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A wind tunnel study of effects of twisted wind flows on the pedestrian-level wind field in an urban environment

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\textbf{ABSTRACT}

The influence of twisted wind flows on the pedestrian-level wind (PLW) field of an urban area was evaluated by testing a typical urban site (Tsuen Wan, Hong Kong) in a boundary layer wind tunnel. Four twisted wind profiles with different magnitudes and directions of yaw angles were employed to investigate variations in wind speed with the properties of the twisted wind flows at the pedestrian level. An additional conventional wind profile with similar wind speeds and turbulence intensities to the twisted winds but with zero yaw angles was simulated for comparisons. The mean wind speeds at 77 locations including the perimeter, roadsides, and groups of high-rise buildings were analysed for the conventional and the four twisted wind flows. The comparisons show a tendency of twisted winds to generate higher wind speeds at the pedestrian level than the conventional wind profile. The wind speeds of the twisted winds have a strong dependence on the magnitude and direction of the yaw angles, particularly at locations where the densities of buildings in the neighbourhood are low and hence local wind circulations are significantly modified by the twisted winds.

\textbf{1. Introduction}

The properties of an approaching wind such as its wind speed, turbulence intensity, and direction are important for evaluating the pedestrian-level wind (PLW) field in an urban area. For example, when a wind flow with high ambient speed strikes a building, it tends to generate windy areas around it near the ground, causing discomfort to pedestrians [1]. Highly intense turbulence, on the other hand, has its advantages: for example, it increases the velocity of the horizontal wind component near the roof of a building, strengthening the street-canyon vortex, facilitating the removal of air pollutants from a street canyon [2]. Kastner-Klein and Plate [3] have demonstrated how pollutant concentration in a street canyon decreases with a change in wind direction from the perpendicular to the oblique and concluded that the effects of wind direction are of practical concern. Given that the properties of the approaching wind are important in assessing the wind environment in a built-up area, researchers have devoted significant time and effort on simulating the atmospheric boundary layer (ABL) wind flows in a boundary layer wind tunnel (BLWT) [4–6] and on computational fluid dynamics (CFD) simulations [7–10].

Wind speed profiles simulated in BLWT and CFD generally conform to an empirical model with logarithmic or power-law relations, even though the ABL wind flows are more complex and deviate considerably from the empirical models. Particularly in an urban area, the accuracy of empirical models becomes low because of the complex morphology. For instance, the shape of the power-law wind model can become distorted because of Urban Heat Island (UHI) effect [11] and the development of an internal boundary layer [12]. Similarly, the assumption of the constant wind direction along the profiles’ height is doubtful in the urban wind field [13,14]. Compared to wind speed and turbulence, the variation in wind directions has not received much attention even though several researchers, such as Kikumoto et al. [14] have emphasised that the deviation in wind directions should be replicated accurately in both physical and numerical simulations to obtain precise results when studying urban wind fields.

The vertical variation in wind directions is a topic that has been insensitively studied in the field of yacht sail’s aerodynamic [15–17]. Conversely, directional variations in a wind flow have not been systematically investigated in the field of wind engineering until very recent when Tse et al. [18–20] conducted a series of wind tunnel tests using twisted wind profiles. Tse et al. [18] first simulated twisted wind profiles, which have varying wind directions along the profile’s height, in a BLWT and then used them for the wind tunnel tests to show the ways that twisted wind flows modify the PLW field near isolated buildings and arrays of buildings [19,20]. Although these wind tunnel tests are indicative of the impact of twisted winds on the PLW field near
generic buildings, it is not yet fully understood whether twisted wind profiles have similar importance in assessing the PLW field in an urban area. This uncertainty arises from the inherited characteristics of an urban area, including its inhomogeneous land use, irregular building arrangement, and non-uniform dimensions, shapes, and forms of buildings; all of them are vastly different from the generic buildings that were previously tested in twisted wind flows. Therefore, it is a timely need to conduct a comprehensive study on the urban PLW field under the influence of twisted winds to expand the existing knowledge. Moreover, such a study would be beneficial in fine-tuning the testing procedures of the urban PLW field such as the Air Ventilation Assessment (AVA) [21].

In this study, five wind flows with and without directional deviations are employed to test a typical urban site in Hong Kong. The wind speeds at the pedestrian level are measured at different locations at the site to evaluate the variations in the PLW field with the properties of approaching winds. The PLW fields at the site perimeter, along main highways, and near a group of high-rise buildings are analysed comprehensively to determine whether the twisted wind flows have significant impacts on the urban PLW field. These three test locations are indicative of the PLW fields under unobstructed wind flows (at the perimeter), wind penetration along main breezeways (along the highways), and wind conditions near buildings (the group of high-rise buildings) resulted in twisted wind flows and the variations in PLW fields with the properties of approaching wind flows.

After the introduction, Section 2 introduces the characteristics of the twisted wind profiles and their existence in Hong Kong. Section 3 presents the experimental setup of this study, the technique for simulating the twisted wind profile in a wind-tunnel test, and the details of the selected urban site. Section 4 compares the pedestrian-level wind fields in twisted and conventional wind flows at different locations including the perimeter, roadside, and near a group of high-rise buildings to demonstrate the overall differences in PLW fields under the influence of the conventional and twisted wind profiles. Section 5 discusses some limitations of the study and Section 6 concludes the paper.

2. Twisted wind profiles and their existence in Hong Kong

In the ABL, the wind profiles often have different flow directions at different heights, as confirmed by mathematical models [22,23] and field observations [13,14,24]. The vertical variation in flow directions is a result of the combined effects of Earth’s rotation, friction between the wind and Earth’s surface, and the pressure gradient force between high- and low-pressure zones [13]. The resulting wind profile is shaped like a spiral commonly known as the Ekman Spiral. The variation in wind direction within the Ekman Spiral is about 20° on average but can vary from 10° to 30° between the heights in the range of 1–1.5 km in the ABL [25]. However, deviations in wind direction observed in field measurement campaigns are larger than the average deviation in wind direction of the Ekman Spiral and are confined to the lower altitudes in the ABL (as opposed to all along its height). For example, Wind-Lidar measurements taken by Peña et al. [13] reveal 25°–45° deviations in wind direction under the neutral and stable atmospheric conditions while Kikumoto et al. [14] report about 70° of the deviations in wind direction for the heights in between 67.5 m and 500 m from SODAR-Lidar measurements.

There is no field measurement campaign ever conducted in Hong Kong to verify the existence of twisted wind profiles nevertheless almost every topographical wind tunnel tests conducted in Hong Kong affirm the twisted wind profiles’ existence. Since the topographical wind tunnel tests reproduce the field conditions under neutral atmospheric stability, it is reasonable to assume that the twisted wind profiles very likely exist in Hong Kong. In fact, Tse et al. [18] confirmed the existence of twisted wind profiles in Hong Kong by analysing 256 wind profiles obtained from topographical wind tunnel tests. Their analysis reveals that the absolute difference in wind directions between the full-scale measurement heights of 25 m and 500 m can be as large as 40° irrespective to wind speeds, in which the yaw angles were measured. Apparently, the wind directional deviations observed from the wind tunnel tests are smaller than those reported by Peña et al. [13] and Kikumoto et al. [14]. Nevertheless, the deviation can still be considered as significant when considering that its magnitude is larger than that of the Ekman Spiral and the deviation is confined to the lower 500 m of the ABL. Based on the results of the wind tunnel tests and CFD simulations carried out by Weerasuriya et al. [26] and Li et al. [27], Tse et al. [18] conjecture that the hilly terrain of Hong Kong may generate large wind direction deviations in the lower part of the ABL. Consequently, the influence of the hilly terrain on the wind direction field should be included in the evaluation of the PLW field in Hong Kong for finding solutions for many wind-related issues, including outdoor thermal discomfort [28], degradation of air quality [29], increase of UHI effect [30], and favourable conditions for spreading airborne pathogens such as the SARS (Severe Acute Respiratory Syndrome) virus [31]. Although the twisted wind profiles observed in Hong Kong are dependent of the underlying hilly terrain, atmospheric stability conditions, in particular, the stable atmospheric stability, can alter the properties of topography-induced twisted wind profiles such as the magnitude of yaw angle [32].

3. Experimental setup

3.1. Simulation of twisted wind profiles

All wind tunnel tests described in this study were carried out in the CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology (HKUST). The wind tunnel in the WWTF is a closed-return type BLWT, which has two test sections, referred to as the high-speed section (maximum operating wind speed is 25 m s\(^{-1}\)) and the low-speed section (maximum operating wind speed is 10 m s\(^{-1}\)) according to their operating wind speeds. The wind tunnel tests in this study were conducted in the low-speed section because of its large dimensions (5 m in width and 4 m in height) under its maximum operating wind speed of 10 m s\(^{-1}\) at 1 m height. The large dimensions of the test section are advantageous for simulating twisted wind profiles because flow reflections from the sidewalls of the wind tunnel are of a considerable concern.

Fig. 1 shows the experimental setup arranged in the low-speed section of the wind tunnel. A wooden vane system, which had 5 individual vanes as shown in Fig. 2, was installed 4 m upstream from the centre of the turntable to generate twisted wind flows. Each vane was 1.5 m tall and was fabricated using laminated wooden strips. The maximum guide angles of the vane systems were 15° and 30°, and strips were rotated in either clockwise or counter-clockwise direction, as shown in Fig. 2(a) and (b). In other words, there were four types of vanes employed to simulate twisted wind profiles in this study. The previous publications of the authors [18–20] provide more details of the vane system.

The simulated wind profiles were measured at five points in the low-speed section to evaluate the consistency of mean wind speeds, turbulence intensities, and yaw angles. A TFI® Series100 Cobra probe fixed into a one-dimensional traverse system was used for the measurements. The Cobra probe can measure fluctuating wind speeds in three orthogonal directions, a range of from 2 m s\(^{-1}\) to 100 m s\(^{-1}\) with an accuracy of ±0.5 m s\(^{-1}\), and pitch and yaw angles with an accuracy of ±1°. The one-dimensional traverse system sets the heights for the Cobra probe to take measurements with an accuracy of ±1 mm.

Fig. 3 shows the wind profiles measured at 5 points in the low-speed section: at the centre of the turntable (A), moving laterally away from the centre of the turntable (B and D) by 2 m, along the centreline at a 2 m distance upstream and downstream from the centre of the turntable (C and E). At each point, mean wind speeds, turbulence intensities, and yaw angles were measured at 12 discrete heights from 10 mm to
1000 mm for a sampling period of 65 s. The sampling period is representative of over a 7-h measurement period according to the linear scale of 1:400 and velocity scale of 1:1. The mean wind speeds were normalised with respect to the mean wind speed at the 600 mm height. The clockwise and counter-clockwise yaw angles were defined as positive and negative, respectively.

The wind speed profiles were fairly consistent at the five test locations with an average difference in wind speeds of about 2%–5% at the lowest measurement height of 10 mm. The measured wind speed at downstream test point E in certain cases can be 6–15% higher than those measured at the centre of the turntable. The higher wind speeds may be related to low turbulence intensity recorded at the test point E, where the largest deviation in turbulence intensity was observed. Compared with wind speed and turbulence intensity, yaw angles present noticeable variations in both longitudinal and lateral directions; more specifically, the magnitude of yaw angle decreased by 20%–30% from the upstream test point C to the downstream test point E. The variation in yaw angles in the lateral direction was dependent on the direction of the approaching wind near ground, such that the test point D had larger yaw angles in clockwise twisted wind flows, while the test point B recorded larger yaw angles in counter-clockwise twisted winds. Similar results have been reported by Flay [15] and Tse et al. [18] and suggest that varying flow properties are an inherent characteristic of twisted wind profiles simulated in a BLWT.

Fig. 4(a) shows the profiles of mean wind speed and turbulence intensity in the four twisted wind profiles and the conventional wind profile (labelled as CWP) measured at the centre of the turntable. The conventional wind profile, which was a common wind profile without any wind directional deviation, had wind speed and turbulence intensity similar to the twisted wind profiles and followed the power-law type wind profile model with an exponent of 0.11. All wind profiles had a wind speed of about 7.9 ms⁻¹ and turbulence intensity about 5.7% at 600 mm height. As shown in Fig. 4(b), both the vanes with clockwise and counter-clockwise maximum guide angles of 15° generated a maximum yaw angle of 13°, while the vanes with the maximum guide angle of 30° produced a maximum yaw angle of 22° at 10 mm height. Based on their respective maximum yaw angle and its direction, the four twisted wind profiles are hereafter referred to as TWP13-CW, TWP22-CW, TWP13-ACW, and TWP22-ACW, where the abbreviations CW and ACW stand for “clockwise” and “counter-clockwise”, for the yaw angles.

3.2. Details of the urban site

A site in Tsuen Wan, Hong Kong was selected as the study area. Fig. 5 shows the geographical location of Tsuen Wan, which is bounded by sea to the south, while Tai Mo Shan, a tall mountain, is located to the north. To the east and west, Tsuen Wan is connected to the mainland and is surrounded by built-up areas such as Kwai Chung in the east. In the south-west direction, Tsuen Wan is separated by a narrow sea strait from Tsing Yi, a small island with some settlements on its east and north coasts.

Fig. 6 shows a detailed map of the study area in Tsuen Wan. The study area spreads over a circular area with a 0.6 km radius and is located at a fair distance away from both the sea and Tai Mo Shan Mountain. Two small topographical features are found from the directions of 110° and 150° close to the site’s boundary. High-rise to low-rise buildings, road infrastructures, such as fly-overs, and open areas are distributed irregularly in the study area. Two main roads, Yeung Uk Road and Leun Yan Street, stretch along in the directions of 120°-300° and 60°-240° and cross each other at a wide intersection at the centre of the study area. In addition, many secondary streets run through clusters of buildings, eventually connecting to the main roads.

In the tests, a scaled model of the study area was fabricated according to a geometric scale of 1:400 using Styrofoam sheets. All buildings, road infrastructures, and small topography features within the study area were modelled explicitly by including all their important features. The greenery areas were not explicitly modelled because trees and bushes were modelled as tiny objects in a linear scale of 1:400, thus having insignificant effects on the surrounding PLW field.

3.3. Measurement technique

A Kanomax1560 thermal anemometer system, which consists of 80 spherical, thermistor-type, omnidirectional wind sensors and a data acquisition system, was employed to measure mean wind speeds at the pedestrian level. For this study, 77 Kanomax sensors were installed to cover important locations, including road intersections, roadsides, clusters of buildings, courtyards, and the perimeter of the study area. The Kanomax sensors were installed 5 mm above the ground to measure mean wind speeds at the pedestrian height, which is equivalent to a 2 m height in the full scale. The wind speeds were recorded at a sampling rate of 10 Hz for 65 s. The sampling period of 65 s is equal to over a 7-h measurement period in field conditions according to a linear scale of 1:400 and an assumed velocity scale of 1:1. In each wind flow, the urban model was tested for 36 wind directions from 0° (north) to 350° at an interval of 10°. Fig. 7 shows the complete experimental setup including the installed urban model and a vane system.

4. Results

4.1. The pedestrian wind comfort criteria

The PLW fields in the twisted and conventional wind flows are evaluated using normalised mean wind speed ratio (K). Several researchers have employed the K value to evaluate PLW fields near isolated buildings and groups of buildings [18,19,33–36]. In this study, the K value is calculated using Equation (1):

$$K = \frac{U_{2m,x,y}}{U_{200,0.015}}$$  

(1)

In Equation (1), $U_{2m,x,y}$ is the mean wind speed at 2 m height at
location \((x, y)\) in the study area and \(U_{200, \alpha=0.15}\) is the mean wind speed at 200 m height of a wind profile with a power-law exponent of 0.15. The \(U_{200, \alpha=0.15}\) is representative of the long-term wind measurements of Hong Kong and is advantageous in using the pedestrian wind comfort criteria shown in Table 1 [36].

Zhang et al. [36] first proposed the pedestrian wind comfort criteria shown in Table 1 to evaluate the PLW field of Hong Kong. The upper and lower bound wind speeds, 5 m s\(^{-1}\) and 1.6 m s\(^{-1}\), are set according to the recommendations of Penwarden [37] and Cheng et al. [28] to prevent unacceptable high wind speeds occurring in the city and to maintain outdoor thermal comfort on a hot, humid, summer day in Hong Kong. An intermediate wind speed, 3.5 m s\(^{-1}\), marks the beginning of wind discomfort due to disarranging of hair, flapping of clothes, etc. [37]. The \(K\) values listed in Table 1 are calculated by normalising the threshold winds speeds with respect to \(U_{200, \alpha=0.15}\), which is about 5–6 m s\(^{-1}\) [38].

The following subsections present the analysis of wind conditions at different locations such as the perimeter, the main roads, and groups of high-rise buildings according to the proposed pedestrian wind comfort criteria.

4.2. Perimeter wind conditions

Test points that are located close to the boundary of the site can better indicate the characteristics of both twisted and conventional winds that approach the site without interference from obstacles. In the present study, five test points, 7, 18, 52, 12, and 63 may be considered as the perimeter points as they are exposed, directly to the wind flows from certain directions. Fig. 8 shows the wind rose diagrams of three perimeter points (12, 63, and 52) subjected to the conventional and four twisted wind flows coming toward each test point.

The wind rose diagram of test point 12 in Fig. 8(a) shows that high \(K\) values are found in the directions between 160° and 180°. The \(K\) values in these directions are higher than 0.3, indicating that the wind conditions at the perimeter of this site are acceptable. The individual maxima of the wind flows’ \(K\) values recorded at test point 12 are different: for example, while CWP’s maximum \(K\) value is 0.37, the maximum \(K\) values of the four twisted wind flows are 0.36 in TWP13-CW, 0.34 in TWP22-CW, 0.40 in TWP13-ACW, and 0.37 in TWP22-ACW. The maximum \(K\) values of the twisted winds with clockwise yaw angles are smaller than the maximum \(K\) value of CWP at test point 12 but with counter-clockwise yaw angles, the twisted winds’ maximum \(K\) values are larger than those of CWP. The directions where maximum \(K\) values are recorded \(\phi_{K_{\text{max}}}\) are also slightly different between the twisted and conventional wind flows at test point 12. In fact, \(\phi_{K_{\text{max}}}\) varies with the twisted wind flow’s yaw angle. On the one hand, \(\phi_{K_{\text{max}}}\) of TWP13-CW and TWP22-CW are 160° and 150°, which are 10° to 20° smaller than \(\phi_{K_{\text{max}}}\) of CWP (170°); on the other hand, \(\phi_{K_{\text{max}}}\) values are same or larger for TWP13-ACW (170°) and TWP22-ACW (180°) than for CWP. The minimum of CWP’s \(K\) value at test point 12 is about 0.03 and happens at 290° resulting a difference in the maximum and minimum \(K\) values of CWP about 0.34 or an equivalent reduction of wind speed about...
The minimum $K$ values of the twisted winds are observed in the same directions as in CWP ($\phi_{\text{Kmin}} \approx 290^\circ - 310^\circ$) but the magnitudes are 4–9% higher than that of CWP. The constant $\phi_{\text{Kmin}}$ of both twisted and conventional wind flows may be attributed to the high density of buildings upstream of test point 12 in directions between 230° and 330°.

The wind rose diagram of test point 63 in Fig. 8(b) further substantiates the dependence of $K$ values on the magnitudes and directions of yaw angles of the four twisted wind profiles. For instance, the $K$ values of TWP13-ACW and TWP22-ACW at test point 63 are 37.6% different in direction 110°. In the same wind direction, TWP22-CW and TWP22-ACW, which have the same magnitude but different yaw directions, record a 44% discrepancy between their $K$ values. These differences in $K$ values are minimum in directions 320° to 70°, from which winds flow over a dense built-up area.

The wind rose diagram of test point 52 in Fig. 8(c) has smaller $K$ values than at test points 12 and 63. The maximum $K$ values of both twisted and conventional winds are smaller than 0.3 indicating low wind speed (LWS) conditions even for the directions between 80° and 140°, from where unobstructed winds approach test point 52. The smaller $K$ values may be a result of sheltering due to a small topographical feature located upstream of test point 52 toward 110° (see Fig. 6). The effects of sheltering from this topographical feature on the wind conditions at test point 52 are considerable, highlighting the importance of modelling all topography features that are located within or near a site of interest in wind tunnel tests, to account for the influences of topographical features on the PLW field at that site.

### 4.3. Roadside wind conditions

The two main roads, Yeung Uk Road and Luen Yan Street, which provide paths for winds to circulate in the study area, are selected to assess the roadside wind conditions. Yeung Uk Road and Luen Yan Street span the study area from 120° to 300° and from 60° to 240°, respectively, and intersect each other at the middle of the study area. Two directions, 60° and 120° that are parallel to the two roads, are selected because of their significance in the evaluation of the PLW field.

The mountain Tai Mo Shan located at 60° could be a source of twisted winds that are frequently found at the site and 120° is a prevailing wind direction with a high probability of occurrence of winds at the site according to the long-term measurements of wind speed in Hong Kong [38].

Fig. 9 shows how $K$ values vary along Yeung Uk Road and Luen Yan Street for winds approaching from 120° and 60°, respectively. The distances in Fig. 9 are measured from the centre of the study area and the positive distances are measured towards the north and east. The
numbered squares in each figure indicate roadside test points. Fig. 9(a) shows a continuous decrease in $K$ values from the windward end (test point 12 toward 120°) of Yeung Uk Road to the centre of the study area (test point 1) before the $K$ values gradually increase towards the leeward end (test point 7 toward 300°) for both conventional and twisted wind flows. The $K$ values at the leeward end are 36–62% smaller, creating LWS condition, than their corresponding values at the windward end, which has acceptable wind conditions for all wind flows. Among the five wind flows, TWP13-CW and TWP22-CW have larger deficits in $K$ values of 58.8% and 61.8% at the two ends of the road compared to the 41.3% deficit for CWP. The deficit of $K$ value is a result of the loss of momentum of winds due to the friction between winds and rough surfaces along the road while the dissimilar deficits may be attributed to the differences in wind-structure interactions of the conventional and twisted wind flows along Yeung Uk Road.

A similar trend (a decrease followed by an increase) is observed for the $K$ values from the windward end of Luen Yan Street to the leeward end (Fig. 9(b)). In contrast to Yeung Uk Road, the $K$ values at the leeward end of Luen Yan Street are 36–62% smaller, creating LWS condition, than their corresponding values at the windward end, which has acceptable wind conditions for all wind flows. Among the five wind flows, TWP13-CW and TWP22-CW have larger deficits in $K$ values of 58.8% and 61.8% at the two ends of the road compared to the 41.3% deficit for CWP. The deficit of $K$ value is a result of the loss of momentum of winds due to the friction between winds and rough surfaces along the road while the dissimilar deficits may be attributed to the differences in wind-structure interactions of the conventional and twisted wind flows along Yeung Uk Road.

For the changes in $K$ value along the roads, the deceleration of the conventional and twisted wind flows ($DW$) are calculated according to Equation (3).

$$DW_i = \frac{K\text{ value of the unobstructed wind} - K\text{ value at test point } (i)}{K\text{ value of the unobstructed wind}} \times 100\%$$

In Equation (3), $DW_i$ is the deceleration of a wind flow at location $i$, and the $K$ value of an unobstructed wind is the normalised wind speed of each wind flow at the upstream boundary of the site (test point C in Fig. 1).

Fig. 10 shows the $DW$ values at 6 test points along Yeung Uk Road for the conventional and four twisted winds that approach from the direction 120°. The $DW$ value of CWP shows a steady increase from about 49% at the windward end (418 m) to about 86% at the centre of the study area (0 m). Similarly, the twisted wind flows have increasing trends in $DW$ but their $DW$ values moderately deviate from the corresponding $DW$ of CWP. In general, the $DW$ values of the twisted winds with small yaw angles deviate less from those of CWP than the corresponding values of the twisted winds with large yaw angles. For
example, the DW value of TWP13-ACW at test point 10 deviates only 1.4% from those of CWP while the corresponding deviation of TWP22-ACW is about 24%. The yaw direction is another factor that causes some deviations in DW values of test points. An example is that the DW values of test point 10 where TWP 22-CW has a 13.2% higher DW value than CWP while TWP22-ACW records a 24.9% smaller DW value. However, none of these trends in DW values is consistent for the twisted wind flows but is significantly varied or occasionally reversed at test points, for instance, at test point 11, TWP22-ACW’s DW value is 6.3% smaller for than CWP opposed to higher DW at test point 10. These differences in DW value diminish as winds penetrate to the study area and eventually, all wind flows have comparable DW values at the centre. Test point 1 (at the centre of the study area) has high DW values, on average, of 85% for all wind flows with small individual deviations.
4.4. Wind conditions around a group of high-rise buildings

Four buildings with the heights of 175 m and 208 m (within the blue shaded area in Fig. 6) are selected to investigate the wind conditions near a group of high-rise buildings. Three test points 71, 73, and 8 are selected for the detailed analysis of three distinct wind conditions that are anticipated occurring upstream/downstream (depending on wind directions) of the buildings, in a passage between two high-rise buildings, and in a deep street canyon next to the buildings.

The wind rose diagram in Fig. 11(a) shows two distinct peaks in $K$ values at 0° and 190°. For these two directions, test point 71 can be considered as located either upstream or downstream of the group of high-rise buildings. When test point 71 is in the upstream direction, all wind flows record their maximum $K$ values. For instance, CWP has its maximum $K$ value of 0.32 at 190° and the four twisted winds record their maximum $K$ values of 0.31–0.32 in directions ranging from 180° to 200°. These maximum $K$ values of the wind flows at test point 71 may be attributed to the intense backflow generated by the high-rise buildings when the buildings are exposed to winds that approach from directions 180° to 200°. Then the variation of $\phi_{K_{\text{max}}}$ (i.e., the wind direction of the maximum $K$ value) may be related to the modifications of upstream flow features by the twisted winds as discussed by Tse et al. [20]. The second peak in $K$ value, which is marginally less than 0.3, is found at 0°, for which the location of test point 71 is downstream of the group of high-rise buildings. When test point 71 is in the downstream direction, it may be subjected to accelerated wind flows that move from the windward sides of the medium-rise buildings located next to the test point to the leeward sides of high-rise buildings. In contrast at 190°, the maximum $K$ values of the wind flows do not show a strong dependence at 0° because of the local flow circulations govern the wind conditions at the test point than the undisturbed wind flow that approaches the site. The high $K$ values in the directions between 180° to 200° indicate likely the existence of the acceptable wind conditions at test point 71 for these wind directions. Nevertheless, the overall wind condition at test point 71 can be categorised as low wind speed (LWS) for all wind flows as evinced by their average $K$ values ($i.e., \bar{K} = \sum_i K_i / N$), which is considerably smaller than 0.3. The LWS condition is likely related to low ambient wind speeds in Hong Kong, which in turn, do not generate unpleasant or dangerous high-speed winds near high-rise buildings as reported by many studies in the literature [39–42].

The wind rose diagram of test point 73 (Fig. 11(b)), too, has two peaks in $K$ values at 190° and 10° and these two directions are approximately parallel to the centre line of the passage between two high-rise buildings (20°–200°). The $K$ values of five winds are considerably different at 190° and 10°, for instance, the $K$ values are within the range of 0.15–0.22 at 10° while the corresponding $K$ values are 0.27–0.33 for the oncoming winds from 190°. This difference in $K$ value is mainly resulted from the location of test point 73 with respect to an oncoming wind. More specifically, test point 73 has higher $K$ values at 190°, where the test point is at the entrance of the passage than when the test point is at the exit for the oncoming wind from 10°. In addition, the type of the wind flow, whether it is the conventional or a twisted wind flow, causes the difference in $K$ values at test point 73 as indicative of the 11.44% higher $K$ value of TWP13-ACW than that of CWP at 190°. The maxima $K$ values and $\phi_{K_{\text{max}}}$ of twisted wind flows are slightly varied with the properties of yaw angles such that the maximum $K$ value of TWP22-CW is 0.29 and is found at 180° whereas TWP22-ACW records the maximum $K$ value of 0.30 at 200°.

Compared to test points 71 and 73, the $K$ values at test point 8 are significantly smaller than 0.3 for all winds (Fig. 11(c)). The small $K$ values are indicative of the adverse impacts of the deep street canyon, where taller buildings on either side of the canyon shelter the test point from winds that approach from many directions. An exception is the oncoming winds from the direction parallel to the street canyon (approximately 90°–270°), where the $K$ values of some wind flows can be reached to 0.13 to 0.17. In these directions, the five wind flows control the wind conditions at test point 8 differently, for example, TWP13-CW and have a 29.8% higher $K$ value at 270° than CWP while the $K$ value of TWP13-ACW is 28.7% smaller.

The pedestrian wind comfort criteria.

| Wind speed (m s$^{-1}$) | $K$ | Remarks |
|------------------------|-----|---------|
| < 1.6                  | < 0.3 | Low wind speed (LWS) |
| 1.6–3.5                | 0.3–0.7 | Acceptable winds |
| 3.5–5                  | 0.7–1  | High wind speed (HWS) |
| > 5                    | > 1   | Unacceptable wind speeds |

(about 2%). The similar $DW$ values of both conventional and twisted wind flows may be related to the high density of buildings at the centre of the study area, overriding the influence of twisted winds on the PLW field at test point 1.

### Table 1

The pedestrian wind comfort criteria.
4.5. Variability of wind conditions under conventional and twisted wind flows

For a broad understanding of the influence of twisted winds in the study area, the probability distributions of normalised difference between the $K$ values of CWP and the twisted winds are plotted in Fig. 12, and their significant statistics are listed in Table 2. The normalised difference between $K$ values of CWP and a twisted wind is defined as in Equation (4).

$$\phi(K)_{ij} = \frac{K(CWP)_{ij} - K(TWP)_{ij}}{K(CWP)_{ij}}$$

In Equation (4), $\phi(K)_{ij}$ is normalised difference between $K$ values of CWP and a twisted wind in direction $(i)$ at location $(j)$, $K(CWP)_{ij}$ is the $K$ value of CWP direction $(i)$ at location $(j)$, and $K(TWP)_{ij}$ is the $K$ value of a twisted wind in the same direction and location.

Fig. 12 shows the probability distributions of $\phi(K)$ of the four twisted wind flows determined using $K$ values of 77 test points obtained for 36 directions. The probability distributions of the four twisted winds follow the normal distribution functions but have different values for the mean and the standard deviation. The mean values of the four probability distributions, as shown in Table 2 vary between $-0.043$ and $-0.081$, indicating that the twisted winds tend to generate 4.3%–8.1% higher wind speeds than CWP in the study area. The difference between wind speeds between the four twisted winds and CWP can be as large as 70% to $-264\%$ and the large differences are observed for the twisted winds with large yaw angles such as TWP13-CW and TWP22-ACW. The impact of the twisted wind flows on the wind speed at the study area is considerable, for instance, 21–26% of the test points are likely to record 25% higher wind speeds for the TWP13 flows than for CWP and for the TWP22 flows the corresponding probabilities are 28–30%.
5. Discussion

This study reveals the variability of wind speed in an urban site of Hong Kong with the magnitude and direction of the yaw angles of the winds that approach the site. The interpretation of the results of this study requires certain concerns as listed below:

- The wind profiles employed in this study had similar wind speeds and turbulence intensities but dissimilar yaw angles because the goal of this study is to investigate the variation of wind speed in an urban site with the magnitude and direction of yaw angles of oncoming wind profiles. However, in field conditions, wind profiles approach the site in different directions may have different wind speeds and turbulence intensities, which are likely to affect the wind conditions at the site. Therefore, all the flow parameters including wind speeds, turbulence intensity, and yaw angles should be considered for a comprehensive analysis of the PLW field in an urban site.

- The fine resolution with 10° increments of wind incidence angle gives an impression of a gradual variation of $K$ value with wind incidence angle for the four twisted flows. However, in engineering applications such as AVA, a limited number of wind incidence angles (e.g. 16 wind directions in AVA) are tested, and therefore, the gradual variation of $K$ value cannot be clearly identified. Moreover, the abrupt changes in $K$ values in few wind directions can cause significant discrepancies in the result of a PLW field when it is assessed for different wind flows.

- In this study, the $K$ value is calculated by assuming that the probability of occurrence of wind is same for all 36 directions. However, in field conditions, some directions are prevalent with high probabilities of occurrence of wind while other directions have low probabilities. An unequal distribution of probabilities makes the wind condition at a location strongly dependent on the approaching wind direction. For instance, a small difference in $K$ values in a prevalent wind direction can cause a larger variation in the wind condition at a test point than the predictions of this study.

6. Concluding remarks

This study shows how twisted winds with different magnitudes and directions of yaw angles affect the PLW field of an urban site in Hong Kong. Compared with wind speeds in a conventional wind flow, the twisted winds can cause more than 35% difference in wind speeds at locations that have a low density of buildings or are exposed to the unobstructed winds that approach the site. In general, the high density of buildings overrides the influence of yaw angles on the PLW fields resulting less than 10% differences in wind speeds in the five wind flows. Nevertheless, PLW fields near high-rise buildings vary with the yaw angles of oncoming wind flows registering more than 100% differences in wind speeds among twisted and conventional wind flows. The wind speeds at the roadside test points strongly depend, as indicated by 0–45% difference in wind speeds, on the magnitude and direction of the yaw angle of the oncoming wind. As a result, the wind penetration along the main roads are different for the conventional and twisted wind flows. However, the directions, where the maximum and minimum $K$ values are found ($\Phi_{K_{max}}$ and $\Phi_{K_{min}}$) for the four twisted...
winds vary with the direction of the yaw angle but do not display an obvious relationship with the magnitude of the corresponding yaw angles at the pedestrian level. This suggests another probable relationship that can be existed between the yaw angle and the $\psi_{Kw}$ or (the $\psi_{Kwmax}$) that is still an unknown. The existence of such a relationship is intended to investigate in a future study because it is advantageous in understanding and predicting the flow modifications in PLW field under the influence of twisted wind flows.

This study confirms that twisted winds can affect the PLW field of an urban site even under low wind speeds thus may have significant impacts on engineering applications such as predicting air pollutant dispersion, assessing of pedestrian wind comfort, or estimating wind circulation at a site using the AVA. For example, The AVA, which requires accurate data on the PLW field at the site of interest to make unerring decisions, tends to make predictions that are different from the field conditions, if AVA does not employ twisted wind profiles for the evaluation. This hypothesis will be tested in a future study by integrating twisted wind profiles into the AVA.

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