occur frequently in this area. Thus, the pedestrian-level wind speeds in this street canyon are not low, creating good urban ventilation. After urban renewal, the peak wind speed occurs for 40° winds (as indicated by a red dotted arrow). Figure 3b shows that the probability of winds approaching from 40° is not high. Thus, the construction of new high-rise buildings for urban renewal could possibly decrease street ventilation. Urban renewal could produce a notable decrease in wind speeds for wind fields with original wind speed above 1 m/s. Before urban renewal, 11 wind directions can produce a mean wind speed above 1 m/s. After urban renewal, there are only three such wind directions. Thus, high-rise buildings could significantly affect comfortable wind fields in C3.

Figure 6a shows the changes in the pedestrian-level wind speeds in C4. Before urban renewal, the wind speed is above 1 m/s for 10°–120° winds and below 1 m/s in all other directions. Figure 3b shows this street canyon could have an adequate urban wind environment. The overall wind speed decreases after the construction of new buildings for urban renewal. After urban renewal, only the winds in the directions of 80°–110° have speeds over 1 m/s, and the wind speed is low in all other directions. The wind speed is further reduced after urban renewal in the directions where the original wind speed was below 1 m/s before urban renewal. Evidently, high-rise buildings could affect the wind speeds in C4 after urban renewal.

Figure 6b shows the changes in the pedestrian-level wind speeds in C5. Before urban renewal, there are comfortable wind fields with wind speeds above 1 m/s for 10°–110° and 250°–270° winds. The maximum wind speed (approximately 1.9 m/s) occurs at 50°, the minimum mean wind speed (approximately 0.2 m/s) occurs near 160°, and the wind speeds in other directions are below 1 m/s. However, after urban renewal, there are significant changes in the wind speeds. The construction of high-rise buildings decreases the wind speed to below 1 m/s in all the directions for which the original wind speeds are above 1 m/s, except for 30°–50°, for which the wind speed is slightly above 1 m/s. However, in the 310°–360° directions, the wind speeds increase from low values before urban renewal to above 1 m/s after urban renewal.

Figure 6c shows the changes in the pedestrian-level wind speeds in C6. Before urban renewal, the wind speeds for 10°–120° winds are above the comfort level (1 m/s), with a maximum wind speed of approximately 1.8 m/s. The wind speeds in other directions are below 1 m/s. The minimum wind speed (0.3 m/s) occurs at 200°. However, after the construction of new high-rise buildings for urban renewal, the wind speeds in all the directions are below 1 m/s. The maximum and minimum wind speeds are 0.9 and 0.2 m/s, respectively.

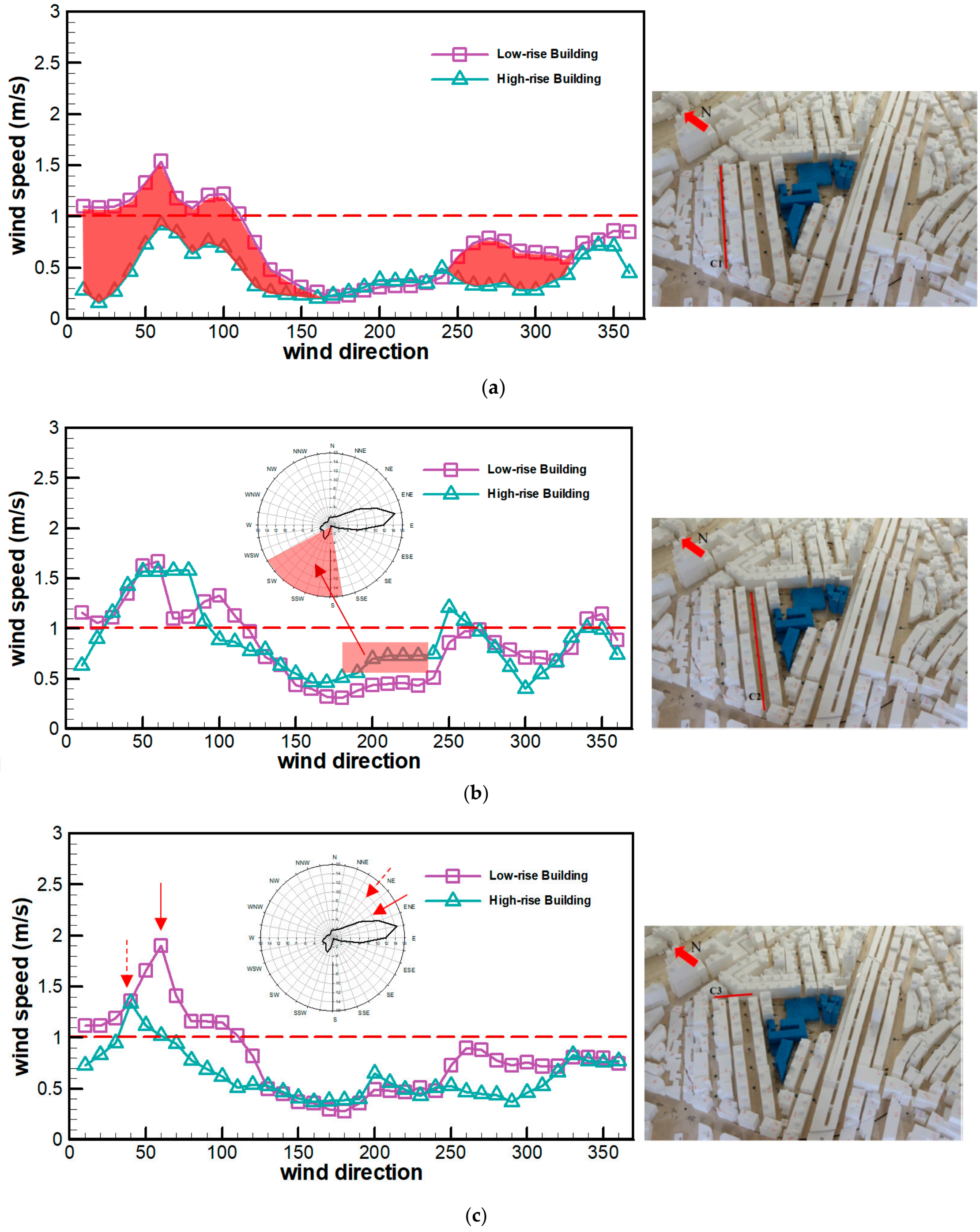
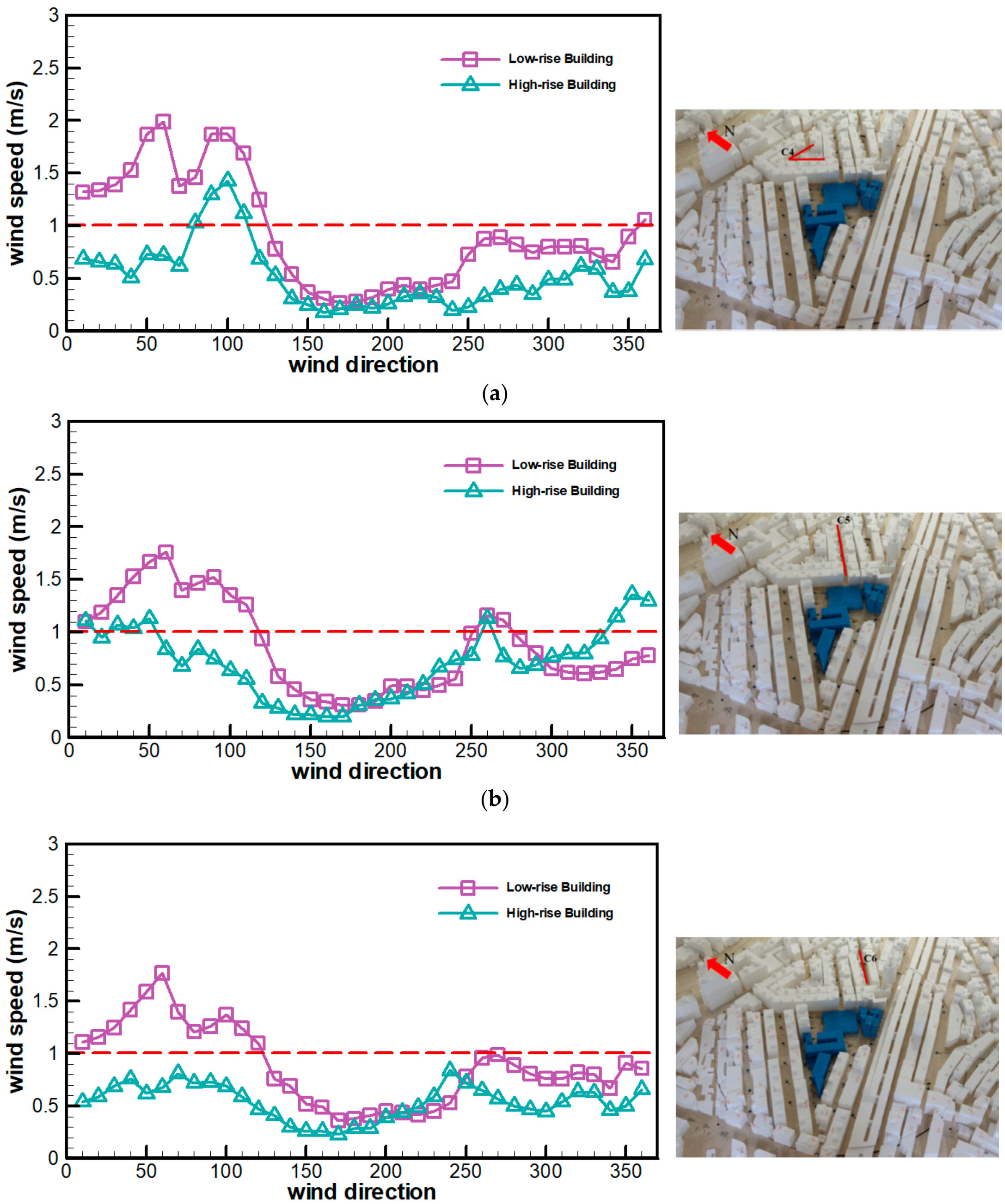



**Figure 5.** Characteristics of pedestrian wind environments in street canyons C1–C3 before and after urban renewal. (**a**) Street canyon C1; (**b**) street canyon C2; (**c**) street canyon C3.




(**a**)

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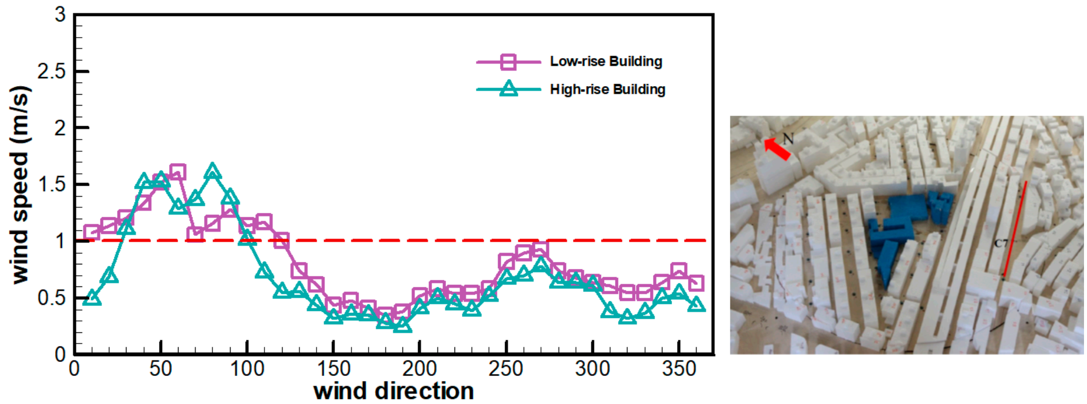
**Figure 6.** Characteristics of pedestrian wind environments in street canyons C4–C6 before and after urban renewal. (**a**) Street canyon C4; (**b**) street canyon C5; (**c**) street canyon C6.

Figure 7a shows the changes in the pedestrian-level wind speeds in C7. Before urban renewal, the maximum wind speed is approximately 1.6 m/s. Wind speeds above 1 m/s are found at 10°–120°. The mean wind speed in all other directions is below 1 m/s. The street canyon C7 is near elevated highways. There is a complex wind flow field after the construction of new buildings for urban renewal. As a result, there are two peak wind speeds at 30°–100° after urban renewal. The maximum wind speed (1.6 m/s) after urban renewal is close to that before urban renewal.

Figure 7b shows the changes in the pedestrian-level wind speeds in C8. The most important difference in the wind field characteristics between C8 and the aforementioned street canyons is the relatively significant changes in the wind speeds C8 after urban renewal in the directions where the pre-urban renewal wind speeds are low (as indicated by the red region). In Figure 7b, the preand post-urban renewal wind speed curves for 10°–180° exhibit similar patterns and nearly coincide. In the 190°–290° directions for which the wind speeds are low before urban renewal, the wind speeds gradually increase and even reach the comfort level (1 m/s) after urban renewal.

Among the investigated street canyons, C9 is the longest and closest to the urban renewal site. In Figure 7c, before urban renewal, the maximum wind speed (1.7 m/s) in C9 occurs at 60°. After urban renewal, the maximum wind speed (2.5 m/s) in C9 occurs at 50°. After urban renewal, the wind speeds are low in the directions for which the original wind speeds were at the comfort level. However, after urban renewal, the wind speeds are high in the directions for which the original wind speeds were low (as shown by the red region.

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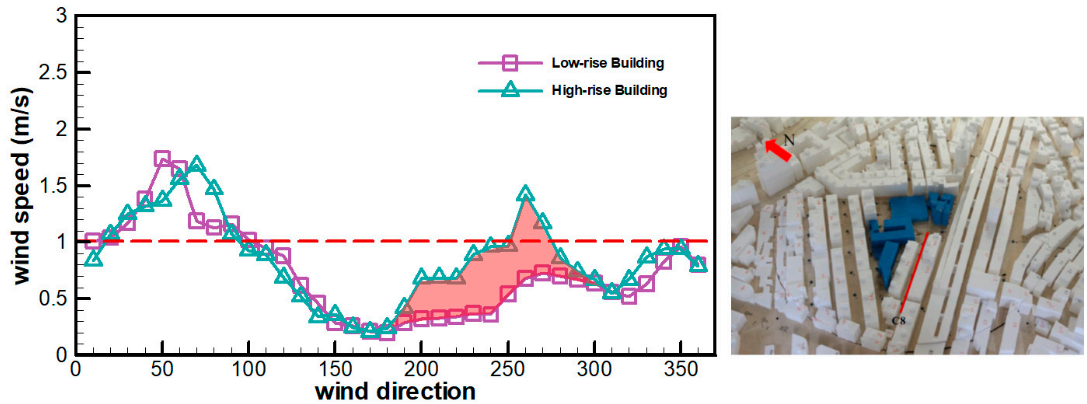


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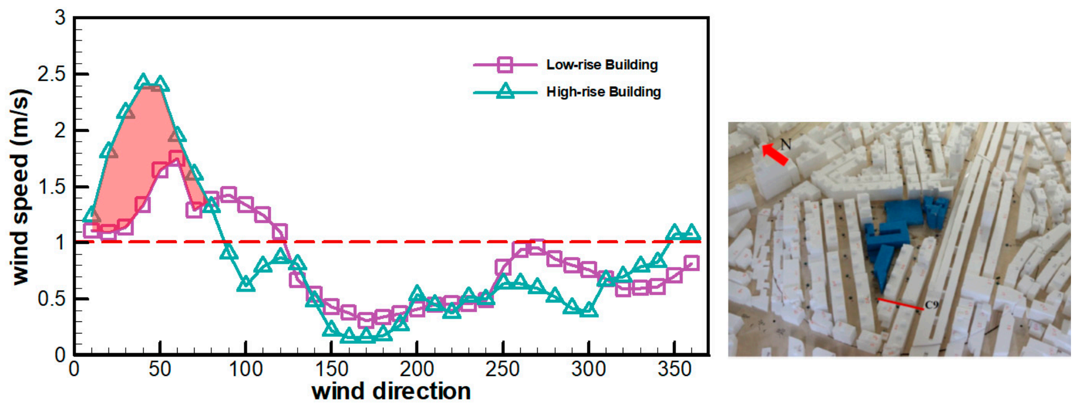
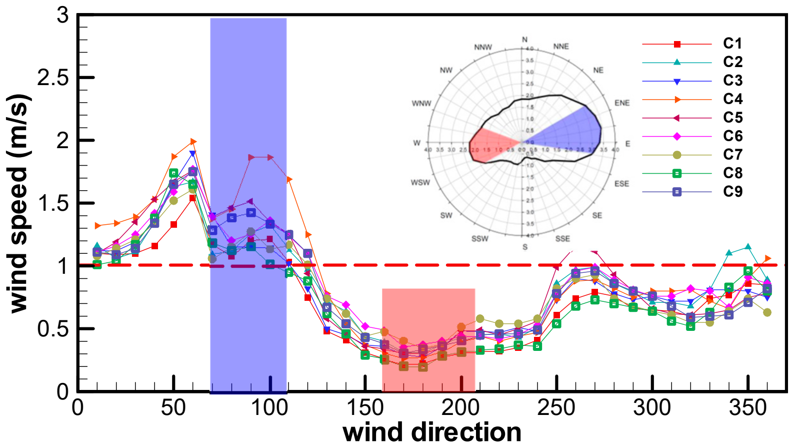



(**c**)

**Figure 7.** Characteristics of pedestrian wind environments in C7–C9 before and after urban renewal. (**a**) Street canyon C7; (**b**) street canyon C8; (**c**) street canyon C9.

A comprehensive analysis of the changes in the pedestrian-level wind fields in the street canyons after urban renewal is presented here. Figure 8a shows the characteristics of wind speeds in various directions in C1–C9 before urban renewal. Before urban renewal, the wind field trend is relatively consistent in each street canyon. Comfortable wind fields can be found at approximately 10°–120° in all the street canyons. The wind speeds are below 1 m/s in all other directions except for one or two street canyons.

Figure 8b shows the changes in the wind speed in each direction in C1–C9 after the construction of high-rise buildings. The wind fields in the street canyons are relatively inconsistent after urban renewal, because of changes in the wind direction and speed from the construction of high-rise buildings. Considering the meteorological data in Figure 3a, relatively high wind speeds occur at 150°–200° in summer (as indicated by the red region). The pedestrian-level wind speeds in these directions are not high before and after urban renewal, indicating poor urban ventilation quality. In winter, the main wind directions are between 60° and 100° (as indicated by the blue region). Before urban renewal, the pedestrian-level wind speeds in the street canyons in these directions are satisfactory. However, the pedestrian-level wind speeds in these directions change after urban renewal. That is, these wind speeds increase or remain unchanged in some street canyons and decrease in others (C1, C3, C5, and C6), resulting in potentially poor urban ventilation quality.

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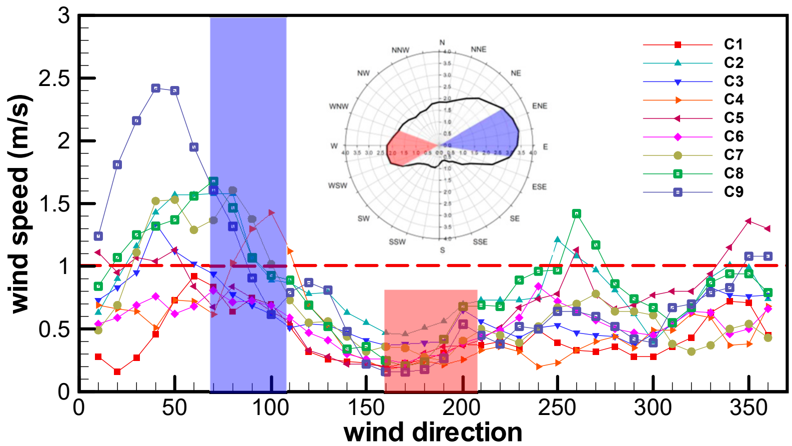


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**Figure 8.** Mean pedestrian-level wind speeds in surrounding street canyons before and after urban renewal. (**a**) Before urban renewal; (**b**) after urban renewal.

## 4. Conclusions

Wind-tunnel tests were performed to observe the effects of high-rise buildings constructed as part of urban renewal on the pedestrian wind environments in the surrounding street canyons. During the wind-tunnel tests, 42 pedestrian-level wind speed measuring points were placed within the urban renewal site and in the nine street canyons surrounding the urban renewal site. The free-stream wind speed was set to 12.5 m/s. A wind-tunnel test was performed at 10° intervals of the wind direction. The following conclusions were obtained from this study.

1. Most of the buildings surrounding the urban renewal base are densely distributed traditional apartment buildings with less than five stories. The surrounding street canyons are small with low and dense buildings. As a result, the dimensionless mean wind speed in the street canyons surrounding the urban renewal base ranges from 0.1 to 0.4, corresponding to low-speed flow fields.
2. Comparing the characteristics of the wind fields in the street canyons before and after urban renewal shows that the construction of new high-rise buildings for urban renewal results in a decrease in wind speeds in the surrounding street canyons.
3. The wind-tunnel test results are used in conjunction with local meteorological data to determine the effects of urban renewal on pedestrian wind environments. In this study, the meteorological data (Figure 3) show that relatively high wind speeds occur at 150°–200° in summer. The wind-tunnel test results show that pedestrian-level wind speeds in the street canyons in these directions are not high both before and after urban renewal, indicating poor urban ventilation quality. In winter, the main wind directions are between 60° and 100°. Urban renewal changes the wind speeds in the street canyons. The pedestrian-level wind speeds increase or remain unchanged in some street canyons and decrease in other street canyons (C1, C3, C5, and C6), resulting in potentially poor urban ventilation quality.
4. Local conditions of an actual city are considered in this study. Highly complex flow fields are generated by approaching winds under the impact of buildings with different morphologies in various street canyons. The characteristics of pedestrian wind environments in the street canyons cannot be interpreted in terms of channeling and shielding effects alone, as is commonly reported in the literature.

**Author Contributions:** T.-L.H. and C.-Y.K. conceived and designed the experiments; T.-L.H. and C.-Y.K. performed the experiments; C.-Y.K., C.-T.T. and C.-M.L. analyzed the data; and C.-Y.K. and C.-M.L. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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