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Integrating twisted wind profiles to Air Ventilation Assessment (AVA): The current status

A.U. Weerasuriya\textsuperscript{a,b}, K.T. Tse\textsuperscript{a}, Xuelin Zhang\textsuperscript{a,∗}, K.C.S. Kwok\textsuperscript{b}

\textsuperscript{a} Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
\textsuperscript{b} School of Civil Engineering, The University of Sydney, Darlington, NSW, 2006, Australia

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ABSTRACT

Twisted wind flows generated by the complex terrain of Hong Kong induce two types of complication to Air Ventilation Assessment (AVA), first, imposing a false boundary condition on the wind tunnel tests done for AVA and, second, creating an ambiguity in determining the approaching wind direction in calculating the probability of occurrence of winds. The latter issue is partially solved using correction methods in post-analysis of AVA but the accuracy of these methods is not yet assessed. This study employs two twisted wind profiles to test an urban area in a boundary layer wind tunnel to investigate the influence of twisted wind flows on the outcomes of AVA and to estimate the accuracy of three common correction methods: No-Shift, Threshold, and Proportional methods. The results reveal significant differences in wind speeds at the pedestrian level for twisted and conventional wind flows at locations with low building densities. The discrepancies in wind speeds are minimum at the locations where the density of buildings is high. The indicators calculated by the No-Shift method frequently deviate from those of the twisted wind flows, while the Threshold and Proportional methods routinely over-predict the indicators of AVA.

1. Introduction

The Air Ventilation Assessment (AVA) was stipulated by the Hong Kong Government in 2006 after the 2003 SARS (Severe Acute Respiratory Syndrome) outbreak [1–6]. Established as a mandatory test for major government and semi-government projects on the development and redevelopment of urban areas, the AVA monitors the projects' effects on external air movements in an attempt to maintain an acceptable macro wind environment [1–3]. Currently, AVA is implemented in the private sector entirely on a voluntary basis, but the number of private projects that adopt AVA continues to grow, as AVA helps better plan a project at its initial design stage [6].

The AVA systematically combines data of wind speed, influences from the complex terrain of Hong Kong, and the pedestrian level wind (PLW) field at any site of interest to assess the acceptability of the macro wind environment. AVA’s main evaluation criterion is to check whether mean wind speed at the pedestrian level (typically about 1.5 m–2 m above ground) exceeds 1.5 m s\(^{-1}\) [1]. The mean wind speed of 1.5 m s\(^{-1}\) is the minimum wind speed required to maintain outdoor thermal comfort on a hot, humid summer day in Hong Kong [7]. This criterion takes a different approach than other existing wind ordinances: other criteria tend to cap the allowable wind speed to prevent pedestrian discomfort, even danger, caused by windy conditions [8–10].

The AVA explicitly includes the influence from complex terrain on the urban PLW field because of the complex terrain of Hong Kong is found to have immense influences on wind speeds and turbulence intensities in built-up areas that are located even few kilometres downstream of mountains [11]. In addition, the hilly terrain of Hong Kong frequently produces twisted wind profiles: at different heights within the profile winds have various directions [12–14]. The authors of this paper have used twisted wind profiles in a series of wind tunnel tests on isolated buildings [16], arrays of buildings [16], and a real urban area [17], and have demonstrated the profiles’ considerable influence on the PLW fields in built-up areas. This influence is even more critical on AVA as reported by Tse et al. [12] after analysing data of 256 wind profiles obtained from 13 previous AVAs. In their analysis, Tse et al. [12] revealed that more than 10% of wind profiles have directional deviations larger than 20° (as much as 40°) within the lower 500 m of the atmospheric boundary layer (ABL).

Twisted wind profiles induce two types of complication for AVA: First, if the twisted wind profiles are not taken as boundary conditions and consequent flow modifications in the PLW field are neglected (see Refs. [15–17]), then the reliability of any AVA outcomes will be
significantly affected. Although few studies attempted to improve the accuracy of AVA by addressing special environmental conditions such as unstable atmospheric stability [18,19], the existence of highly complex terrain [20], the presence of buildings with different heights [21], and heterogeneous urban morphology and surface roughness [22] but to the best of the authors’ knowledge, no AVA has ever used twisted wind profiles as a boundary condition. This omission is partially attributable to inadequate understanding on simulation techniques, as only limited information has been made available by several studies on yacht sail’s aerodynamics [23–26] and a few PLW studies done by the authors [15–17]. Constraints in cost, time, and resources pertaining to simulating twisted wind profiles give further reasons for omitting them from AVA.

Second, wind directions in the twisted wind profiles vary a great deal and cause ambiguity in calculating indicators of AVA, which require the probabilities of wind occurring in any given directions to be determined. Currently, the AVA only adopts corrections methods in post-analysis to adjust these probabilities according to the how wind directions vary in the twisted wind profiles, but these correction methods are empirical: neither their accuracy nor impact on the outcome of AVA is assessed. In fact, without any AVA data obtained using twisted wind profiles, neither the accuracy nor the impact of these correction methods can be assessed, and this needs to be remedied by incorporating twisted wind profiles into AVA, something that has been unavailable to the wind engineering community until now.

The goal of this paper is threefold: (1) to incorporate twisted wind profiles as a boundary condition into the wind tunnel tests for AVA; (2) to evaluate the influence of twisted wind profiles on the outcomes of AVA; and (3) to estimate the accuracy of correction methods currently used in AVA. Each sub-goal is achieved by testing a real urban area in a boundary layer wind tunnel (BLWT) according to AVA guidelines. Two twisted wind profiles with different yaw angles are systematically integrated into AVA, and the impact of twisted wind flows on the outcomes of AVA is estimated by comparing wind speeds under the two twisted wind profiles with wind speeds measured in a conventional wind flow, which has similar wind speeds and turbulence intensity but without any wind twists. Several indicators are calculated based on pedestrian-level wind speeds in the two types of wind flow (i.e., conventional and twisted winds) and are adjusted using the correction methods. The two sets of indicators (original and adjusted) are then compared to estimate the accuracy of the correction methods and their impact on the outcomes of AVA.

In Section 2, the procedures of implementing AVA are introduced with details of assessment techniques, main indicators, and the evaluation process. The correction methods are described in Section 3 in terms of calculation procedures, underlying assumptions, and limitations. Section 4 provides details of the experimental setup including the selected urban area, approaching wind profiles, and measurement techniques. Section 5 analyzes the PLW field using the main indicators calculated for the two types of wind flows and the correction methods. Finally, some limitations of the current study are discussed in Section 6 and several conclusions are stated in Section 7.

2. Methodology

2.1. Assessment criteria

The influence of twisted wind flows on the outcomes of AVA is evaluated by calculating three indicators: wind velocity ratio (VR), directional wind velocity ratio (VRw), and spatially average wind velocity ratio (SAVR) [1–3]. VR reflects the wind conditions modified by the project using a ratio between mean wind speeds measured at the pedestrian level and approaching upper-level wind at a suitable reference height (e.g., 500 m), as defined in Equation (1);

\[ VR = \frac{V_{500,m}}{V_{500}} \]  

(1)

In Equation (1), \( V_{500,m} \) is the mean wind speed in m/s at the pedestrian level (i.e., measured at 2 m above ground) and \( V_{500} \) is the reference mean wind speed in m/s at a height of 500 m directly above the centre of the modelled area in the ith wind direction.

VRw is estimated in Equation (2) by combining the VR value in each wind direction with the corresponding probability of occurrence of wind calculated from the probabilistic wind climate model of Hong Kong.

\[ VR_{w,i} = \sum_{j=1}^{n} p_i \times VR_{500,i,j} \]  

(2)

where, \( p_i \) is the probability of occurrence of wind in the ith wind direction.

The spatially average velocity ratio (SAVR) estimates pedestrian-level wind conditions in the subzones of a project site [6]. To calculate the SAVR, the project site is first divided into a number of subzones based on buildings’ characteristics (e.g., height). Then the SAVR value for each sub-zone is estimated using Equation (3).

\[ SAVR = \sum_{j=1}^{n} \frac{VR_{w,i,j}}{n} \]  

(3)

where, \( n \) is the number of test points within the sub-zone.

The probability of occurrence of wind (\( p_i \)) used for calculating VRw and SAVR can be estimated using a probabilistic wind climate model of the nearest anemometer station to the site. Fig. 1 shows a probabilistic wind climate model constructed using non-typhoon wind speeds recorded for the period January 1953 to May 2000 at the Waglan Island meteorological station. In Fig. 1 and 0° indicates north and the 16 wind directions from 0° to 337.5° are marked at 22.5° intervals. The magnitudes of wind speed are marked by different colors and the radial distances indicate the probability of occurrence of winds at contour levels of 2%. According to Fig. 1, both the highest wind speeds about 26 m s\(^{-1}\) as well as the highest probability of occurrence of wind about 24% is found in the east direction. However, the mean wind speed at the 200 m height on Waglan Island is estimated to be 5–6 m s\(^{-1}\), and combining that with the minimum required wind speed of 1.5 m s\(^{-1}\) would result in VRw = 0.3, which is the minimum acceptable VRw value in AVA.

![Fig. 1. Directional probability distribution of annual non-typhoon wind speed of Hong Kong (radial distance represents the probability of occurrence of wind).](image-url)
2.2. The selection of correction methods

Three of the most common correction methods: No-Shift, Threshold, and Proportional methods are selected for this study to integrate the effect of twisted winds on the outcome of AVA. These correction methods are common practices of AVA but are not documented officially. The important details and calculation technique of each correction method are described below.

2.2.1. No-shift method

Any deviation in wind direction of an approaching wind profile is ignored in the No-Shift method. Therefore, the probability of occurrence of wind in a given direction at the site is similar to the corresponding probability in the same direction far upstream of the project site.

2.2.2. Threshold method

The Threshold method defines a threshold angle \( \theta_T \), of which the exceedance is only considered for adjusting the probability of occurrence of wind. When a deviation of wind direction, also known as yaw angle \( \theta \), exceeds \( \theta_T \), the wind is considered to be approaching in a direction other than the direction far upstream of the site. Consequently, the corresponding probability of occurrence of wind \( p_i \) is shifting from the original wind sector, \( i \), to an adjacent wind sector, \( i \pm 1 \), according to the direction of yaw angle (i.e., clockwise or anticlockwise). As a result of the shift in wind direction, the probability of occurrence of winds of the \( i \)th wind sector becomes zero \( (p_i = 0) \) and the \( i \pm 1 \)th wind sector has the sum of probabilities of the original and the adjacent wind sectors \( (p'_{i \pm 1} = p_i + p_{i \pm 1}) \).

There are two main drawbacks in the Threshold method: first, there is not a generally accepted value for \( \theta_T \). Second, the method to compare \( \theta \) with \( \theta_T \) is not well defined. The latter can be any of the maximum yaw angle, the average yaw angle, or the yaw angle at the pedestrian level of the approaching wind profile. Therefore, the outcomes of the Threshold method can vary significantly according to the selection of \( \theta \) and \( \theta_T \) for the calculation.

2.2.3. Proportional method

The Proportional method modifies the \( p \) value of a given wind sector using the values of \( \theta \) and \( p \) of the given and adjacent wind sectors. Compared to other two correction methods, the Proportional method is well-organized with clearly defined variables and a calculation method. For example, the method uses \( \theta \) averaged over the profile height and considers clockwise angles as positive. The calculation procedure of the Proportional method is shown in Equation (4).

\[
\begin{align*}
\text{Case A}(\theta^+ \geq 0; \theta^- \geq 0): & \quad p'_i = p_{i-1} \frac{\frac{22.5 \theta^-}{\theta^+} + \theta^-}{22.5 \theta^- + \theta^-} + p_i \frac{22.5 \theta^+ - \theta^-}{22.5 \theta^+} + p_{i+1} \frac{22.5 \theta^- + \theta^-}{22.5 \theta^- + \theta^-} \\
\text{Case B}(\theta^+ \leq 0; \theta^- \geq 0): & \quad p'_i = p_{i-1} \frac{22.5 \theta^- - \theta^-}{22.5 \theta^-} + p_i \frac{22.5 \theta^+ + \theta^-}{22.5 \theta^+} + p_{i+1} \frac{22.5 \theta^+ + \theta^-}{22.5 \theta^+ + \theta^-} \\
\text{Case C}(\theta^+ \geq 0; \theta^- \leq 0): & \quad p'_i = p_{i-1} \frac{22.5 \theta^- - \theta^-}{22.5 \theta^-} + p_i \frac{22.5 \theta^+ + \theta^-}{22.5 \theta^+} + p_{i+1} \frac{22.5 \theta^- - \theta^- + \theta^-}{22.5 \theta^- + \theta^- + \theta^-} \\
\text{Case D}(\theta^+ \leq 0; \theta^- \leq 0): & \quad p'_i = p_{i-1} \frac{22.5 \theta^- + \theta^-}{22.5 \theta^-} + p_i \frac{22.5 \theta^+ - \theta^-}{22.5 \theta^+} + p_{i+1} \frac{22.5 \theta^- + \theta^- + \theta^-}{22.5 \theta^- + \theta^- + \theta^-}
\end{align*}
\]

where, \( p'_i \) = the adjusted probability of occurrence of \( i \)th wind direction;
\( p_i \) = the probability of occurrence for the \( i \)th wind direction;
\( p_{i-1} \) = the probability of occurrence for the sector to the left of the \( i \)th wind direction;
\( p_{i+1} \) = the probability of occurrence for the sector to the right of the \( i \)th wind direction;
\( \theta_T = \frac{\theta_i + \theta_{i+1}}{2} \)
\[ \theta_i = \frac{\theta_{i-1} + \theta_{i+1}}{2} \]

\( \theta_i \) = the mean yaw angle for the i\textsuperscript{th} tested wind direction, where clockwise is taken as positive;

\( \theta_{i-1} \) = the yaw angle for the sector to the left of the i\textsuperscript{th} tested wind direction;

\( \theta_{i+1} \) = the yaw angle for the sector to the right of the i\textsuperscript{th} tested wind direction.

2.3. Case study

A site in Tsuen Wan, Hong Kong is selected as the study area for this study. Tsuen Wan, as shown in Fig. 2, is bound by the sea in the south and tall Tai Mo Shan Mountain in the north. In the east and west directions, Tsuen Wan is connected to the rest of Hong Kong and is surrounded by built-up areas such as Kwai Chung. Beyond Tsing Yi, a small Island to the west, there are two other Islands; Lantau and the Hong Kong International Airport in the southwest direction.

The selected site is one of 13 locations where site wind availability studies were conducted by PlanD (the Planning Department of the Government of Hong Kong). The site wind availability test of the selected site was carried out in the CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology (HKUST) using a 1:2000 topographical model. Wind profiles measured at the site for 16 wind directions are presented in both graphical and tabular forms in the report published by PlanD (http://www.pland.gov.hk/pland_en/info_serv/site_wind/index.html). Fig. 3 shows the profiles of mean wind speed, turbulence intensity, and yaw angles in the 16 wind directions constructed using the data from the PlanD report. Each profile extends from the lowest measurement height of 25 m to the gradient height of 500 m in full scale. The mean wind speed profiles in Fig. 3(a) are normalised with respect to the mean wind speed measured at 500 m. The negative values of yaw angles shown in Fig. 3(c) indicate anti-clockwise deviations of wind directions.

Fig. 4 shows a detailed map of the site covering a 1.2 km diameter circular area that was modelled for the detailed AVA test. The selected site is located a fair distance away from both the sea and the Tai Mo Shan Mountain, and there is no other significant topographical feature (defined as topographical features are not taller than 100 m and not larger than 1 km in base length according to [27,28]), nearby that can influence the local wind environment. Most buildings within the site are low-to medium-rise buildings (height about 25 m–50 m) and several tall towers situated on podium structures are scattered over the site. Some of the buildings, such as a group at the centre of the site and two groups in the directions 290° and 310°, are taller than 150 m. In addition, the...
site consists of two highways, road infrastructures, and few open areas. The two main highways, Yeung Uk road and Luen Yan street span the 120°-300° and 60°-240° directions respectively, and intercept each other at a wide intersection at the centre of the site. In directions between 240°-270°, a large open area is located near the site boundary where less obstructed winds are expected to approach the site.

2.4. The wind tunnel experiment

The wind tunnel test described in this paper was 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 WWTF is a closed-return type BLWT with two parallel test sections. The wind tunnel test was conducted in the largest test section, 5 m in width and 4 m in height, under its maximum operating wind speed of 10 m s⁻¹. The largest test section was selected because its larger dimensions are advantageous in minimising the flow reflections from wind tunnel’s side walls when simulating twisted wind flows [12].

Fig. 5 shows the 1:400 scale model of the site set inside the wind tunnel. In the model, all buildings and some of the road infrastructures were modelled explicitly with important features. Greenery areas such as trees, bushes, and lawn areas were not replicated explicitly in the model because they were modelled as tiny objects in the linear scale of 1:400, thus might not have significant effects on the surrounding wind field.

A multichannel thermal anemometer system (Kanomax1560) was employed to measure wind speeds at 5 mm height, which is equivalent to the 2 m height in the field condition. The 77 Kanomax sensors installed are marked in the model by blue dots (Fig. 4), covering important locations such as the perimeter, road sites, road intersections, near low-, medium- and high-rise buildings, courtyards, and open areas to assess the pedestrian-level wind environment. The wind speeds were simultaneously recorded for 65 s at a sampling frequency of 10 Hz using a data acquisition system. The sampling period of 65 s represents more than 7 h measurement period in field conditions according to an assumed velocity ratio of 1:1.

Generally, the detailed AVA test is conducted using 3–4 approaching wind profiles, which are representative of the 16 wind profiles obtained from the site wind availability study. The use of twisted wind profiles as a boundary condition demands more resources as the simulation requires to include yaw angle in addition to wind speed and turbulence. Considering the available resources, technical difficulties, and the required accuracy, the following method is adopted for the current study rather than replicating all 16 wind profiles observed from the site wind availability study.

Two twisted wind profiles and a conventional wind profile were employed as approaching wind profiles for the detailed AVA test. The two twisted wind profiles were simulated using a novel vane system originally developed by Tse et al. [12] and were proven to be having consistent wind speeds and turbulence intensities to conduct successful pedestrian-level wind tunnel studies as reported previously [15-17]. Fig. 6(a) shows the approaching profiles of normalised mean wind speed and turbulence intensity and Fig. 6(b) shows the profiles of yaw angle of the two twisted winds as measured at the centre of the turntable using a Cobra probe. The two twisted wind profiles have similar mean wind speeds and turbulence intensities but different yaw angles at any given height. In fact, the two twisted wind profiles have maximum yaw angles 13° and 22°, representing respectively ‘moderate’ and ‘high’ deviations in wind directions observed from previous site wind availability studies [12]. Based on these maximum yaw angles, the two twisted wind profiles are hereafter referred to as TWP13 and TWP22. The additional conventional wind profile, which has no yaw angle along the profile’s height, was simulated with similar wind speeds and turbulence intensities to the twisted wind profiles and is hereafter referred to as CWP. The CWP is a power-law type wind profile with an exponent of 0.11 and has the mean wind speed of 7.5 m s⁻¹ and turbulence intensity of 5.7% at the height of 0.6 m. The height of 0.6 m (240 m in full scale) was selected as the reference height because it was well above the tallest building in the study area.

By assuming the yaw angle at 25 m height is the same as the yaw angle at the pedestrian level, which is 2 m above the ground, the three wind profiles were applied in the 16 wind directions matching the yaw angle at the lowest height (25 m full scale) in the site wind availability test and the yaw angles at the lowest height (4 m full scale) in simulated twisted winds in the BLWT. For example, CWP was applied at 22.5° because the yaw angle at 25 m height was −5.2°. Similarly, TWP13 and TWP22 were used for directions 45° and 67.5°, where the recorded yaw angles were −11.5° and −23.6°.

2.5. Adjusted probability of occurrence of wind

The three correction methods adjust the p values in the 16 wind directions as shown Table 1. The p values listed under the No-shift method are the original probability of occurrence of winds extracted from the probabilistic wind climate model of Hong Kong. The Threshold method adjusts the p value by considering 11.25° as the threshold angle, which is subsequently compared with the yaw angle at the lowest measurement height of 25 m. The threshold angle 11.25° is equal to the half of a wind sector, of which the exceedance indicates the wind that
3. Results and discussion

Approaches from an adjacent wind sector. Therefore, the exceedance of threshold yaw angle may result in \( p_i = 0 \), as at 135° or \( p_i - P_{i+1} \) as at 225°. The values adjusted by the Proportional method are considerably different from those of the No-Shift and Threshold methods for most wind directions. For example, the value of the proportional method at 157.5° is 29% smaller than those of the No-Shift and Threshold methods, while at 202.5° and 225°, the Proportional method estimates 8% higher values than the other two methods. The noticeable deviations in values of the Proportional method are attributed to large variations in average yaw angles between a given wind sector and its neighbours.

3.2. Roadside test points

Six test points along Yeung Uk road are selected to assess the roadside wind conditions in the study area. Among the six test points, four (R1, R2, R3, and R4) are located between test point P1 at the end of the road and test point R5 at the road intersection at the centre of the study area.

The VR values at P1 are higher than 0.3 in the wind directions between 112.5° to 180° where the unobstructed wind flows approach the test point (Fig. 8(a)). High VR values are observed at R1 to R3 for the CWP in the directions approximately parallel to Yeuen Uk road. The high VR values at the roadside points are likely a result of channeled CWP flow through the street canopy. The trend of high VR values at roadside test points is not consistent for the CWP-TWPs, as evident from R1 and R2, for which small VR values are observed in the direction parallel to the road. At these test points, the VR values of the CWP-TWPs in the direction parallel to the road are noticeably different from those of CWP. For example, CWP-TWPs records a 17% higher VR value for R1 at 45° than CWP (Fig. 8(b)), while R2 has a 61% smaller VR value for CWP-TWPs at 67.5° (Fig. 8(c)). In addition, the overall decrease in VR value along the road is dissimilar for CWP and CWP-TWPs. In the wind direction 135°, the decrease of VR value between test points R1 and R4 is 0.620 for CWP, while the corresponding decrease is about 0.90 for CWP-TWPs. The noticeable differences in VR value and its decrease along the road for CWP and CWP-TWPs shows that the outcome of AVA at roadside test points may vary significantly under the influence of twisted wind flows. The noticeable variations in VR values of CWP and CWP-TWPs at roadside test points diminish near the centre of the study area as both wind flows produce similar VR values at test points R4 and R5 for all wind directions. Similar and uniform magnitudes of VR recorded for CWP and CWP-TWPs relate to the high density
of buildings at the centre of the study area, which overrides the influence of twisted winds that approach the site.

Table 3 shows the VRw values and wind speeds with a 50% probability of exceedance calculated for the 6 roadside test points. All roadside test points have the VRw value equal to or greater than 0.2 and wind speeds higher than 1.5 m s\(^{-1}\) more than 50% of the time. These figures indicate that the wind conditions along Yeung Uk road are

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**Table 3**

Directional velocity ratio (VRw) and wind speed with the probability of exceedance 50% at roadside test points.

| Point | VRw | Wind speed with the probability of exceedance 50% (m s\(^{-1}\)) |
|-------|-----|---------------------------------------------------------------|
|       | CWP-TWPs | No-Shift (CWP) | Threshold Proportional | CWP | CWP-TWPs |
| P1    | 0.26  | 0.26           | 0.26                    | 0.26 | 2.151    | 1.883    |
| R1    | 0.27  | 0.28           | 0.24                    | 0.25 | 2.254    | 2.180    |
| R2    | 0.26  | 0.28           | 0.24                    | 0.25 | 2.143    | 1.917    |
| R3    | 0.23  | 0.23           | 0.23                    | 0.23 | 1.723    | 1.723    |
| R4    | 0.21  | 0.21           | 0.20                    | 0.20 | 1.723    | 1.723    |
| R5    | 0.22  | 0.21           | 0.22                    | 0.22 | 1.971    | 1.970    |

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Fig. 7. Wind rose diagrams of three perimeter points of (a) P1, (b) P2, and (c) P3 for conventional (CWP) and conventional-twisted (CWP-TWPs) wind flows (green and magenta arrows show the incident wind directions of TWP13 and TWP22, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 8. Wind rose diagrams of six roadside test points of (a) P1, (b) R1, (c) R2, (d) R3, (e) R4, and (f) R5 for the conventional (CWP) and conventional-twisted (CWP-TWPs) wind flows (green and magenta arrows show the incident wind directions of TWP13 and TWP22, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
satisfactory. In general, wind speeds at the test points are higher under CWP than CWP-TWPs, except at R1, where CWP records smaller wind speeds despite its VRw value being higher. The VRw values along the road show a steady decreasing pattern, particularly under CWP-TWPs. For instance, the VRw value is reduced from 0.26 to 0.23 between P1 to R3 under CWP-TWPs, while under CWP, the VRw value only decreases from 0.26 to 0.25. Similar VRw values and wind speeds at R5 further substantiate the significant effect of high density of buildings that suppresses the influence of twisted winds that approach the site.

In contrast, the Threshold and Proportional methods underestimate the VRw values at all roadside test points. The degree of underestimation varies between 14% and 5% with the larger underestimation found at test points with high wind speeds, and the minimum difference is at the test locations further inside the study area. The VRw values of the Proportional method, which predicts slightly higher VRw values than the Threshold method, are more comparable with the VRw values of CWP-TWPs. Overall, the differences in VRw between the Threshold and Proportional methods indicate that these correction methods are less accurate in predicting the VRw values compared to the VRw values of CWP-TWPs.

3.3. Near a group of high-rise buildings

The AVA predictions on the wind conditions near a group of high-rise buildings under CWP and CWP-TWPs are assessed using ten test points H1 to H9, and R4. These test points surround the group of podium structures with three tall towers, whose average height is about 190 m and are located close to the centre of the study area. Fig. 9 shows the wind rose diagrams of H1, H4, and H8 near the group of tall buildings. H1 is located near a corner of one of the tall buildings and H7 is in front of the group. H4 is situated near a passage between two tall buildings. The wind rose diagram of H1 (Fig. 9(a)) has VR value higher than 0.3, indicating possible windy conditions commonly found near the windward corners of tall buildings [29–31]. Under windy conditions, the VR values at H1 show some discrepancies between CWP and CWP-TWPs such as in wind directions 337.5° and 135°, where the VR values of CWP-TWPs are 59% and 26% smaller than those of CWP. The high VR values of H4 in wind directions of 202.5° and 225°, as shown in Fig. 9(b), are likely a result of high-speed wind flow in the passage between two tall buildings. While similar VR values are recorded in the directions parallel to the passage, CWP-TWPs and CWP have differences in VR values in other directions. For example, in wind directions 67.5° and 112.5°, CWP-TWPs has 25% higher VR values than CWP. The difference in incident wind directions of twisted and conventional wind profiles is clearly visible from the significantly reduced VR values in the wind directions of 112.5° and 135° at H7 for CWP-TWPs (Fig. 9(c)). Due to the altered incident wind directions, H7 is heavily sheltered from buildings upstream and has 75.8% and 62.5% smaller VR values at 112.5° and 135° for CWP-TWPs than for CWP.

The VRw values and wind speeds listed in Table 4 are higher than 0.2 and larger than 1.5 m s⁻¹, thus indicating satisfactory wind conditions for the group of tall buildings. Both high VRw values and wind speeds are attributed to the windy conditions commonly found near tall buildings [24–26]. However, owing to the low ambient wind conditions in Hong Kong, these windy conditions are advantageous in achieving the acceptable wind conditions (≥ 1.5 m s⁻¹). The small VRw value of 0.15 and wind speed of 0.924 m s⁻¹ at H6 are a result of excessive sheltering from surrounding buildings, thus points out a great reduction of wind speed near tall buildings within closely-spaced buildings.

The three correction methods show no consistent trend in predicting VRw value for the 10 test points. The inconsistent trends in predicting VRw values may be related to the fact that the wind environment near the tall buildings is greatly modified by local circulations rather than by the properties (wind speed and direction) of winds that approach the site. Nevertheless, the prediction of VRw values by the No-Shift method has a maximum difference of 7% with respect to the VRw values of CWP-TWPs, while the Threshold and Proportional methods have maximum differences of 26.7% and 14.2%, respectively. The larger differences in prediction of VRw value indicate possible errors that could be induced by the correction methods to the outcomes of AVA when AVA evaluates the PLW field near tall buildings.

3.4. Near a cluster of low-rise buildings

The wind conditions near a cluster of low-rise buildings, whose average height is about 26 m, are evaluated using 8 test points. The group of buildings is west of the centre of the study area and is bound

Table 4

| Point | VRw | Wind speed with the probability of exceedance 50% (m s⁻¹) |
|-------|-----|-------------------------------------------------------|
|       |     | CWP-TWPs  | No-Shift (CWP) | Threshold | Proportional | CWP | CWP-TWPs |
| H1    | 0.24| 0.25  | 0.29  | 0.27  | 1.718 | 1.702 |
| H2    | 0.20| 0.21  | 0.21  | 0.21  | 1.453 | 1.551 |
| H3    | 0.20| 0.20  | 0.20  | 0.20  | 1.446 | 1.438 |
| H4    | 0.21| 0.21  | 0.20  | 0.20  | 1.737 | 1.712 |
| H5    | 0.20| 0.20  | 0.21  | 0.20  | 2.500 | 2.399 |
| H6    | 0.15| 0.15  | 0.19  | 0.17  | 0.924 | 0.924 |
| H7    | 0.29| 0.29  | 0.35  | 0.28  | 2.490 | 2.490 |
| H8    | 0.22| 0.21  | 0.21  | 0.21  | 1.575 | 1.728 |
| H9    | 0.25| 0.26  | 0.35  | 0.32  | 1.911 | 1.880 |

Fig. 9. Wind rose diagrams of three test points (a) H1, (b) H4, and (c) H7 under conventional (CWP) and conventional-twisted (CWP-TWPs) wind flows (green and magenta arrows show the incident wind directions of TWP13 and TWP22, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
by Yeung Uk road to the south and by three secondary streets on the other sides. One of the test points, L1 is located in a courtyard and the rest of the test points L2 to L8 are in roadside around the cluster of the buildings.

Fig. 10 shows the wind rose diagrams of a test point on Yeung Uk road (L2), a test point in a narrow secondary road (L6) and the test point in the courtyard (L1). Among the three test points, L2 (Fig. 10(a)) has a substantially high VR value about 0.5 for both CWP and CWP-TWPs in the wind directions between 225° to 270°. The high VR values in these directions may be related to the less obstructed winds that travel along Yeung Uk road and some accelerated wind flows resulted from a “short-circuiting” between the positive and negative pressure zones of the surrounding buildings [32]. In some other directions, CWP-TWPs and CWP have different VR values. For example, CWP-TWPs record about 16% higher VR values at 292.5° and 337.5°, and a 61.5% smaller VR value at 67.5° than CWP. Neither high VR values nor significant differences can be identified from the wind rose diagram of L6, as shown in Fig. 10(b), for CWP and CWP-TWPs. The small but similar VR values of both wind flows may be related the test location, which is on a narrow, secondary road surrounded by closely-spaced low-rise buildings. The VR values of L1 are extremely low for both CWP and CWP-TWPs in all 16 directions as shown in Fig. 10(c). The small VR values of L1 shows inadequate air circulations in the courtyard under both types of wind flow.

Table 5 shows the VRw values and wind speeds with the probability of exceedance of 50% calculated for the 8 test points near the cluster of low-rise buildings. The VRw values of CWP (No-Shift method) and CWP-TWPs are similar for most test points. Even if they are not, the differences are slight. The other two correction methods, Threshold, and Proportional methods have noticeable deviations in VRw value from those of CWP-TWPs. In particular, both Threshold and Proportional methods overpredict the VRw values at test locations such as L2 and L4, which are exposed to less obstructed wind flows. In contrast to more than 10% difference in VRw values at L2 and L4, test points such as L6 and L1 that are sheltered by surrounding buildings have less or no deviation in VRw value compared with those of CWP-TWPs. The surrounding buildings have a similar effect on wind speeds, for instance, test points exposed to less obstructed winds display large variations in wind speeds in CWP and CWP-TWPs. For example, about 15.6% difference in wind speeds is found between CWP and CWP-TWPs at L2. At locations with high density of surrounding buildings, both CWP and CWP-TWPs produce extremely small but similar wind speeds as reported at L6 and L1. Of note is that while both CWP and CWP-TWPs record below-par standard wind speeds (< 1.5 m s⁻¹) at most test points, CWP-TWPs show more adverse wind conditions with lower wind speeds than CWP. Such adverse wind conditions would be hidden in the outcomes of AVA if AVA does not use twisted wind profiles as a boundary condition.

3.5. Spatially average velocity ratio (SAVR)

The Spatially Average Velocity Ratio (SAVR) is calculated according to Equation (3) for a cluster of low-rise buildings, a cluster of medium-rise buildings, and a group of high-rise buildings. Table 6 shows the SAVR values calculated for the group of high-rise buildings and the cluster of low-rise buildings presented in sections 5.3 and 5.4. A cluster of medium-rise buildings has an average height of 50 m and is located south of the group of high-rise buildings. The SAVR value of the cluster of medium-rise buildings is based on the wind speed measurements of 13 test points (i.e., M1-M10, H1, H9, P2 in Fig. 4) located around and within the cluster.

The SAVR values of different wind flows and the correction methods have a steady increase in magnitude as building height increases from 26 m for the low-rise buildings to 190 m for the high-rise buildings. The increase in SAVR value essentially relates to the increase in wind speed with building height as reported by several researchers [15, 16, 33-35]. In contrast to the noticeable differences in VR and VRw values presented in previous sections, the SAVR values of CWP (No-Shift) and CWP-TWPs

**Table 5**

| Point | VRw | Wind speed with the probability of exceedance 50% (m s⁻¹) |
|-------|-----|--------------------------------------------------------|
|       | CWP-TWPs | No-Shift (CWP) | Threshold | Proportional | CWP | CWP-TWPs |
| L1    | 0.10  | 0.10  | 0.09  | 0.10  | 0.500 | 0.500 |
| L2    | 0.19  | 0.20  | 0.21  | 0.21  | 1.354 | 1.142 |
| L3    | 0.16  | 0.17  | 0.19  | 0.18  | 1.296 | 1.228 |
| L4    | 0.19  | 0.19  | 0.22  | 0.21  | 1.414 | 1.370 |
| L5    | 0.15  | 0.15  | 0.15  | 0.15  | 1.277 | 1.180 |
| L6    | 0.10  | 0.10  | 0.11  | 0.11  | 0.672 | 0.672 |
| L7    | 0.12  | 0.12  | 0.10  | 0.10  | 0.605 | 0.605 |
| L8    | 0.15  | 0.16  | 0.14  | 0.14  | 1.285 | 1.102 |

**Table 6**

| Building group | SAVR |
|----------------|------|
|                | CWP-TWPs | No-Shift (CWP) | Threshold | Proportional |
| Low-rise       | 0.14  | 0.15  | 0.15  | 0.15  |
| Medium-rise    | 0.21  | 0.21  | 0.23  | 0.22  |
| High-rise      | 0.22  | 0.22  | 0.24  | 0.23  |
are identical for the medium- and high-rise building subzones while slightly different SAVR values are observed for the low-rise buildings. The Threshold and Proportional methods, on the other hand, tend to over-predict the SAVR values by 5%–9% compared to the SAVR value of CWP-TWPs. The minor differences between the SAVR values of the Threshold and Proportional methods and the same SAVR values of CWP and CWP-TWPs are a result of the averaging process, which offsets the differences in VR value resulted from the two wind flows and the correction methods. Therefore, the direction dependency of wind conditions under different wind flows cannot be identified from the SAVR value.

4. Discussion

In this study, two twisted wind profiles were integrated into AVA to assess the accuracy of three most empirical correction methods: No-Shift, Threshold, and Proportional methods used in AVA to incorporate effects from twisted profiles into the AVA results. Although this study tested a typical urban area in Hong Kong according to the guidelines of AVA, the findings of this study have few following limitations:

- The current study only used two twisted wind profiles due to the constraints of cost, time, and available resources in simulating twisted wind profiles in a BLWT. Otherwise, twisted wind profiles observed in the field conditions are diverse in wind speed, turbulence intensity, and yaw angles in different wind directions. Therefore, it is necessary to conduct detailed AVA tests using twisted wind profiles with different profiles of wind speed and turbulence intensity and maximum yaw angles as observed from the site wind availability study for better accuracy of AVA.
- Based on the wind profiles extracted from the site wind availability study, this study applied the twisted wind profiles for only 6 wind directions (out of 16 wind directions). Therefore, more significant differences in the outcomes of AVA are expected if twisted wind profiles are applied in all 16 wind directions according to the extracted wind profiles from the site wind availability study.
- The findings of this study are based on one particular case study. Although the selected site is representative of a typical urban area in Hong Kong and the test locations selected for the study indicate various flow patterns possibly found in an urban area it is necessary to test more sites, especially that are located near to topography features and large water bodies and experience change of approaching wind conditions.
- Selection of correction methods is based on, to the best of the authors’ knowledge, their popularity in common AVA practice. The authors admit that other correction methods that lead to more or less accurate results may exist. Moreover, some of the factors selected for the correction methods such as threshold angle and cut-off yaw angle are subjective decisions of the authors. Therefore, the results of the correction methods can vary to some extent if the values selected for these factors are different than those of this study.

5. Concluding remarks

This study demonstrates strong dependency of the outcomes of AVA on the type of oncoming wind flow (conventional or twisted wind profile) and the selection of correction methods. The results of this study clearly indicate the influence of twisted winds on the AVA results, that are obtained for the locations where unobstructed wind flows prevail and density of buildings in the surroundings is low. In those locations, the differences in wind speeds between the twisted and conventional wind flows are attributed to the associated yaw angles, which define the incident wind direction at the location. Although pronounce differences are found for the VR values and the wind rose diagrams, the indicators, VRw and SAVR do not reveal any significant discrepancies owing to the averaging process, which masks any differences between VR values.

The three correction methods cannot accurately account for the effects of twisted wind flows but predict the indicators differently from those of the twisted winds. In particular, the Threshold and Proportional methods tend to over-predict the VRw value compared to the corresponding values of twisted wind flows. These discrepancies become less at locations where the density of buildings is high and the PLW field is governed by local wind circulations. The strong dependency of the outcomes of AVA on the approaching wind type and the less accuracy of the correction methods suggest using twisted wind profiles for AVA to obtain results with better accuracy.

Cost, time and technical difficulties are all significant constraints at present when simulating twisted wind profiles for AVA in a BLWT. Therefore, it is prudent to develop a novel, cost-effective technique to replicate similar wind conditions as in twisted wind profiles for the wind tunnel tests done for AVA.

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