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A SHORT REVIEW ON PEDESTRIAN WIND ASSESSMENT TECHNIQUES IN URBAN AREA

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A R T I C L E I N F O

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A B S T R A C T

High-rise buildings in urban areas increase wind speeds, causing discomfort to the community and infrastructural damages at the pedestrian level. Wind components, turbulence intensity, and magnitude are studied when evaluating these issues. Pedestrian wind assessments can be conducted through wind tunnel experiment and numerical studies. Numerical studies are performed using Computational Fluid Dynamics (CFD) tools. Both methods are preferable due to its reliability. There are studies conducted on-site measurements for validation or comparison purposes. Different urban topography in urban area creates different outcomes and hence, essential to assess wind flow at the pedestrian level. Subsequently, some remedial measures may suggest improvents to the problems posed by various urban topographies. Although there are different assessment criteria proposed, there are no specific criteria to be referred. In this paper, some pedestrian wind studies are compiled, and the research standards and techniques conducted by researchers are reviewed, which may provide fundamental understanding in developing a framework for future exploratory pedestrian wind research.

1. Introduction

In recent years, urban development is increasing, which leads to a higher density of high-rise buildings in urban areas. The wind can be a contributor in wind power generation yet we should not overlook the significant damage that could be caused by strong winds. The wind in urban areas might pose some degree of risk especially to pedestrian or community living nearby. High-rise buildings have contributed to locally-induced high wind speeds, which knocked down trees and power lines or even caused damages on building structures. The urban morphology may contribute in the amplification of wind speed at the pedestrian level (Razak, Hagishima et al. 2013, Razak, Rodzi et al. 2015). The worst incident may endanger human lives as well. Pre-assessment of wind before building construction is a better choice than creating remedial action after its construction. This review compiles studies regarding pedestrian wind, including criteria and techniques used, which can serve as fundamental knowledge for a pre–exploratory research framework.

Countries from temperate region, which experienced strong wind impacts such as Japan, Netherlands and the United Kingdom, had been paying more attention to the wind at pedestrian level. In contrast, the countries from low-latitute climate such as Malaysia did not develop any standard of control to address this issue due to less interest.. Correspond to economy growth in some low-latitute climate countries which might experience rapid urbanization has contributed to densely built of high-rise buildings. In fact, such phenomenon might have contributed to the aritifical strong wind such as wind gust or wind

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loading which poses some risks towards the community nearby high-rise buildings. A study of pedestrian level wind has been conducted in Klang Valley, Malaysia by Razak et al. (2015), but it is still lacking of literature and related documentations if we would like to construct an implementation standard. Thus, this motivated us to explore in this area of interest.

Therefore, this review will focus on comparing several studies done that are related to the wind in an urban area. The evaluation of wind could be conducted through wind tunnel experiments, which is used to predict the impact of wind. The wind tunnel is set up by installing anemometer sensors at different measuring points whereby the wind speed and the wind directions can be manipulated. This method is preferable for researchers as it saves time (Yoshie and Ohba 2009).

Modern technique, with a higher level of confidence, has emerged and gained popularity among scientists, which is the application of Computational Fluid Dynamics (CFD) in analysing and exploring solutions (Yoshie and Ohba 2009, Fadl and Karadelis 2013). However, due to the lack of understanding on such as the parameters control that may affect the simulation results, the preciseness of the prediction should be of concern. On-site measurements were also conducted for validation purposes as well as to assure the trustworthiness of the simulation. Each sub-section below reports some of the different methods of pedestrian wind assessment studies of several countries.

2. Pedestrian wind studies in Japan

In Japan, violent wind surrounds high-rise building and has been an issue for decades. The general assessment technique used in Japan was wind tunnel experiment and CFD simulation (Yoshie and Ohba 2009). Although it is not mandatory to conduct an evaluation for wind at pedestrian level, preliminary research and estimation of impact is demanded from developers by local governments. The wind tunnel experiment was widely used to conduct the assessment in Japan. However, Yoshie and Ohba (2009) mentioned that one of the drawbacks of conducting wind tunnel experiment was the low sampling frequency of the anemometer (below 1 *Hz*) which unable to capture the wind gust speeds. To improve the reliability of conducting the CFD simulations, a research group organized by Architectural Institute Japan (AIJ) has worked out practical guidelines for wind prediction (Tominaga, Mochida et al. 2008). Different types of flow studies have been conducted using numerical simulation, and the results were used to compare with wind tunnel experiments and on-site measurements. Testing on factors such as computational domain, grid, boundary conditions, numerical schemes for advection terms and turbulence models were necessary for confirming its effects on the CFD results. Few types of flow field configurations were tested: (1) single high-rise building, (2) around a high-rise building within a city and (3) high-rise buildings in an actual urban model (Yoshie, Mochida et al. 2007).

The pedestrian wind assessment in Japan was mainly conducted based on two main criteria, which are cumulative frequency of mean wind speeds and occurrence frequencies of wind speeds. Table 1 shows the cumulative frequency method with averaged of ten minutes, proposed by Wind Engineering Institute (1989) and employed in Japan . The above latter criteria were based on the daily maximum gust speed, which was suggested by Murakami et al. (1986) as shown in Table 2. The calculations could be done using meteorological data and wind tunnel experiments or simulations. Reynolds averaged turbulence models are referred in most of the CFD simulations. Hence, instead of gust factor, mean wind velocities are obtained. The assumption of gust factor should be made if Murakami's criteria are employed. Although there are some recommendations to estimate the gust factor, the preciseness was not theoretically proven (Nishimura and Takamori 2002, Hongo and Nakayama 2003). Both criteria are shown in Table 1 and 2 respectively.

Table 1: Criteria for assessment of pedestrian wind environment based on cumulative frequency of mean wind velocity (Institute 1989)

Region	Mean wind speed at cumulative frequency of 55% (m/s)	Mean wind speed at cumulative frequency of 95% (m/s)	Wind environment
A	≤1.2	≤2.9	Residential area
B	≤1.8	≤4.3	Residential area and urban area
C	≤2.3	≤5.6	Office area
D	>2.3	>5.6	Around super high-rise building

Table 2: Criteria of pedestrian wind assessment based on occurrence frequency of daily maximum gust speed (Yoshie and Ohba 2009)

Class	Effect of strong wind	Areas applicable (example)	Level of assessment of strong wind and acceptable exceedance frequency (at height of 1.5 m)		
			Daily maximum gust speed (m/s)		
			10	15	20
			Daily maximum mean speed(m/s)		
			10/G.F	15/G.F	20/G.F
1	Areas used for purposes most susceptible to wind effects	Shopping street in residential area, Outdoor restaurant	10% (37 days per year)	0.9% (3 days per year)	0.08% (0.3 days per year)
2	Areas used for purposes not too susceptible to wind effects	Residential area, park	22% (80 days per year)	3.6% (13 days per year)	0.6% (2 days per year)
3	Areas used for purposes least susceptible to wind effects	Office street	35% (128 days per year)	7% (26 days per year)	1.5% (5 days per year)

GF: Gust Factor (the ratios of peak gust wind velocity to mean wind velocity)

3. Pedestrian wind studies in United Kingdom

A case study on wind at the pedestrian level has been conducted in a university campus in United Kingdom using CFD simulation to reveal the effect of building shapes at different wind directions. Some remedial measures are suggested to alleviate the existing problems (Fadl and Karadelis 2013). The results show that the wind speed enhanced at diverging passages compared to converging passage. In this study, the Lawson pedestrian comfort criteria (Lawson 1990) (shown in Appendix) is referred where the area experiencing high wind speed is classified per Table 3.

Table 3: Desirable pedestrian wind comfort classes for various location types (Fadl and Karadelis 2013)

Comfort Classes	Description	Location Types (Examples)
Sitting	$W_{wind} \leq 3.9$ m⁄s Occurrence: > 70% of the time. Acceptable for sedentary activities, including sitting.	Outdoor Cafes, Patios, Terraces, Benches, Gardens, Fountains, Monuments.
Standing	$W_{wind} \leq 6.1$ m⁄s Occurrence: > 80% of the time. Acceptable for standing, strolling, etc.	Building Entrances, Exits Children’s Play Areas
Walking	$W_{wind} \leq 8.3$ m⁄s Occurrence: > 80% of the time.Acceptable for walking, or rigorous activities	Public/Private Vehicular Drop-Off Zones, Sidewalks, Pathways
Uncomfortable	$W_{wind} > 8.3$ m⁄s Occurrence: > 20% of the time. Unacceptable for walking	
Dangerous	$W_{wind} > 25$ m⁄s Occurrence: > 0.01% of the time. Dangerous to walk	

Referring to the previous studies as guidelines (Blocken, Roels et al. 2004, Blocken and Persoon 2009), this case study was conducted using Fluent and three-dimensional steady RANS equation while the standard turbulence model (k-ε) was employed (Franke, Hirsch et al. 2004). The boundary conditions assumptions made for this simulations studies were commonly used by other researchers (Blocken, Roels et al. 2004, Franke, Hirsch et al. 2004). Fadl and Karadelis (2013) had used two wall function models for the mesh implementation with approximately 360000 grid elements. The dissipation rate and the turbulent kinetic energy that could be derived from the known turbulent intensity were required to determine the comfort criteria used. Seven years of local meteorological data were applied to discover wind speed and wind direction throughout the year. The flow field between two buildings in the campus was revealed by performing CFD simulations. The results showed that the building design caused wind nuisance and the university department had successfully implemented some vegetation for wind speed mitigating purposes.

4. Pedestrian wind studies in Netherlands

A design code for wind comfort assessment in The Netherlands has been compiled by Netherlands Normalisation Institute (NEN), and the results of this Dutch code NEN 8100 (NEN 2006) publication were discussed by Willemsen and Wisse (2007). This code has provide some guidelines for wind assessment for the building programme, including the criteria to conduct wind tunnel and CFD simulations, although it was not mandatory for building plans. The criteria for wind assessment suggested by Lawson and Penwarden (1975) was referred for the building validations. In common, the decision of incorporating wind assessment in building plans is dependent on the building height, as shown in Table 4.

Table 4: Decision scheme of wind assessment according to building height (Willemsen and Wisse 2007)

Building height (m)	Wind assessment	Remark
< 15 (sheltered)	No	No further evaluation is necessary.
15 – 30 (sheltered or unsheltered)	Yes	Expert decide the necessity to conduct CFD or wind tunnel experiment.
< 30	Yes	Investigation is a must.

Wind speed ratios C_v between pedestrian wind and relevant reference wind are typically calculated. The value of C_v for wind tunnel approximate the C_v for an in-situ condition when a simulation is running well. It is essential to determine the threshold wind speed V_{THR} and a probability of occurrence P that a local wind speed exceeded the threshold value. In code NEN 8100, the threshold mean wind speed is set at 5 m/s and dangerous at 15 m/s. For wind comfort at the pedestrian level, 5 m/s is commonly used in the Netherlands. Table 5 shows the choices made in NEN 8100.

Table 5: Criteria for wind comfort and danger (Willemsen and Wisse 2007)

Wind comfort				
P (local wind speed exceed 5 m/s) in % hours per year	Grade	Activity area		
		Traversing	Strolling	Sitting
< 2.5	A	Good	Good	Good
2.5-5.0	B	Good	Good	Moderate
5.0-10	C	Good	Moderate	Poor
10-20	D	Moderate	Poor	Poor
> 20	E	Poor	Poor	Poor
Wind danger				
P (local wind speed exceed 15 m/s) in % hours per year		Limited risk Dangerous	0.05-0.3% hours per year > 0.3 % hour per year	

Willemsen and Wisse had mentioned that there are some essential aspects that need to be concerned for incorporation of both wind tunnel and CFD simulations (2007): (1) adequate knowledge on theory of mechanical and climate as well as practical simulations, (2) documents which address appropriate guideline, criteria or procedure in modelling and wind tunnel or CFD code, including the instruments and (3) proper data munging with well documentation of set-up, calculations methods and some others relevant informative records. There is a customized application established by the Royal Netherlands Meteorological Institute (KNMI) where meteorological data is transformed, and the statistical wind data (at a reference height of 60 m) is obtained directly from the building site.

A CFD simulation was conducted with incorporation of Dutch standard NEN 8100 and the result was compared with on-site measurement (Janssen, Blocken et al. 2013). 3D steady Reynolds-averaged Navier-Stokes (RANS) equations and turbulence model of (k-ε) were used to examine the pedestrian wind around the tall buildings. Three on-site measurements were collected with a reference position at an elevation of 44.6 m. Eight wind directions with above ten measurement intervals were used in the comparison. Reference from Franke et al. (2007) and Tominaga et al. (2008) was used in computational domain and grid selection. The domains for upstream and downstream area were set as 5H and 15H respectively, where H represents the height of tallest structure near the edge of the model. The overall height for the domain was five times the height of the tallest structure. Fourteen million cells were set in the computational grid for this case study. As for boundary conditions, the following parameters was determined: inlet mean wind speed, U (m/s); turbulent kinetic energy, k (m^2/s^2), turbulence dissipation rate, ε (m^2/s^3), roughness length, z_0 (m) and friction velocity, u^* (m/s). The range of longitudinal turbulence intensities for z_0 = 0.5 m and z_0 = 1.0 m were manipulated from 29% (pedestrian height of z = 1.75 m) to 5% (gradient height); while the latter roughness length was from 39% (z = 1.75 m) to 8% at gradient height. The sides and top of the model were operated as slip wall domain. The ground domain was separated into three different zones, and each zone has a different roughness parameter which shown in Table 6. Zone 1 was with first cell height of 2.8 m while Zone 2 was 200 m wide between the border and model of interest. Zone 3 was the model area of interest with the buildings. The amplification factor is a ratio, which was derived to show the comparison between the simulation and on-site measurements. In the result of Jassen et al. (2013) study, the cause of the wind nuisance at pedestrian level is identified, and the simulation indicated that adding a canopy could solve the problem. The same group of researcher has also studied the entire flow field data in a complex urban (Janssen, Blocken et al. 2013)

Table 6: Roughness parameters at three different zones at ground domain (Janssen, Blocken et al. 2013)

Zone	Roughness, z_0	Equivalent sand-grain roughness height, k_s	Roughness constant, C_s
Zone 1 Near border	0.5-1 m (depends on wind direction)	Has maximum value of half the first cell height of 1.4 m	7
Zone 2 Transition area	0.5 m	First cell height decrease to 1.4 m for a better transition to zone 3	7
Zone 3 Model area	0.5 m	0.14 m	7

A review has been published, discussing the related techniques (Blocken, Stathopoulos et al. 2016). Other wind assessment studies may also be credited for contributing ideas for conducting exploratory framework (Iqbal and Chan 2016, Johansson, Onomura et al. 2016, Yuan, Norford et al. 2016, Zheng, Li et al. 2016).

5. Conclusions

Conducting a pedestrian wind assessment before the completion of a building is encouraged as it may reduce the cost and minimize the risk towards the surrounding community. This paper has gathered some information of the technique and criteria for wind assessment, which may provide some ideas in constructing a framework for exploratory wind studies at the pedestrian level. Remedial measures can always tested using CFD, and the best option could be suggested to improve the current wind nuisance. The exisiting CFD needs to be explored and enhanced through conducting more research as there is no universal criteria for some of the parameter such as induced wind gust standard.

Although most of the wind assessments were performed per certain criteria, the criteria did not differ much regarding paremeters concerned. Besides the simulation techniques mentioned above, there are others models, such as Large-Eddy Simulation (LES) that could simulate turbulent flows, which may also implemented in wind studies. However, improvements on existing simulation modelling shall be continued to approach a greater level of reliability.

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Appendix

Lawson pedestrian comfort criteria (Lawson 1990)

Lawson Comfort Classification	Mean Wind Velocity Range (m⁄s)	Tolerable Location	Tolerable Activity
5	0-2	Seating areas in open air cafes, parks	Pedestrians sitting for a long time and wind velocity in the vicinity of entrance doors
6 and 7	2-6	Entranced to buildings	Standing or sitting for a short time
8	6-8	Pedestrian footpaths, public spaces, shopping areas	Pedestrian walking, e.g. strolling and sightseeing
9	8-10	Around buildings	People at work (maintenance deliveries)
10	10-12	Roads and car parks	Fast pedestrian waling, e.g. waling to a destination and cycling