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Criterion for wind environment assessment with consideration to the effect of turbulence

Kryterium oceny środowiska wiatrowego z uwzględnieniem wpływu turbulencji

Abstract

Turbulence affects the human perception of wind, the wind-induced damage to buildings, the values of wind speeds measured by 3-cup anemometers, and so on. The wind environment assessment criterion proposed by the Wind Engineering Institute Co., Ltd. is based on the relationship between the mean wind speeds measured by 3-cup anemometers and the condition of surrounding terrain. This criterion does not consider the influence of turbulence. Considering the significant urbanization of large cities and the change in anemometers used for wind speed measurements, a new criterion of wind environment assessment that considers the effect of turbulence is required. The present study discusses such a criterion based on a wind tunnel experiment, the observation at various locations, and a questionnaire survey on the wind environment that was conducted with for the residents and pedestrians in Tokyo.

Keywords: wind environment assessment, turbulence intensity, questionnaire survey, field observation, wind tunnel experiment

Streszczenie

Turbulencja wpływa na postrzeganie wiatru przez człowieka, wywołane wiatrem uszkodzenia budynków, wartości prędkości wiatru mierzone przez anemometry 3-filiżankowe etc. Kryterium oceny środowiska wiatrowego zaproponowane przez Instytut Inżynierii Wiatrowej opiera się na zależności między średnią prędkością wiatru mierzoną przez anemometry 3-filiżankowe a stanem otaczającego deszczu. To kryterium nie uwzględnia wpływu turbulencji. Biorąc pod uwagę znaczną urbanizację dużych miast i zmianę anemometrów używanych do pomiarów prędkości wiatru, wymagane jest nowe kryterium oceny środowiska wiatrowego, które uwzględnia wpływ turbulencji. Niniejszy artykuł omawia takie kryterium oparte na eksperymencie z tunelem aerodynamicznym, obserwacji w różnych miejscach oraz ankiecie dotyczącej środowiska wiatrowego, która została przeprowadzona dla mieszkańców i pieszych w Tokio.

Słowa kluczowe: ocena środowiska wiatrowego, intensywność turbulencji, badanie ankietowe, obserwacja w terenie, eksperyment w tunelu aerodynamicznym

1. Introduction

The criterion for wind environment assessment proposed by the Wind Engineering Institute Co., Ltd. (WEI), as shown in Table 1, has been used for several decades in Japan. This criterion is based on the relationship between the mean wind speeds measured by 3-cup anemometers and the condition of surrounding terrain with consideration to building heights and densities, as shown in Nakamura et al. [7]. However, the criterion doesn't consider the effects of turbulence on the human perception of wind. Wind turbulence significantly affects not only the human perception of wind but also the wind speed values measured by 3-cup anemometers. Therefore, the present study discusses the effects of turbulence on the current WEI criterion.

In recent years, the urbanisation of cities has progressed significantly, particularly in large cities such as Tokyo. This has resulted in a major change in public opinion concerning wind environment. In addition, ultrasonic anemometers that have lower cost and higher performance are becoming increasingly popular; these can precisely measure turbulence. In the light of these circumstances, the present study proposes a new criterion for wind environment assessment with consideration to the effect of turbulence, based on the results of field observation, a wind tunnel experiment, and a questionnaire survey on wind environment in Kamiosaki, Shinagawa-ku, Tokyo.

Table 1. WEI wind environment assessment criterion

Rank	Mean wind speeds at cumulative frequencies of 55% and 95%	
	55%	95%
A	≤ 1.2 m/s	≤ 2.9 m/s
B	≤ 1.8 m/s	≤ 4.3 m/s
C	≤ 2.3 m/s	≤ 5.6 m/s
D	> 2.3 m/s	> 5.6 m/s

2. Outline of field observation

The field observation of wind was performed at six points (MG1–MG6) close to the ground (3–5 m high) and at four points (MGO–MGR) on the rooftop of a high-rise building (Bldg. P, 115 m high) in Kamiosaki. Their locations are shown in Fig. 1. Ultrasonic anemometers were installed at MG1–3, and 3-cup anemometers were installed at MG4–6. A thermometer was installed at MG6. The period of the observation was from October 2016 to September 2017. The averaging time of the observation data was 10 minutes, and the instantaneous wind speed was obtained as a 3 second moving average. The wind speed values measured by the 3-cup anemometers were converted to these by ultrasonic anemometers, using the correction method proposed by Akahoshi et al. [1]. In order to obtain the rooftop observation data which is free from the effect of Bldg. P, the most appropriate data among those at MGO–R was selected for each wind direction. The selection of the point for each wind direction was determined on the basis of the results of a CFD analysis and a wind tunnel experiment. The selected observation point is referred to as point 'MGZ'.

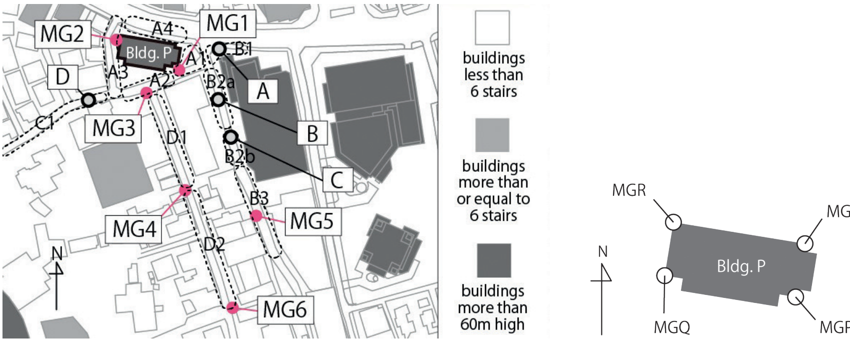


Fig. 1. Location of observation points, measurement points of wind tunnel experiment (selected) and areas of questionnaire

3. Outline of results of wind tunnel experiment

In the wind tunnel experiment, the wind speed ratio, gust factor, and turbulence intensity were measured at many points in Kamiosaki using hot-wire anemometers. The scale of the model was 1/400. The boundary layer was modelled on Category IV specified in the AIJ recommendations (2015). The reference point for these values was MGZ. In Fig. 2, these values are compared with the values obtained at the same locations in the field observation. The dashed line represents an approximate line obtained by applying the least squares method. Strong agreement is observed for the mean wind speed ratio. However, the experimental results for the gust factor and turbulence intensity are generally smaller than the observed results by approximately 20%. One of the reasons for this discrepancy is considered to be that the turbulence intensity of the inflow in the wind tunnel was smaller than that of the flow at full-scale.

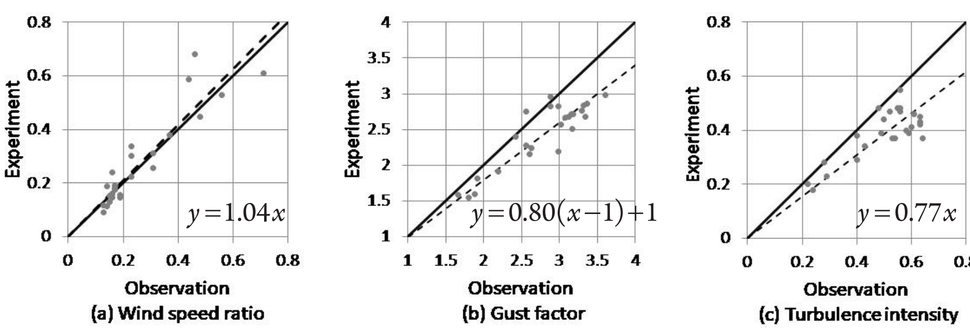


Fig. 2. Comparison for wind speed ratio, gust factor and turbulence intensity between the experiment and the field observation

4. Outline of questionnaire survey on wind environment

The questionnaire survey on the wind environment conducted with the pedestrians and residents in Kamiosaki consisted of three questions referring to Murakami et al. [5]. The details of the questions are provided in Table 2. The respondents were required to select one of the eleven areas (A1–D2) shown in Fig.1 and answer the questions in that area on as many days as possible. The appropriate period of time for evaluating the human perception of wind was not clear. Therefore, it was initially defined as one day referring to Murakami et al. [5]. There were thirty-eight respondents for the questionnaire, and 3664 answers were obtained during the period from May 2016 to October 2017. The number of answers to each question is shown in Fig. 3. Although the age and gender of respondents may affect these answers, this was not considered in this paper.

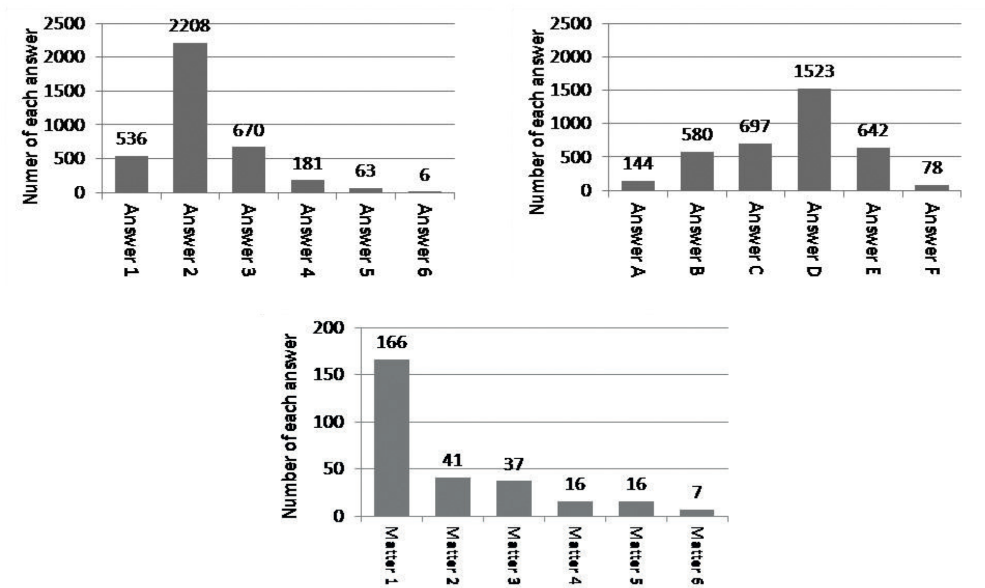


Fig. 3. Number of answers to each question

Table 2. Details of the questions

Question 1: "How was the wind strength today?"
Answer 1: calm
Answer 2: moderate
Answer 3: slightly strong
Answer 4: strong and uncomfortable
Answer 5: rather strong
Answer 6: dangerously strong

Question 2: "How was the temperature of wind today?"
Answer A: unpleasantly hot
Answer B: slightly hot
Answer C: comfortable
Answer D: neither hot nor cold
Answer E: cold
Answer F: so cold as to feel pain
Question 3: "What kind of wind-induced discomfort did you experience or see today?"
Matter 1: dishevelment of hair and/or clothing
Matter 2: difficulty in walking or falling down
Matter 3: difficulty in using umbrella or breakage of umbrella
Matter 4: falling down of bicycles or motorcycles
Matter 5: blowing up or drift of dust
Matter 6: wind too strong to go out

5. Relationship between the results of field observation, wind tunnel experiment, and questionnaire survey

5.1. Relationship between the perception of wind strength, wind speed, and turbulence intensity

The relationship between the human perception of wind and the statistics of wind speed is discussed here using the results of the field observation and wind tunnel experiment discussed above. The correspondence between the observation points (MG1–6), the measurement points of experiment (A–D), and the area of questionnaire survey (A1–D2) are shown in Fig. 1.

Figure 4 shows the dependence of relative frequency of each answer to Question 1 on the daily mean wind speed and turbulence intensity. The relative frequency of each answer, $f_i(U,I_u)$, is defined by Eqn. (1):

$$f_i(U,I_u) = \frac{N_i(U,I_u)}{\sum_{i=1}^{6} N_i(U,I_u)} \tag{1}$$

where N is the number of answers to each question; U is the mean wind speed; and I_u is the turbulence intensity.

In Fig. 4, the warm colours represent a higher relative frequency of the answers, while cold colours represent a lower relative frequency. It was found that the number of people who feel the wind strongly increases as the daily mean wind speed and turbulence intensity increase.

Figure 4 shows a clear tendency of the relationship between wind speed, turbulence intensity and human perception, although there is a dispersion. The reason for this dispersion may be that the respondents answered the question based on the perception for some specific period of time, for example, within a few minutes, not 1-day. Therefore, it was necessary to identify the specific period for which the respondents experienced the perception of wind. Although the period of time could be presumed from the time at which the respondents answered, there

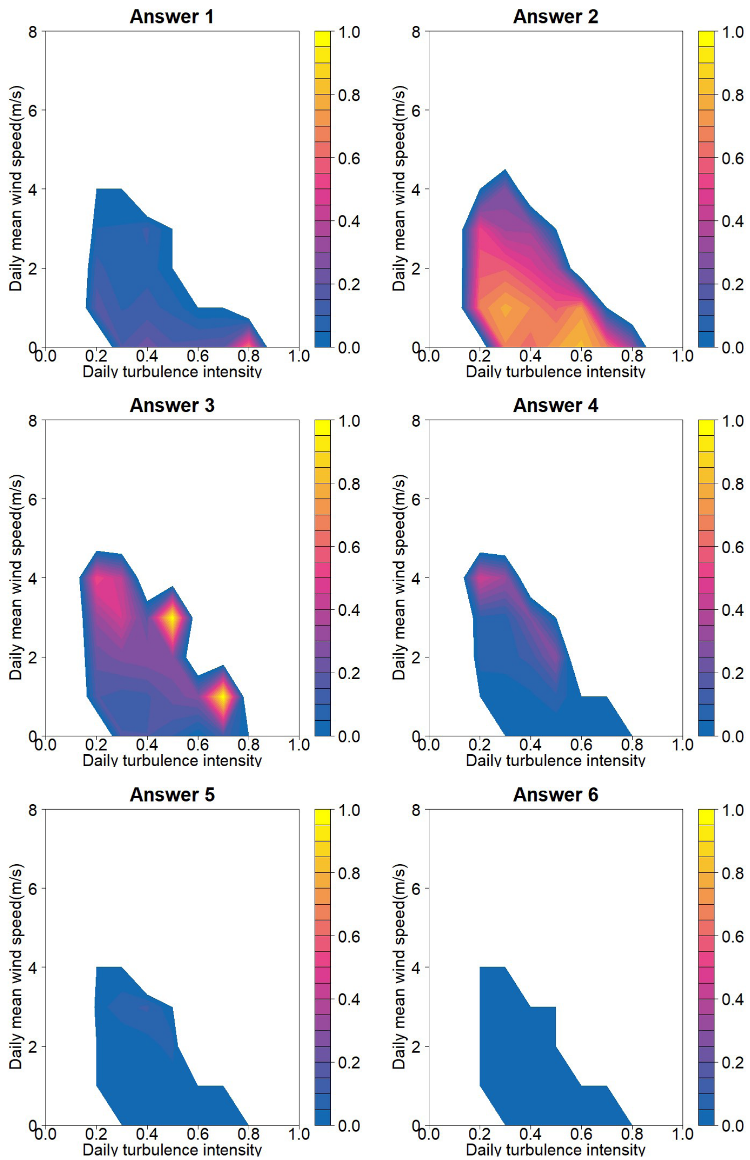


Fig. 4. Dependence of relative frequency of each answer to Question 1 on daily mean wind speed and turbulence intensity

are concerns about the error. In order to investigate this error, another questionnaire survey about the period of time for which respondents felt the perception was conducted from August 2017. The results of this survey showed that the respondents mostly answered the questions within one hour at most of when they experienced the perception. Therefore, the data of the questionnaire survey was reorganised as every 1-hour data, considering the uncertainty.

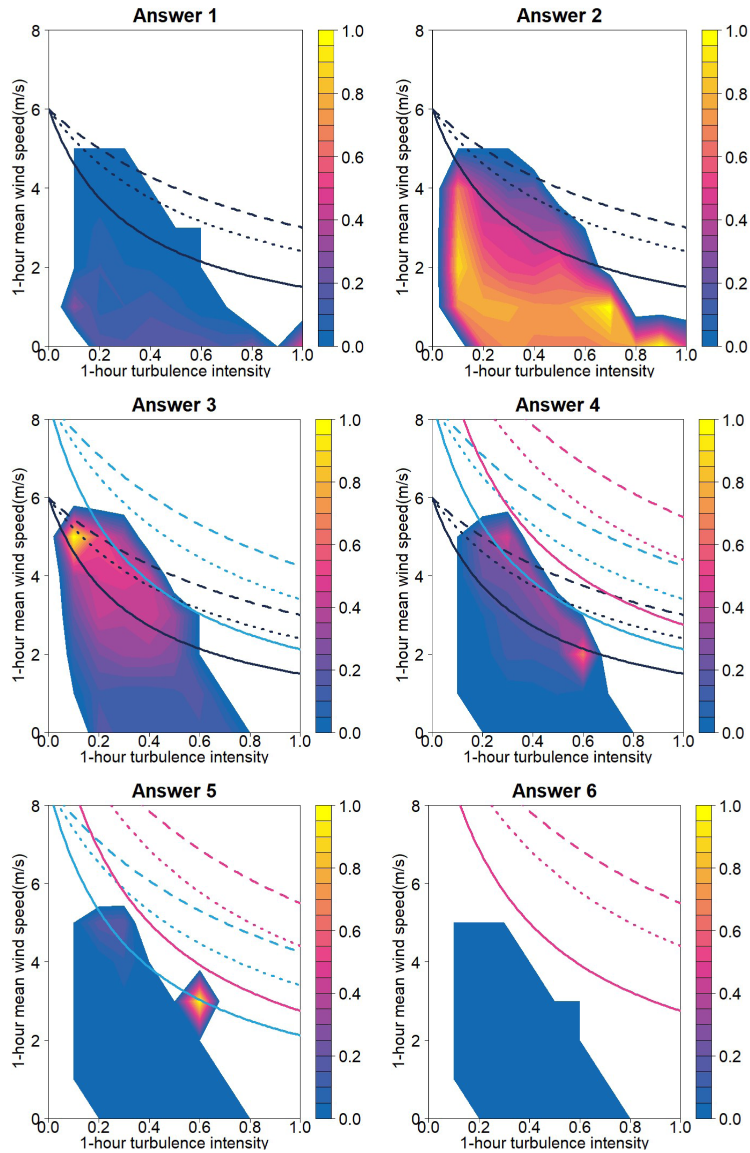


Fig. 5. Dependence of relative frequency of each answer to Question 1 on 1-hour mean wind speed and turbulence intensity (solid line: $k = 3$, dotted line: $k = 1.5$, dashed line: $k = 1$, black: $U_e = 6$ m/s, blue: $U_e = 8.5$ m/s, pink: $U_e = 11$ m/s)

Figure 5 shows the dependence of the relative frequency of each answer to Question 1 on 1-hour mean wind speed and turbulence intensity. The figure has less dispersion and shows the relation between them more clearly than Fig. 4. The curves in Fig. 5 represent the effective wind speeds U_e defined by Eqn. (2):

$$U_e = U + k\sigma_u = U(1 + kI_u) \tag{2}$$

where k is the weight coefficient, and σ_u is the standard deviation of the fluctuating wind speed.

Although we have not performed any statistical test, it seems that the curve corresponding to $k = 3$ correlates well with the data. Therefore, we tentatively propose this value of k in the following discussion. Figure 6 shows the relationship between the 1-hour effective wind speed with $k = 3$ and the relative frequency of each answer to Question 1. It is found that the relative frequency of Answers 1 and 2 (Answer 1+2) is the highest in the case where the 1-hour effective wind speed is lower than or equal to 6.5 m/s. Similarly, the relative frequency of Answer 3 is the highest in the case where the 1-hour effective wind speed ranges from 6.5 m/s to 9 m/s. The relative frequency of Answers 4 and 5 (Answer 4+5) is highest in the case where the 1-hour effective wind speed is higher than 9 m/s. These results are consistent with those of Hunt et al. [4], who showed that the effective wind speed corresponding to "For comfort and little effect on performance" is lower than 6 m/s. Similarly, they showed that the effective wind speed corresponding to "Most performance unaffected" is lower than 9 m/s. Furthermore, they explained that the upper limit of effective wind speed corresponding to "Control of walking" is 15 m/s. Based on the results mentioned above, the relationship between the perception of wind strength and the effective wind speed with $k = 3$ is proposed as shown in Table 3.

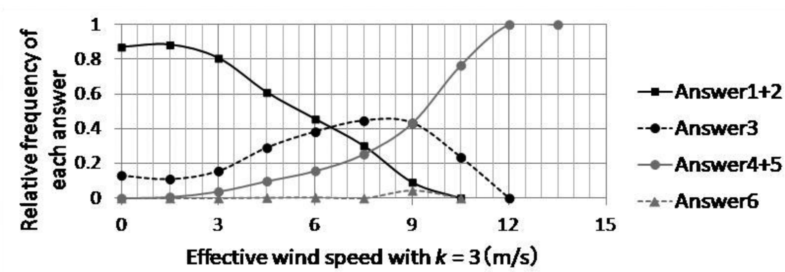


Fig. 6. Relationship between the effective wind speed with $k = 3$ and the relative frequencies of Answers 1–6

Table 3. Relationship between the perception of wind strength and the effective wind speed with $k = 3$

Effective wind speed	Perception of wind strength
$U_e \le 6.5$ m/s	I : "agreeable"
6.5 m/s < $U_e \le 9$ m/s	II : "slightly strong"
9 m/s < $U_e \le 15$ m/s	III: "strong and uncomfortable"
$U_e > 15$ m/s	IV: "dangerous"

5.2. Relationship between the perception of the temperature of wind, the wind speed, and the air temperature

In this section, the dependence of the perception of the temperature of wind on the wind speed and the air temperature is discussed using the answers to Question 2. The subject of this discussion is the discomfort caused by low wind speed and high temperature. In this case, as pointed out by Murakami et al. (1985), it seems more appropriate to discuss this problem based on the mean wind speed, which corresponds to the effective wind speed with $k = 0$.

Figure 7 shows the relationship between the relative frequencies of Answers A–D and the mean wind speed when the temperature is higher than or equal to 25 °C. The relative frequency of Answers A and B (Answer A+B) is higher than those of Answers C and Answer D in the case where the mean wind speed when the temperature is higher than or equal to 25°C is lower than or equal to 1 m/s. Figure 8 shows the dependence of the relative frequencies of Answers D–F on the mean wind speed when the temperature is lower than 10°C. The relative frequency of Answers E and F (Answer E+F) is higher than that of Answer D in the case where the mean wind speed when the temperature is lower than 10 °C is higher than 0.5 m/s. Based on these results, the dependence of the perception of the temperature of wind on the mean wind speed and temperature may be provided as shown in Table 4.

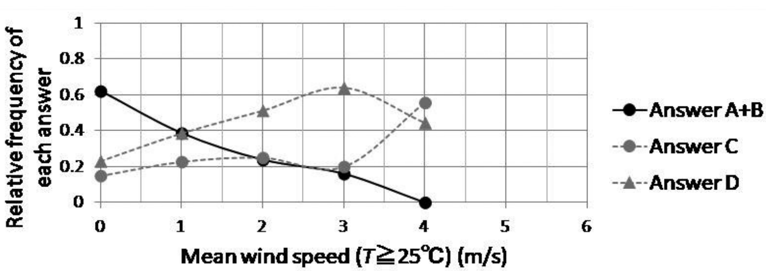


Fig. 7. Relationship between mean wind speed (air temperature is higher than or equal to 25°C) and relative frequency for Answers A–D

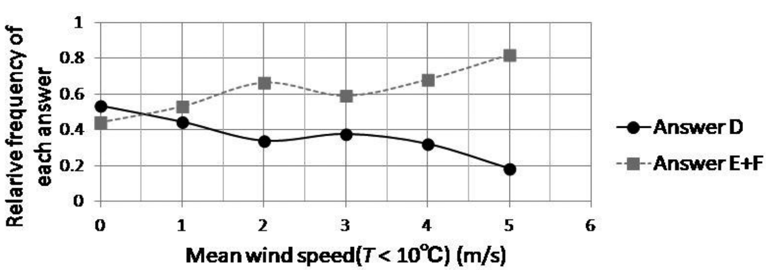


Fig. 8. Relationship between mean wind speed (air temperature is lower than 10°C) and relative frequency for Answers D–F

Table 4. Dependence of the perception of the temperature of the wind on the mean wind speed and air temperature

Mean wind speed and air temperature T	Perception of temperature of wind
$U \le 1$ m/s ($T \ge 25$ °C)	a : "unpleasantly hot"
$U > 0.5$ m/s ($T < 10$ °C)	b : "it gets cold by the wind"

5.3. Dependence of wind-induced discomfort on the wind speed and the turbulence intensity

In this section, the dependence of wind-induced discomfort on the wind speed and the turbulence intensity is discussed, using the answers to Question 3. It may be appropriate to use the instantaneous wind speeds for this discussion. Note that the maximum instantaneous

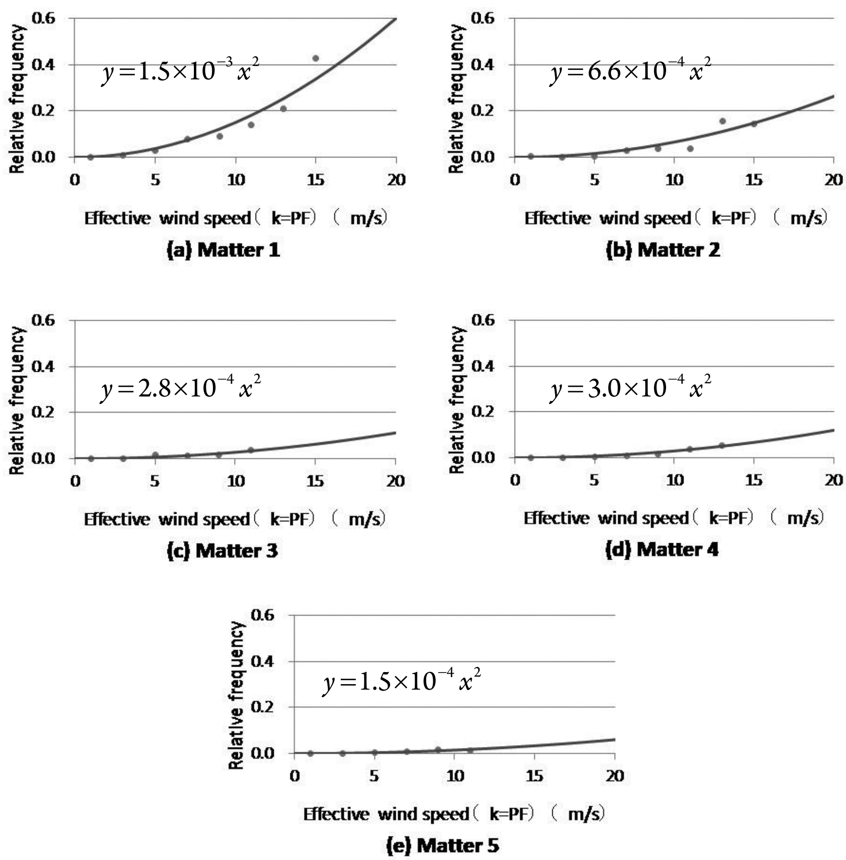


Fig. 9. Relationship between the effective wind speed with k = PF and the frequency of the wind-induced discomfort which respondents experienced or witnessed

wind speed corresponds to the effective wind speed with k = PF (peak factor). For the consistent again discussion, the effective wind speed with k = PF is used, although the maximum instantaneous wind speed can be obtained directly from the observation and experiment. In the present study, PF is provided by Eqn. (3), which is derived from an empirical formula proposed by Akahoshi et al. [2] based on the field observation at a height of 3 m above the ground. Note that this equation is a simplified form of the original:

$$g = 2.76\overline{I_u} + 2.77 \tag{3}$$

where g is a peak factor; and Iu represents 1-hour mean turbulence intensity.

The frequency of the wind-induced discomfort which the respondents experienced or witnessed is provided by Eqn. (4):

$$f_{e,i}(U_{e,PF}) = \frac{N_i(U_{e,PF})}{N(U_{e,PF})} \tag{4}$$

where $N_i(U_{e,PF})$ is the number of answers of Matter i at an instantaneous wind speed $U_{e,PF}$; $N(U_{e,PF})$ is the number of all answers at an instantaneous wind speed $U_{e,PF}$.

Figure 9 shows the relationship between the effective wind speed with k = PF and the frequency of the wind-induced discomfort which respondents experienced or witnessed.

Note that Matter 6 is excluded from the discussion because the number of answers is too small. The quadratic curve in each figure represents an empirical formula obtained by applying the least squares method to the plotted data. This result corresponds well to a finding by Nakamura et al. [8] that the frequency of the reports of human falling down by strong winds can be evaluated by the square of maximum instantaneous wind speed.

6. Proposed criterion for wind environment assessment with consideration to the effect of turbulence

6.1. Relationship between WEI criterion and the perception

Based on the results shown in Table 3 and 4, the relationship between the WEI criterion and the perception of wind is discussed. The mean wind speeds at a cumulative frequency of 55% and 95% were obtained from the field observation performed for one year at thirty-three observation points in urban area. In the same way, the relative frequencies of 1-hour effective wind speeds corresponding to the Perception I, I + II and I + II + III were obtained. Figure 10 shows the dependences of the mean wind speed at the cumulative frequencies of 55% and 95% on the cumulative frequency of the effective wind speeds corresponding to Perceptions I, I + II and I + II + III. In each figure, the solid line represents an empirical formula obtained by fitting the data, which is similar to the Weibull distribution. The vertical dashed lines represent the boundary values in the WEI criterion. From this figure, it is found that the mean wind speed at a cumulative frequency of 95% is stronger correlated with the cumulative frequency of effective wind speed than that at a cumulative frequency of 55%.

This may be due to the fact that the duration of stay of the respondents was relatively short. Therefore, in order to investigate the relationship between the perception of wind and the mean wind speed at a cumulative frequency of 55%, a longer duration of stay should be taken into account. Based on these results, the empirical formulae representing the relationship between the mean wind speed at a cumulative frequency of 95% and the perception of wind strength are proposed as follows:

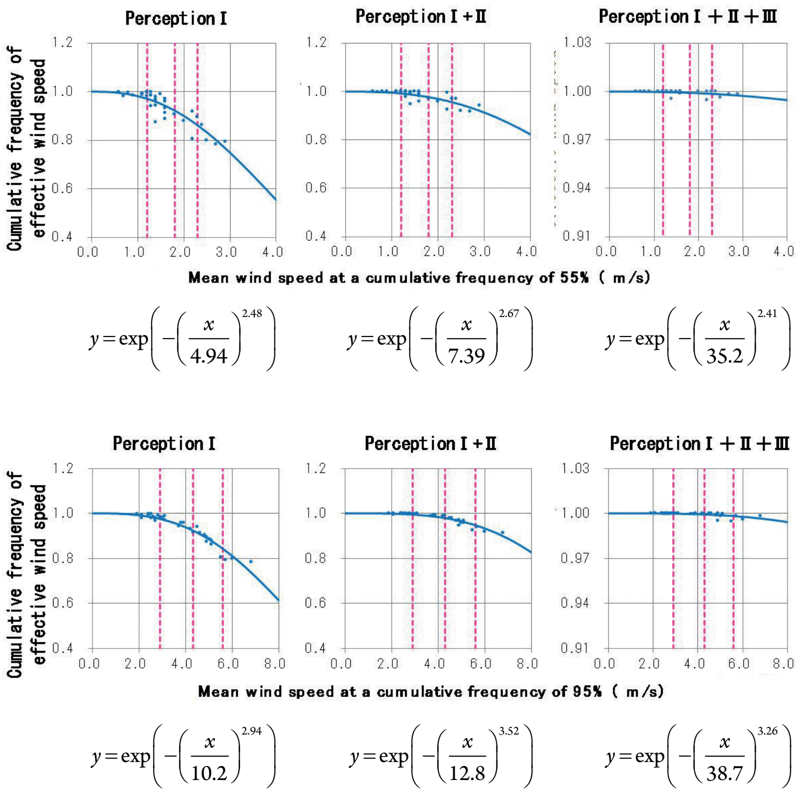


Fig. 10. Relationship between the mean wind speed at the cumulative frequencies of 55 % and 95 % and the relative frequency of effective wind speed corresponding to Perceptions I, I+II, I+II+III

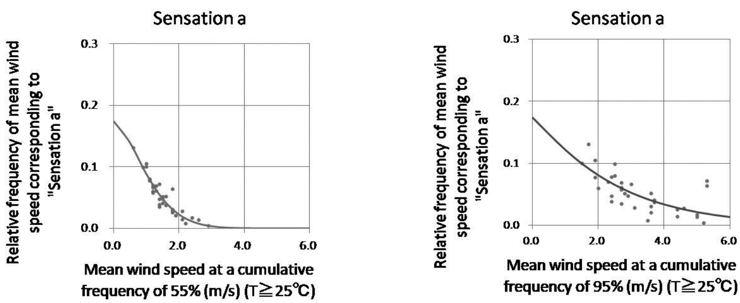
$$F_1=\exp\left(-\left(\frac{U_{95}}{10.2}\right)^{2.94}\right) \tag{5}$$

$$F_{1+2}=\exp\left(-\left(\frac{U_{95}}{12.8}\right)^{3.52}\right) \tag{6}$$

$$F_{1+2+3}=\exp\left(-\left(\frac{U_{95}}{38.7}\right)^{3.26}\right) \tag{7}$$

where F_1, F_{1+2} and F_{1+2+3} are the cumulative frequencies of the effective wind speeds corresponding to the Perceptions I, I + II and I + II + III, respectively; U_{95} is the mean wind speed at a cumulative frequency of 95%.

Figure 11 shows the dependence of the mean wind speed at the cumulative frequencies and 55% and 95% when $T \geq 25°C$ on the relative frequency of the mean wind speed corresponding to Perception a (see Table 4). From the figure, it was found that the mean wind speed at a cumulative frequency of 55% is better correlated with the relative frequency of the mean wind speed than that at a cumulative frequency of 95%. The solid line represents an empirical formula obtained by fitting the data, which is similar to the Weibull distribution. The intercept of the approximate curve, 0.174, corresponds to the mean value of the relative frequency of temperature higher than or equal to 25°C obtained from the 33 observation points. Based on these results, an empirical formula representing the relationship between the mean wind speed at a cumulative frequency of 55% when $T \geq 25°C$ and the perception of the temperature of the wind is proposed by Eqn. (8):



$$y = 0.174 \exp\left(-\left(\frac{x}{1.28}\right)^{1.59}\right)$$

Fig. 11. Relationship between the mean wind speed at the cumulative frequencies of 55% and 95% and the relative frequency of mean wind speed corresponding to Perception a ($T \geq 25°C$)

$$F_a = 0.174 \exp\left(-\left(\frac{U_{55,T25}}{1.28}\right)^{1.59}\right) \tag{8}$$

where F_a is the relative frequency of the mean wind speed ($T \geq 25°C$) corresponding to Perception a; $U_{55,T25}$ is the mean wind speed at a cumulative frequency of 55% ($T \geq 25°C$).

6.2. New criterion

In this section, a new criterion for wind environment assessment with consideration to the effect of turbulence is proposed, using the results shown in the previous subsections. The new criterion is based on the effective wind speeds with $k = 0$ and $k = 3$.

Firstly, the criterion based on the effective wind speed with k = 3 is discussed. The cumulative frequencies of the effective wind speeds corresponding to the boundary values of the WEI criterion were provided by Eqs. (5)–(7) and the results are shown in Table 5. Furthermore, it was found that the effective wind speed followed the Weibull distribution, using the observation data at thirty-three observation points in the chosen urban area. Assuming that the relative frequency of the effective wind speed follows the Weibull distribution, the Weibull coefficients were obtained by using the least squares approximation; Table 5 presents the results. The effective wind speeds at a cumulative frequency of 95% corresponding to the boundary values of the WEI criterion were obtained from the Weibull distribution with the coefficients in Table 5; the results are summarised in Table 6.

Secondly, the criterion based on the effective wind speed with k = 0 is discussed. The ISO recommends that PPD (predicted percentage of dissatisfied) related to PMV (predicted mean vote) should be less than or equal to 10 %. In the present study, the effective wind speed, V, with k = 0 which makes the relative frequency of Perception a less than or equal to 10 %, is investigated. V is provided by Eqn. (9) assuming that coefficients in Eqn. (8) are constant regardless of the relative frequency of temperature higher than or equal to 25 °C:

$$V = 1.28\left\{-\ln\left(\frac{0.1}{P_{T25}}\right)\right\}^{0.63} \tag{9}$$

where P_{T25} is the relative frequency of temperature higher than or equal to 25°C (≥ 0.1).

The case where the effective wind speed at a cumulative frequency of 55% when $T \geq 25$°C is less than or equal to V is regarded as 'discomfort'.

The above discussion is based on the evaluating time of one hour. This should be changed to 10-minute values, because the WEI criterion is based on 10-minute values. A preliminary analysis of the data obtained at Thirty-three observation points indicated that the relative frequency of 1-hour effective wind speeds was almost the same as that of 10-minute effective wind speeds. Regarding the temperature, we obtained the similar result. Therefore, it is not necessary to convert the values obtained above to the 10-minute values.

Based on the above-mentioned results, the relationship provided in Table 6 is proposed as a new criterion for wind environment assessment with consideration to the effect of turbulence.

Table 5. Cumulative frequency of the effective wind speed corresponding to each perception, Weibull coefficients and boundary value of WEI criterion (95%)

WEI criterion		F_1	F_{1+2}	F_{1+2+3}	Weibull coefficient	
Rank	Boundary values (95%)				C	K
A	2.9 m/s	0.976	0.995	1.000	1.71	0.98
B	4.3 m/s	0.924	0.979	0.999	2.99	1.22
C	5.6 m/s	0.842	0.947	0.998	4.28	1.47

Table 6. Proposed criterion for wind environment assessment with consideration to the effect of turbulence

U_e with $k = 0$ at 55% cumulative frequency ($T \geq 25°C$)		U_e with $k = 3$ at 95% cumulative frequency	
discomfort	$\leq V$	Rank A	≤ 5.2 m/s
		Rank B	≤ 7.4 m/s
		Rank C	≤ 9.1 m/s
		Rank D	> 9.1 m/s

7. Comparison between new criterion and present criteria

A comparison between the new criterion proposed in the present study and the current criteria is made using the field observation data at thirty-three observation points in the urban area. Note that the current criteria refer to the WEI criterion shown in Table 1 and the criterion of Murakami et al. (1983) shown in Table 7.

Table 8 shows a comparison between the results evaluated by these criteria. Firstly, comparing the new criterion based on U_e with $k = 3$ and the WEI criterion, it is found that the evaluated results became worse at three points, for example, from A to B, while those at six points became better. This means that the evaluated results become better or worse by considering the effect of turbulence on the human perception. Secondly, according to the new criterion based on U_e with $k = 0$, the evaluated results at Points 17 and 33 are both 'discomfort'. At Point 33, the result evaluated by the WEI criterion is 'A', while by Murakami et al. criterion, it is 'rank 1'. Therefore, the wind is thought to be weak throughout the year. By contrast, at Point 17, the evaluated result by the WEI criterion is 'B', while by Murakami et al. criterion, it is 'rank 2'. This result indicates that the wind at Point 17 is weaker in summer than in other seasons. These results indicate that the new criterion proposed in the present study evaluates the wind environment more appropriately than the current criteria.

Table 7. Criterion of Murakami et al.

Rank	The exceeding probably of the daily maximum instantaneous wind speed		
	10 m/s	15 m/s	20 m/s
1	≤ 10 %	≤ 0.9 %	≤ 0.08 %
2	≤ 22 %	≤ 3.6 %	≤ 0.6 %
3	≤ 35 %	≤ 7 %	≤ 1.5 %
4	> 35 %	> 7 %	> 1.5 %

Table 8. Comparison between the evaluated results by the three criteria ('-' means that the evaluated result isn't 'discomfort')

Point No.	Evaluated results			
	WEI	Murakami et al.	new criterion	
			$k = 0$	$k = 3$
1	D	4	-	D
2	B	1	-	B
3	C	2	-	C
4	D	3	-	C
5	B	1	-	B
6	A	1	-	B
7	C	2	-	B
8	A	1	-	A
9	C	2	-	B
10	B	1	-	A
11	B	2	-	B
12	C	4	-	C
13	B	2	-	B
14	A	2	-	A
15	B	2	-	B
16	B	1	-	B
17	B	2	discomfort	B
18	C	3	-	C
19	C	4	-	D
20	D	4	-	D
21	C	2	-	C
22	B	1	-	A
23	A	1	-	A
24	C	3	-	C
25	D	4	-	D
26	C	2	-	B
27	A	1	-	A
28	B	1	-	A
29	B	2	-	B
30	A	1	-	B
31	A	1	-	A
32	A	1	-	A
33	A	1	discomfort	A

Table 9. Boundary values of each criterion which are redefined

Rank	WEI		Murakami et al.			new
	55 %	95 %	10 m/s	15 m/s	20 m/s	$k = 3$
1	≤ 0.40	≤ 0.97	≤ 3.33	≤ 0.30	≤ 0.03	≤ 1.73
2	≤ 0.80	≤ 1.93	≤ 6.66	≤ 0.60	≤ 0.06	≤ 3.46
3	≤ 1.20	≤ 2.90	≤ 10.0	≤ 0.90	≤ 0.08	≤ 5.20
4	≤ 1.40	≤ 3.37	≤ 14.0	≤ 1.80	≤ 0.25	≤ 5.93
5	≤ 1.60	≤ 3.84	≤ 18.0	≤ 2.70	≤ 0.42	≤ 6.66
6	≤ 1.80	≤ 4.30	≤ 22.0	≤ 3.60	≤ 0.60	≤ 7.40
7	≤ 1.97	≤ 4.73	≤ 26.3	≤ 4.73	≤ 0.90	≤ 7.97
8	≤ 2.13	≤ 5.16	≤ 30.6	≤ 5.86	≤1.20	≤ 8.54
9	≤ 2.30	≤ 5.60	≤ 35.0	≤ 7.00	≤ 1.50	≤ 9.10
10	> 2.30	> 5.60	> 35.0	> 7.00	> 1.50	> 9.10

In order to compare the results evaluated by the three criteria with each other in more detail, each criterion's boundary values are redefined by dividing them equally into 10 ranks, as shown in Table 9. Figure 12 shows a comparison between the evaluated results by the three criteria based on Table 9. It was found that the results evaluated by the new criterion approximately lie approximately between those by the WEI and the Murakami et al. criteria. This result indicates that the new criterion reflects the characteristics of both criteria.

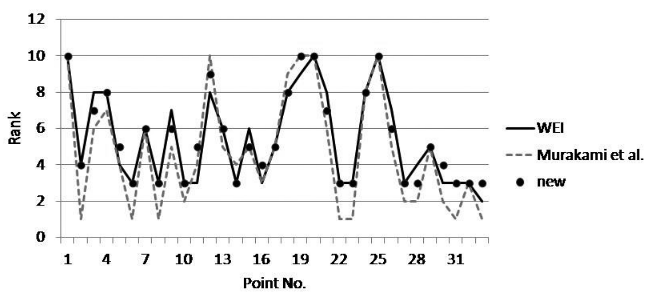


Fig. 12. Comparison between the evaluated results of three criteria by using the boundary values shown in Table 9

8. Conclusion

On the basis of the results of the field observation, the wind tunnel experiment, and the questionnaire survey in Kamiosaki, the relationship between the WEI criterion for wind environment assessment and the human perception of wind was investigated. In addition, a new criterion considering the effect of turbulence was proposed; this evaluates the wind environment more appropriately than the current criteria. However, it is necessary to improve this criterion by increasing the number of items of data in the field observation and in the questionnaire survey.

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